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OPERATION GREENHOUSE

SCIENTIFIC DIRECTOR'S REPORT

ANNEX 1.6 BLAST MEASUREMENTS

PART IV — PRESSURE-TIME MEASUREMENTS IN THE MACH REGION

SECTIONS 1 AND 2

NUCLEAR EXPLOSIONS

1951

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Annex 1.6

Blast Measurements

Part IV — Pressure-Time Measurements in the Mach Region

Sections 1 and 2

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BLAST MEASUREMENTS

Part IV—Pressure-Time Measurements in the Mach Region

Section 1

Measurement with Diaphragm-type Variable-inductance Gauge

Section 2

Measurement with Spring-piston Gauge

Approved by: FREDERICK REINES
Director, Program 1

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White Oak, Maryland

July 1951

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Acknowledgments

The work reported here was done under the supervision of G. K. Hartmann.

The authors wish to acknowledge the excellent laboratory and field work performed on the project by Joseph E. Berry and John A. Rowe, both of the Naval Ordnance Laboratory.

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SECTION 1 – MEASUREMENT WITH DIAPHRAGM-TYPE VARIABLE-INDUCTANCE GAUGE

SECTION 2–MEASUREMENT WITH SPRING-PISTON GAUGE

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Abstract

Pressure-time measurements on Tests Dog and Easy were made in the Mach region between 5 and 100 psi with a diaphragm-type inductance gauge and a spring-piston gauge. Measurements were made at constant height along a single radius on Test Dog and along two different radii for Test Easy. In addition, diaphragm-type inductance gauges were installed at five different heights on approximately the same radii on Test Easy. From these data the following blast parameters were obtained: maximum pressure, impulse, and duration, both positive and negative; arrival time of the shock; rise time to the initial maximum pressure; time of occurrence of the maximum pressure; and decay constant from the maximum pressure.

The diaphragm-type inductance-gauge measuring system had an accuracy of 2 per cent in pressure and a resolving time of approximately 1 msec. Data were stored electrically on magnetic recording tape. The spring-piston gauge was a direct-recording mechanical system capable of 5 per cent accuracy in pressure with a resolving time of 15 msec.

Complete details concerning equipment design, field operation, and recommendations for future use of the systems are presented.

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Section 1

MEASUREMENT WITH DIAPHRAGM-TYPE VARIABLE-INDUCTANCE GAUGE

by

JOHN F. PRICE

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Chapter 1

Introduction

1.1 OBJECTIVE

The objective of the laboratory and field work described in this report was to make accurate measurements of air blast in the Mach region from two explosions of Operation Greenhouse. These measurements were of overpressure as a function of time and were taken at a fixed height above ground and at distances from ground zero selected so that the peak-pressure levels varied from 5 to 100 psi. In addition, measurements were made at selected heights above ground at three different distances from ground zero. The data were analyzed to determine the following blast parameters: maximum positive and negative pressures, positive and negative durations, and positive and negative impulses. Additional information obtained from the records and recorded was as follows: time constant of decay from the maximum pressure, time of arrival of the shock wave at the measuring point, rise time to the initial peak pressure, and time of occurrence of the maximum positive pressure.

In order to make these measurements, it was necessary to design and construct a reliable system of instrumentation that could be used readily in the field. The experience on Operation Sandstone in this type of measurement was of considerable value in the design of the equipment. The end instrument used on these tests was a modified version of the one used on Sandstone. Magnetic recording tape used for the first time on this type of test as an electric storage medium for pressure-time data proved quite reliable for that service.

1.2 REQUIREMENTS FOR A SYSTEM OF INSTRUMENTATION FOR OPERATION GREENHOUSE

The basic requirements for a pressure-time measuring system for Operation Greenhouse were largely derived from data and field experience obtained from previous tests on nuclear explosions, particularly Operation Sandstone. These basic requirements separated logically into two classes: the first class included the requirements imposed on the measuring system by the phenomena to be measured, and the second included the requirements imposed on the system by the conditions under which the measurements had to be made. The system requirements due to the phenomena could be accurately determined because data from previous tests, together with information on air blast from small charges, allowed rather accurate predictions of the expected pressure-time relations at various measuring points in the Mach region. These requirements were principally resolution or response requirements. The operational requirements were determined from previous field experience and included capacity for accommodating a large number of measurements, an insensitivity to electromagnetic radiation, and an ability of the system to operate unattended.

1.2.1 Response Requirements

In order to estimate the high-frequency-response requirements for the system, the Fourier Transform method of analysis was

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used. An approximate analytic pressure-time relation was selected which fitted the Sandstone data well during the positive duration of the pressure cycle at peak pressures less than 30 psi. This relation is

$$p = P_0\left(1 - \frac{t}{\tau}\right) e^{-t/\theta}, \quad t \geq 0; \qquad p = 0, \quad t = 0 \qquad (1.1)$$

where p = overpressure in pounds per square inch

P_0 = maximum value of overpressure

t = time in seconds, where zero time is taken as the time of arrival of the shock wave at the measuring position

τ,θ = parameters that vary with the measuring point and the tonnage and are analogous to charge weight and distance. τ is equal to the positive duration, and $\tau + \theta$ is the time of occurrence of the negative maximum.

The procedure was to transform an analytic approximation of the pressure-time relation to its spectrum equivalent and successively pass this spectrum through networks of limited but known response. The resultant responses were then plotted with the original pressure-time function, and the response requirements were determined for a 2 per cent error in peak-pressure measurement. (This error figure of 2 per cent was held as the design objective throughout because it was believed to be a practical limit for systems of this type and represented an improvement of a factor of 3 over the Sandstone data. See Sandstone Report, Vol. 20, Table 2.) Figure 1.1 shows the system high-frequency-response requirements for this error plotted against peak pressure in the range expected for different TNT tonnage equivalents. Clearly, the over-all system high-frequency response must extend to 500 cycles to limit the response error to 2 per cent for measurements for a 50-kt explosion.

In addition to the high-frequency-response requirements, there is the consideration of low-frequency response for the measuring system. It is evident from the extremely long durations of the pressure wave that the system must resolve very low-frequency components. One of the measurements is impulse, and this requires an integration of the pressure-time data. If there is insufficient low-frequency response, there will be a corresponding error in the indicated value of impulse. Therefore it is necessary that the system accurately indicate changes of pressure that occur over periods of time in the order of 10 sec. Because of limitations in vacuum-tube circuit design, this requirement effectively imposes a direct current or zero frequency response on the system. This means that if the system is to be electronic it must be one in which the pressure information is carried as a modulation. On the basis of the arguments just presented, it is clear that any system designed to measure air blast in the Mach region to within 2 per cent must be capable of resolving information varying at rates between 0 and 500 cycles, and, if the system is to be electronic, it must be a carrier system.

Additional basic requirements for an air-blast measuring system for atomic explosions are that the elements of such a system be insensitive to electromagnetic radiation and that the fundamental design be such that the system is capable of accommodating a large amount of information without size, complexity, and power requirements becoming prohibitive.

1.2.2 Unattended Operation

Another requirement was imposed on the system by the personnel hazards inherent in an atomic explosion. Safety considerations demanded that all personnel be several miles away from the blast range during the time of the explosion. It was therefore necessary that all equipment placed on the blast range be capable of unattended operation and remote control. This requires positive operation of all individual components, ruggedness under shock conditions, and long life of all parts as referred to expected operating time. Ability to operate under remote control specifically requires positive operation of all control elements. Control had to be limited to nothing more complex than power on-off switching, and all equipment had to be capable of having adjustments preset so that no adjustment would be necessary during operation.

Conditions at the blast range imposed the additional requirement that the equipment be capable of operation without an external source of power. Batteries were therefore considered exclusively as the prime power source at the

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measuring site. This imposed the final requirement that the power drain of the measuring system be minimized and, in any case, be sufficiently low so that the space required for batteries would not become excessive.

1.3 HISTORY AND EVALUATION OF PREVIOUS INSTRUMENTATION

Pressure-time information from atomic explosions have in the past been obtained from several different gauges. Piezoelectric gauges, commonly used to obtain such information for small-charge explosions, have been found unsatisfactory for measurements on atomic explosions owing to inadequate low-frequency response, low signal level, and excessive sensitivity to electromagnetic radiation. As noted previously, the time durations involved in air blast from an atomic explosion are so long that the low-frequency response of the measuring system must be essentially flat to direct current, and therefore a carrier system is mandatory. Among those carrier systems which have been tried is one utilizing a condenser microphone gauge which frequency-modulates an r-f carrier and is therefore well suited to telemetering.[1] An amplitude-modulated a-f carrier system has also been used, in which a strain gauge varies the balance of an a-c bridge. When used with very short cable, this gauge has produced acceptable results; however, spurious signals, possibly due to temperature and hysteresis effects, detract from the usefulness of the strain gauge for such measurements as are being considered here.

1.3.1 Pressure-Time Measurements on Operation Sandstone

Strain gauges were chosen for use on Operation Sandstone because of previous success with them in air-blast measurements on Operation Crossroads. Other pressure-time measurements were telemetered by means of a modified version of the Bumblebee telemetering system.[2] The pressure gauge in the Bumblebee system was a corrugated diaphragm whose motion varied the inductance of a vacuum-tube oscillator and thus produced a frequency-modulated a-f signal. This system had the necessary response to direct current, and, although the high-frequency response was limited to well under 100 cps, the method had the overwhelming advantage that the Bumblebee system was in a high state of development, having been developed during World War II to telemeter pressure and acceleration information from missiles in flight. Therefore the gauges, oscillators, and other component units could be obtained commercially, and no extensive development was necessary.

On Operation Sandstone the frequency-modulated audio signal was used to frequency-modulate an r-f transmitter. At each measuring point on the blast range, a gauge, oscillator, and transmitter were mounted in a single unit, cushioned by foam rubber, and placed in a hole in a concrete footing set in the ground. Six such installations were used for each explosion. A short whip antenna, mounted on the cover plate which sealed each hole, transmitted the r-f signal to a receiving antenna 120 ft above the ground several miles away. At the receiving site an f-m receiver demodulated the signal from each antenna, reproducing the audio carrier. This carrier, in turn, was demodulated to produce a voltage varying in time with the pressure changes at the gauge. The voltage was then applied to a recording galvanometer to produce graphically a pressure-time curve. This system proved to be the most accurate and reliable device used to obtain pressure-time curves on Operation Sandstone.[3] The pressure-time curves thus obtained showed unusually good agreement with Friedrich's parametric expression for the pressure-time relation.[4] It was concluded that, although the telemetering system as used on Sandstone had several limitations, the Bumblebee pressure gauge produced results which strongly recommended its consideration for use in any subsequent atomic tests.

1.3.2 Limitations of the Telemetering System

The telemetering system used on Operation Sandstone was limited primarily by the small amount of information it was capable of handling. There were limitations (1) on the number of measurements that could be made at any one time and (2) on the frequency response available for each measurement. These two limitations, moreover, were interrelated so that, in general, improvement in one could be obtained only at the expense of the other.

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The number of measurements was limited by the fact that at each measuring point a separate transmitter was used, thus requiring a separate receiving antenna and receiver as well as a separate r-f channel for each measurement. It was therefore impractical to take more than six measurements on any one explosion, and impossible to take more than eight, in spite of the large complement of men and equipment devoted to the telemetering program.

The frequency response of each measurement was limited by several factors. The gauge itself, originally intended to measure slow variations in pressure on the surface of a missile in flight, was developed without special concern for high-frequency response. As used on Sandstone, the diaphragm was coupled to the measuring point by a rubber tube $\frac{1}{8}$ in. in inside diameter, approximately 1 ft in length, with a tortuous path at either end. Moreover, considerations of bandwidth and gauge linearity imposed a limitation on the frequency deviation of the audio carrier to $\pm 7\frac{1}{2}$ per cent of the carrier center frequency, and the over-all system bandwidth was designed to this figure. Audio center frequencies of from 2,300 to 12,300 cps were used; and, therefore, on the basis of full-scale deviation ($77\frac{1}{2}$ per cent) and a deviation ratio of 5, an approximate frequency response can be computed.[5] At the lowest subcarrier frequency the response of the f-m system could not have been much above 35 cps, and at the highest carrier frequency the response was probably limited to about 180 cps. The over-all response, including the gauge and the recording galvanometer, was estimated, on the basis of a treatment similar to that described in Sec. 1.2.1, to be at best 45 cps.

An examination of these limitations, in light of the requirements for Operation Greenhouse set forth in Sec. 1.2, led to the conclusion that the system used on Sandstone was incapable of the large number of measurements to be made, particularly in view of the increased frequency response necessary for the desired accuracy. However, the inductance gauge, limited in its response characteristic more by the pressure entry path than by its inherent design, promised to provide a significantly higher frequency response with minor modifications. Furthermore, the gauge, with its audio oscillator, could easily be made to provide an f-m signal at a level of several volts. A signal of this level could be expected to be quite insensitive to extraneous effects such as radiation, temperature changes, or cable signal associated with the blast and would be well suited to any type of transmission, whether by cable or radio link.

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1. W. C. Bright, Condenser Gauges, Los Alamos Scientific Laboratory Report, LA-366.
2. Sandstone Report, Vol. 22, Annex 5, Chap. 13.2.
3. Sandstone Report, Vol. 20, Annex 5, p 9.
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5. MTRI 13/14 Comm'tt[illegible] Guided Missiles; RDB Telemetering Stan[illegible]ization Program, Technical Information.

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Chapter 2

Design and Test of Measuring System

2.1 CHOICE OF SYSTEM

On the basis of the considerations outlined in Chap. 1, the choice of a system to make the desired measurements was based on the initial choice of the Bumblebee diaphragm-type variable-inductance gauge. Several possible methods were available for transmitting the signal from this gauge to a remote recording point. These methods were examined, and the system was finally chosen which incorporated magnetic-tape recorders in blast huts at low-pressure locations on the blast ranges.

2.1.1 Comparison of Possible Systems

Perhaps the simplest and most straightforward scheme considered for use with the chosen end instrument consisted in the placement of a gauge with its oscillator at each measuring point and the transmission by cable of the f-m audio carrier back to a sheltered point at the end of the blast range where a blast hut could be located. Here each signal could be fed into a discriminator and demodulated. All the pressure-time signals on any one atomic explosion could then be recorded simultaneously on a multichannel recording oscillograph. The advantage of such a system would be its simplicity and the small amount of equipment required, as compared to the Sandstone telemetering system. A further advantage over the telemetering system would be the possibility of using the same carrier frequency for all gauges. This frequency could be chosen to be quite high, thus allowing transmission of a large amount of information. Such a system would, essentially, replace each radio link in the telemetering system by a length of cable but would require, as in telemetering, a separate discriminator for each measurement. All the equipment, moreover, would have to operate unattended during the time of the measurements.

Another system considered was a combination of cabling and radio link. The signal in such a system would be cabled back to the hut in the same way as in the system just described and would be used to modulate a high-power transmitter. Such a system would have many advantages. By means of frequency-division multiplexing, many different frequencies, each carrying a separate signal, could be made to modulate each transmitter simultaneously, thus reducing the necessary number of transmitters and receivers. The number of discriminators, however, would still be as great as the number of individual measurements. A second advantage would be that the transmitter, being located in a low-pressure area, could be quite large and capable of high-power transmission. A highly efficient antenna array could also be constructed in this area without fear that it might be blown down by the blast.

However, the disadvantages of this system would be numerous. In addition to the need for large numbers of discriminators, there would also be the necessity of retaining all the Bumblebee subcarrier frequencies and therefore the limited frequency response accompanying them. There would also be the problem of maintaining several r-f channels clear of interference. This proved to be a difficult problem on Operation Sandstone.

The system which seemed most promising involved cabling the data signal from the gauge oscillator back to the hut as previously described and at that point recording the

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modulated carrier itself for later reduction. One advantage of such a scheme is the reduction of the unattended equipment in the field to two major components: the gauges with their oscillator units and the sound recorders. The high state of development of sound-recording techniques recommended their use, particularly since the a-f nature of the carrier signal made possible the use of most of the features existing in commercially available sound recorders. The magnetic-tape recording medium was felt to be especially well suited to this type of signal. This type of recorder, which had received so much attention since 1945, was capable of unattended operation with great reliability. Remote control of tape recording was possible by means of simple on-off switches, since it was quite feasible to preset recording levels for a constant amplitude signal such as was here to be recorded. Furthermore, the design of multiple recording heads was known to be feasible, and tape recorders could therefore be readily adapted to multichannel operation in which many separate data signals could be recorded simultaneously on the same strip of tape. Still another advantage would be the great simplification of the data-reduction equipment resulting from the fact that each signal could be recorded independently on a multichannel tape recorder, and all signals could be at the same carrier frequency. Thus the data-reduction equipment could be reduced to a single discriminator and associated recording oscillograph, and the tape could be played back many times, once for each data signal. Also worth noting is the fact that the roll of tape carrying the f-m carrier signal would provide a permanent record capable of being played back an indefinite number of times and recorded at different oscillograph recording speeds or gains to obtain the optimum graphical representation for analysis, report illustration, or any other need.

A major disadvantage arises from the problem of tape speed instability or flutter, which causes instantaneous variations in the frequency recovered in playback from a recording of an f-m carrier signal. This variation, being itself a frequency modulation of the carrier, would compete with the data modulation and appear as noise on the final pressure-time record. In the best commercially available tape recorders the flutter index is approximately 0.1 per cent rms. Since the variations in speed and, consequently, in frequency can be considered as approximately sinusoidal, although of no fixed period, the instantaneous signal played back might differ from the actual signal recorded by as much as 0.17 per cent peak. Using the inductance-gauge end instrument, the frequency deviation due to peak pressure could be expected to be about 6 per cent. Therefore uncertainty or error in the peak-pressure measurements could be as much as 2.3 per cent. However, various electronic schemes were available to compensate for this error at the expense of increased equipment.

Another contribution to such error arises from the stretching or shrinking of the tape itself between the time of recording and the time of playback. This causes an apparent change in the recorded frequency of as much as 5 per cent but at a very slowly varying rate. Such error can be corrected during playback by adjusting the tape playback speed so that it will accurately reproduce a reference frequency that was recorded from a standard frequency source at the time of the explosion.

Because these disadvantages could be overcome, largely by equipment used in playback rather than in recording, and because the advantages of magnetic-tape storage seemed basic, it was decided that this method compared favorably with all others considered. Therefore a complete instrumentation system was designed, using magnetic-tape recorders, to record in a blast hut the f-m carrier from each gauge.

2.1.2 Description of the Proposed System

An air-blast measuring system for Operation Greenhouse was designed to meet the objectives set forth in Sec. 1.1. The elements of this system are shown in the functional diagrams of Figs. 2.1 and 2.2. As may be seen in Fig. 2.1, the pressure being measured causes a deflection of the gauge diaphragm and therefore a change in the gauge inductance. Since the inductance is the tuning element of a vacuum-tube oscillator, a frequency shift proportional to the pressure change appears at the oscillator output terminals. The oscillator output is transmitted by cable to the blast hut where its frequency is heterodyned to

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an intermediate frequency and recorded on part of a magnetic tape in a transverse track approximately 0.05 in. wide. A single tape carries six gauge signals and a calibration signal, each in its separate track. The signals are recorded on tape at an intermediate frequency in order to minimize the effec of flutter in the final record. This is possible because the amount of uncertainty in the record is proportional to the frequency that carries the information on the tape. If, for example, a 1-kc tone is recorded on a machine with a flutter index of 0.1 per cent, this flutter will frequency-modulate the 1-kc tone. On playback, the instantaneous frequency of the reproduced signal will vary between 999 and 1,001 cycles. However, if the 1-kc tone is heterodyned to 100 cycles and then recorded with the same flutter index, the reproduced signal will vary between 99.9 and 100.1 cycles. When this signal is heterodyned back to 1 kc, the tone will vary between 999.9 and 1,000.1 cycles. The uncertainty in the latter case is one-tenth that of the directly recorded 1-kc tone, or an increase in the signal-to-noise ratio of 10 times.

After the blast, the tape is removed and played back in the laboratory on the reproducing machine. As shown in Fig. 2.2, a switch (S1) connects any one of the six signal playback heads to an amplifier which delivers the intermediate frequency to the poststorage mixer at the proper level. After mixing, the f-m carrier is restored to the gauge oscillator frequency and is demodulated. The output, which is the pressure-time information in d-c voltage form, drives a galvanometer in a recording oscillograph. The pressure-time record is photographed on film or paper in the oscillograph and, after developing, is in the final form for purposes of analysis.

Pressure calibration is obtained from two crystal-derived frequencies, one corresponding to the gauge quiescent frequency and the other to the gauge frequency at the expected peak pressure. These are continuously recorded on the calibration channel of the tape and are passed through the playback system in sequence by a switch (S2) just before and just after the desired pressure information. Thus a calibration step simulating a precisely known pressure appears on the final photographic record.

The time calibration on the final photographic record is obtained from a standard frequency source applied to a separate galvanometer in the oscillograph. The accurate use of this sinusoidal time base is possible only if the information is extracted from the tape at exactly the same rate at which it was originally recorded.

2.2 DETAILED DESCRIPTION OF SYSTEM

2.2.1 End Instrument

The end instrument used for obtaining pressure-time data was an improved version of the diaphragm-type inductance gauge used in Operation Sandstone. The gauge was originally developed by the Applied Physics Laboratory, The Johns Hopkins University, for use in the Bumblebee telemetering system. Essentially, the gauge is a variable-reluctance instrument consisting of two pressure chambers separated by a corrugated beryllium-copper diaphragm. Attached to the diaphragm and facing an inductor is a disk of a high-permeability alloy, hydrofined mumetal. This chamber is sealed at atmospheric pressure to provide the reference pressure. A length of tubing is fitted to the other chamber for connection to the source of pressure to be measured. Pressure applied through the tube causes a deflection of the diaphragm, thus changing the air gap of the magnetic circuit. Used as the frequency-controlling element of an oscillator, the gauge can be adjusted to produce, on the application of pressure, any desired frequency shift from the quiescent frequency. The basic features of the gauge are shown in Fig. 2.3. Figure 2.4 is a photograph of the gauge and its component parts.

A detailed discussion of the Sandstone inductance gauge, Mark 3, Mod 5, is presented in the reports on that Operation.[1] Basically, the Mark 5 gauge used in Operation Greenhouse differs from the Mark 3 mainly in its size. In the Mark 3 the diaphragm diameter is 1.375 in., whereas for the Mark 5 it has been reduced to 1.194 in., thus increasing the high-frequency response.

The effect of temperature variation is to change the position of the diaphragm and hence the air gap of the magnetic circuit. This shifts the quiescent frequency of the oscillator controlled by the gauge inductance. In order to

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verify the manufacturer's characteristics (Table 2.1) and to determine an order of magnitude for errors due to temperature effects, the gauge was tested with an oscillator tuned to 14,070 cps. The temperature of the air surrounding the gauge was raised from a room temperature of 74 to 94°F. The oscillator frequency was then measured and found to be 14,025 cps, a change of about 0.3 per cent for a 20°F change in temperature.

TABLE 2.1 MARK 5 INDUCTANCE-GAUGE CHARACTERISTICS FROM MANUFACTURER'S SPECIFICATIONS

Characteristics	Specifications
Temperature errors	Less than 2 per cent of pressure range for change of 40°F. Shift in zero reading for 2-min contact with 300°F surface less than 2 per cent.
Acceleration error	Negligible with plane of diaphragm in plane of acceleration. With diaphragm perpendicular to acceleration, 5 g produces shift in zero of about 0.1 per cent for 60-psi gauge; 0.3 per cent for 30-psi gauge.
Natural frequencies of diaphragm	Vary from 500 cps for low-pressure gauges to 2,000 cps for high-pressure gauges.
Response	Generally limited by recording equipment; also dependent on length of connecting tubing.
Accuracy of gauge	1.5 per cent.

The daily temperature variation at the Eniwetok Proving Ground is only a few degrees, and the gauge locations and the nature of the tests precluded any temperature effects from the blast itself during the period of measurement. Because of these considerations and because the oscillators could be trimmed to the correct quiescent frequency under conditions corresponding to test conditions, the errors due to temperature effects were considered negligible. A source of error inherent in the design and use of the gauge, which manifests itself in the same way as the variation in temperature, is the variation in atmospheric pressure. The atmospheric pressure at South Bend, Ind., at the time the gauge is sealed and calibrated does not always equal that at the measuring site. Again, however, proper tuning of the oscillators just prior to test makes errors due to this source negligible.

The pressure-frequency characteristics of the Mark 5 gauges are very nearly linear. Hence, after the final settings of the oscillators, any slowly varying quiescent conditions shifting the zero-pressure points can be detected and compensated for in the analysis of the final record by measuring the actual shifts in frequency caused by the actuating shock phenomenon.

Since no accelerations greater than 1 g were expected on Operation Greenhouse, this factor was considered of minor importance in so far as its effect on the inductance gauge was concerned.

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The TTP-3A gauge is able to reproduce its results within 1.5 per cent under constant test conditions. This figure is termed its accuracy. It is not meant to indicate that the results produced will be a reproduction of the actuating phenomenon with a maximum error of 1.5 per cent, because it is the frequency-response limitation which prevents the gauge from following precisely very rapid changes of the phenomenon.

The response requirements for Bumblebee telemetering were approximately 50 cps. Shock-tube tests on the gauge, using various lengths and diameters of inlet tubing, showed that the limit of maximum response was approximately 200 cps. Since the requirements for Operation Greenhouse varied from 300 to 500 cps, the gauge was modified to produce the required response.

The sensitive elements of the gauge are the pole faces of the E magnet on which the inductive coil is wound and the mumetal disk on the diaphragm. The spacing between elements is set under critical tolerances by the manufacturer and determines the linearity of the gauge. Alteration of this section would be equivalent to the development and production of an entirely new gauge. The gauge back, which, together with the diaphragm, forms the air chamber open to the atmosphere through the inlet tube, offered the only opportunity for modification.

In reaching the final design of the gauge back, the following considerations were held important:

1. The air space behind the diaphragm must be as small as possible to reduce the filling time.

2. The inlet passage for the transmission of air pressure must be as smooth as possible to eliminate resistance to flow.

3. The length of the passage from shock space to the air chamber must be as short as possible to reduce both the filling time and also the severe acoustical filtering due to a long narrow flow chamber.

4. The inlet passage must be of as large a diameter as possible to provide the maximum rate of air-chamber filling without overexciting the diaphragm and causing high-amplitude vibrations, or "ringing."

The over-all configuration of the air chamber was found to be already at its minimum depth in the Mark 5 gauge. When the depth was reduced by as little as 10 per cent, diaphragm resonance caused the diaphragm to strike the gauge back.

The minimum possible inlet-tube length was determined mainly by the mounting requirements described in Sec. 3.2.1. Essentially, the gauge was to be mounted behind a metal wall of 1-in. thickness. It was decided, therefore, that an external length of 1.5 in. for the inlet tube was the minimum length which could be used in mounting the gauge in the wall access.

The inner diameter of the inlet tube was determined for each gauge range by shock-tube tests at about 60 per cent of its maximum rated pressure. With large inner diameters, the response was very high, but the diaphragm resonated under strong shock excitations. This had the effect on the record of an underdamped system. Therefore the inner diameter of tube used was one which gave the best compromise of maximum response and minimum overshoot to provide a usable record. An outside tube diameter of 0.25 in. was chosen to provide an over-all sturdy construction for the gauge.

The path in the gauge housing from the tube recess to the air chamber was drilled at an angle of 17.5°. The inner diameters of the inlet tubes necessary to provide the desired response characteristics in the various gauges were large. Direct entry in the plane of the diaphragm would have ruptured the seal between portions of the gauge and would also have enlarged the air space. The 17.5° angle was used as a compromise between the minimum angle usable without breaking the pressure seals and convenience of manufacture. Sketches of both the original and modified gauge backs are shown in Fig. 2.5.

It will be noted in Fig. 2.3 that the axis of the inlet tube does not coincide with the axis of the short 17.5° section in the gauge back. The decision to insert the inlet tube in the plane of the diaphragm was reached after it was noted that with the tube at 17.5°, offering the air pressure a direct transmission path to the air chamber, the diaphragm appeared to be excessively shock-excited, producing high-amplitude low-frequency oscillations which could not be filtered from the record. With the tube in the plane of the diaphragm, the pressure, and hence the air mass moving into the air chamber, is deflected by the short

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17.5° section in the gauge back. This reduced considerably the effects of shock excitation of the diaphragm, perhaps because the moving air mass retained some momentum along the diameter of the air chamber.

Considerable improvement in response was noted when the inlet passage was changed from the original right-angle turn to a smooth entry from the outside.

Tests made on the Mark 5 gauge were performed on the low-pressure and high-pressure shock tubes of the Explosive Effects Division at the Naval Ordnance Laboratory. Variations of the gauge oscillator frequency, caused by a shock wave traveling by the gauge inlet tube, were discriminated and photographed from the face of an oscilloscope in the form of a pressure-time curve.

Test results of the response characteristics are recorded in Table 2.2.

TABLE 2.2 INDUCTANCE-GAUGE TEST RESULTS

Gauge* (psi)	Selected Tube Diameter† (in.)	Response‡ (cps)
+10 to −4	0.055	320
+20 to −8	0.076	410
+30 to −10	0.136	500
+60 to −14	0.136	500§

* The 15-psi gauge was not available during the test program. Limitations in the shock tubes prevented tests of the 100- and 150-psi gauges.

† It was not feasible to use a tube diameter larger than 0.136 in. because of the shallow depth of the air chamber.

‡ See reference 2.

§ Approximate.

A sample test record is shown in Fig. 2.6. This is the output of the test system with a 30-psi gauge. A pressure step of 21 psi was applied, and the response was calculated to be 500 cps (rise time, 1 msec).

At the test site the gauges were placed in the field in structures, the sides of which were constructed of steel plates with access openings of large diameter at each of the gauge stations. The closure plates for the openings were drilled to provide a $\frac{1}{2}$-in. hole near the center. The $\frac{1}{4}$-in.-OD inlet tube was shock-mounted in rubber in this hole; the end of the inlet tube was flush to the outside of the closure plate. The closure plates for the vertical gauge stations were drilled with the $\frac{1}{2}$-in. hole rising at an angle of 15° to the inside. At these stations, therefore, the body of the gauge was slightly higher than the inlet tube opening, thus preventing rain and dirt from getting into the air chamber.

In order to hold the gauge on the closure plate against the external shock pressure, foam rubber was placed around the body of the gauge and firmly pressed against it by a U bracket attached to the plate itself. Figure 2.7 is a sketch of the mounting arrangement.

2.2.2 Gauge Oscillator and Power Supply

The gauge just described formed the inductance in the tank circuit of a conventional vacuum-tube oscillator of the Hartley type, utilizing a type 6C4 miniature tube as shown in the circuit diagram of Fig. 2.8. In order to assure oscillator frequency stability independent of impedance changes and other effects in the cable leading from the gauge station back to the blast hut, a cathode-follower stage was incorporated into the oscillator unit. The cathode follower consisted of two 6AQ5 miniature tubes, which were connected in parallel to double the capacity of this stage for carrying load current. Such an arrangement permitted the cathode follower to match the high oscillator impedance output to a 500-ohm load resistor and also permitted the development of a high-level signal (12 to 15 v) across this low-impedance load. The load resistor itself was located in accordance with common practice at the far end of the signal-carrying cable rather than within the oscillator unit. This arrangement reduced considerably the heat dissipated within the oscillator.

An oscillator was placed with each gauge at its measuring point. Plate and filament power was delivered to the oscillator over conductors of the same cable which carried the signal back to the blast hut. When mounted in its assembly and placed at the measuring point, the oscillator showed satisfactory stability. Each oscillator was tuned to 14.5 kc, and drift from a cold start never exceeded 2 cps in the first 5 min of operation and tended to be about 10 cps in the first hour. Such drift introduced no appreciable error into the measurements.

Because frequency instability due to plate voltage variation could introduce errors of as much as 1 or 2 per cent, a simple regulated voltage supply was chosen to provide plate power. A circuit diagram of this supply is shown in Fig. 2.9. Heater power was obtained from batteries, and, in order to reduce loss in the cable, the heaters of the three vacuum tubes were connected in series so that the heater current delivered to the oscillator unit was minimized. Direct-current heater voltages were used to reduce hum pickup problems. The details of the heater power are discussed in Sec. 2.2.11.

2.2.3 Signal and Power Transmission

Four-conductor shielded cable, Navy type MCOS-4, was used to connect each gauge station on the blast range to the equipment in the hut at the end of the range. The four conductors carried plate current, filament current, the signal, and a common ground connection. All cables were buried several feet beneath the surface of the ground, and at each end they were connected to the electronic units by standard AN connectors of the 3100 series.

2.2.4 Prestorage Mixer

For reasons outlined in Sec. 2.1.2, the signal from the gauge oscillator in the field could not be directly recorded but had to undergo a frequency change before it was recorded. This change was accomplished by a vacuum tube connected as a frequency converter or mixer. Such a circuit has two input voltages, each of different frequency, and a single output voltage whose frequency can be the sum or difference of the two input frequencies. In the present application, a low-pass filter was used in the output circuit of the mixer to eliminate all but the difference frequency of the two signals to be heterodyned.

At atmospheric pressure, the frequency of the gauge oscillator was adjusted to be 14,500 cps. This frequency changes with the pressure applied to it, the maximum frequency change being 1,088 cycles from the center value of 14,500 cycles. This maximum change or deviation from the center value corresponds to 7.5 per cent of the center value, which is the analogue of 100 per cent modulation in the amplitude-modulated case. The spectrum or bandwidth required to transmit a carrier with this deviation depends on the amount of information to be transmitted. In this application, a maximum response (information) of 500 cps was required. From an analysis of f-m transmission, the bandwidth required to transmit a 14.5-kc signal with a 6 per cent deviation and carrying 500 cycles of information is approximately 5,000 cycles.[3] This means that the bandwidth of the mixer output circuit had to be at least this wide so as not to distort (up to 500 cycles) the information carried by the oscillator signal.

This bandwidth requirement sets the lower frequency limit for the intermediate signal to be recorded at 2,500 cycles for its center or atmospheric-pressure value. The certainty or noise in the final record due to flutter is minimized when this intermediate frequency has a minimum value; therefore a figure close to 2,500 cycles is the indicated choice. A figure of 2,600 cycles was chosen to allow for oscillator drift. Thus the frequency that heterodyned the gauge frequency was the sum of the intermediate and gauge frequencies, 17.1 kc.

The schematic diagram of this mixer is shown in Fig. 2.9. Mixing is accomplished with a 12AU7 dual-triode vacuum tube, each control grid taking one of the signals to be mixed, 14.5 and 17.1 kc. The anodes of the 12AU7 were parallel-connected to a low-pass filter where cutoff frequency was approximately 5,100 cycles. The use of the filter in this manner rejected all frequencies out of the pass band by not providing any impedance on which such signal voltages could be developed.

The output of the low-pass filter went directly to the tape recorder. The 17.1-kc beating frequency was derived from a crystal source mounted on another chassis in the same relay rack and will be described in Sec. 2.2.10. Electric power for the mixer was obtained from a voltage-regulated power supply on the same chassis with the mixer. This power supply also was used to power the gauge oscillator unit on the blast range.

2.2.5 Magnetic-tape Recorder and Reproducer

There was, at the time that this system was being designed, no commercially available magnetic-tape recorder which met all the requirements for the type of data recording here being considered. However, the Ampex Electric Corporation Model 301 magnetic-tape sound recorder contained many features well suited to such data recording, and a contract was let for the fabrication of recorders patterned closely after the Ampex sound recorders.

In setting up the specifications for this data recorder, several basic design objectives were considered and may be listed as follows:

1. Seven separate heads were required so that seven separate channels could be recorded simultaneously on a single tape, providing facilities for six data channels and one calibration channel.

2. Tape-speed regulation had to be constant to the extent that the combined wow and flutter from both the recording and the playback process was less than 0.1 per cent rms. This meant that when a constant frequency note was fed into the recorder it would be reproduced during playback with an instantaneous frequency value never more than 0.14 per cent different from the frequency originally recorded. Such speed regulation had to be maintained regardless of the fact that in the field the 60-cps 110-v power was expected to vary by as much as ±10 per cent in frequency and ±5 per cent in voltage.

3. The recorder had to be capable of proper operation under exposure to conditions of limited shock and vibration.

4. The recorder had to be capable of unattended operation and of simple and positive remote control.

5. In order to prevent the possibility of loss of records, no erase head and no provisions for any separate erase voltage could be present on either the recorder or the reproducer.

With the above as major design criteria, two separate instruments were designed. The recorder, shown in Fig. 2.10, was mounted on a relay rack, and the rack was supported by springs which served as shock mounts to reduce the effects of any vibrations transmitted to the structure in which the recorder was located. The reproducer, or playback machine, shown in Fig. 2.11, was mounted in a console and was intended for use under laboratory conditions.

A great reduction in shock and vibration effects, with no increase in flutter index, was obtained by adopting a belt drive in which the drive motor was always engaged to the capstan flywheel by means of a nylon belt. A prototype recorder operated satisfactorily when equipped with belt drive, shock-mounted, and subjected to accelerations much greater than any expected in the field during operation.

Except for the change from rim to belt drive, the only important modification of the Model 301 tape-transport mechanism resulted from the fact that for multiple-channel operation $\frac{1}{2}$-in.-wide tape was necessary rather than the $\frac{1}{4}$-in. tape used on the commercial instrument. This called for increased dimensions on various tape guides, spindles, and the capstan, but these changes did not call for any major design or development.

The conversion to $\frac{1}{2}$-in. tape width was made necessary by problems connected with head design. When used for seven channels, $\frac{1}{2}$-in. tape permitted each channel to be 0.050 in. wide with separation between adjacent channels of 0.020 in. Practical difficulties prevented the arrangement of all seven heads in a single stack, and therefore two adjacent stacks were made, one of four individual heads, the other of three. The stack of four heads recorded the signal onto, or reproduced the signal from, the first, third, fifth, and seventh channels as counted down from the top of the tape. In the same way the stack of three heads corresponded to the second, fourth, and sixth channels. Staggering the heads in this way permitted 0.090 in. on each stack for support and shielding.

The construction of the individual heads is shown in Fig. 2.12. The completed head was assembled as shown in Fig. 2.13. Each core and winding was placed in a brass holder and separated from adjacent cores by alternate layers of mumetal and copper which provided magnetic isolation between the adjacent heads. Record and playback heads were essentially the same except that the gap width between the core halves on the record head was 0.002 in. and on the playback head, 0.005 in.

The recording and playback electronics are quite conventional. The record amplifier

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consists of seven identical single-stage amplifiers, all powered from the same power supply and all obtaining bias voltage from the same 60-kc bias oscillator. The amplifier circuit diagram is shown in Fig. 2.14, and the power supply and bias oscillator are shown in Fig. 2.15.

Two separate playback amplifiers are shown in Fig. 2.16, each of which could be connected to any one of the playback heads. Each amplifier unit consisted of a three-stage resistance-coupled amplifier with a cathode-follower output stage which was capable of developing 5 v across a load of 27,000 ohms. A tuned amplifier, selective to 900 cps, provided a separate output for speed control.

Speed-control considerations are of two types. First, there are instantaneous variations in tape speed, which may occur at rates from a few cycles per second up to several hundred cycles. Careful machining of critical components had already provided an acceptable flutter index of 0.1 per cent due to variations of this sort. In addition, however, in order to maintain a constant tape speed during recording, a constant-frequency power source for the capstan drive motor was considered essential. This was necessary because the capstan drive motor was of the hysteresis synchronous type. Because the field power source could not be expected to provide a constant frequency, a tuning-fork oscillator was used as the frequency standard. A Riverbank tuning fork of 69 cps with an accuracy of 5 ppm/°C was chosen as the oscillator whose output drove a 100-watt push-pull power amplifier shown in Fig. 2.17. Power for all other parts of the recorder was obtained directly from the motor generator used as a primary power source.

The second speed-control consideration arises from the stretching or shrinking of the tape between the time of recording and the time of playback. This effect may cause apparent variations in the recorded frequency of as much as 5 per cent. In order to compensate for these variations, a manual method for playback speed control was adopted. A 900-cps note was recorded on the calibration channel during the recording process. During playback this 900-cps signal from the tape was applied to the tuned amplifier whose output was fed to a cathode-ray oscilloscope. Against this signal there was heterodyned the output of a standard 900-cps tuning fork. Since the playback capstan drive motor was of the synchronous type, it was possible, by varying the frequency of the power to the motor, to obtain and maintain on the oscilloscope face a zero-beat Lissajous pattern between the 900 cps from the tape and that from the tuning fork. The variable-frequency oscillator used to control the capstan speed was of the Wien bridge type and is shown in Fig. 2.18. The coarse frequency adjustment varied the frequency over a range of approximately 6 cycles, and the fine adjustment varied frequency over a fraction of a cycle. The output of this oscillator was made to drive a 100-watt power amplifier similar to that in the recorder. The schematic diagram of the amplifier which drove the playback capstan drive motor is shown in Fig. 2.19.

2.2.6 Poststorage Mixer

The calibration and pressure-data signals that were stored on the tape were in intermediate-frequency form. Before these signals could be discriminated they had to be changed in frequency so their deviations or bandwidths could be accommodated by the discriminator. (The choice of discriminator was made largely on the basis of availability as a commercial item.) A vacuum tube connected as a frequency converter was used for this operation in much the same manner as in the prestorage mixer. The schematic diagram of the poststorage mixer is shown in Fig. 2.20. The dual triode, 12AU7, had the two signals to be mixed applied to its control grids as before. One of these signals was the beat-frequency oscillator whose frequency was again 17.1 kc as in the prestorage mixer. The other control grid was switched automatically or manually to one of three signals from the tape. One of these three signals is the pressure-data signal; the other two are pressure-level calibration signals which are recorded as a composite and separated by electrical filters before mixing.

In the output circuit of the mixer a band-pass filter is used as the impedance upon which the desired mixer product developed. This filter

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has sufficient bandwidth to accommodate a 14.5-kc signal carrying 500 cycles of information. The output of the band-pass filter is amplified in one vacuum-tube stage and developed on a 500-ohm impedance by a cathode-follower stage for transmission to the discriminator for demodulation. The mixer unit includes the mixer itself, the amplifier, the cathode follower, necessary band-pass filters (or signal separators), and a power supply.

2.2.7 Discriminator

A discriminator was used to convert the output signals of the poststorage mixer into an electrical replica of the recorded intelligence suitable for driving a final recorder to obtain visual records. The discriminator was made by Electro-Mechanical Research, Inc., under the title Subcarrier Discriminator Model No. 27A.

The input circuit of the discriminator was a cathode follower having an input impedance of at least $\frac{1}{2}$ megohm, preceded by an attenuator enabling utilization of input signals ranging in level from 10 mv to 10 v.

Following the input cathode follower was a band-pass filter which allowed selection of the desired f-m signal and provided rejection of two other signals which were simultaneously applied to the input.

After filtering, the desired f-m signal was amplified and limited, the limited signal actuating a pulse-forming circuit which delivered one pulse for each cycle of the limited signal.

Each of these pulses triggered a one-shot multivibrator which returned to its rest state after a time interval equal to half the reciprocal of the center frequency of the selected f-m signal. The return time of the multivibrator was determined by the circuit constants of a plug-in network augmented by a fine adjustment. By the proper choice of one of a number of such plug-in networks, the return time of the multivibrator could be adjusted, with the aid of the fine adjustment, to correspond to any chosen f-m signal in the frequency range 400 cps to 80 kcps.

When the return time of the multivibrator was adjusted to correspond to the center frequency of the selected f-m signal, the average voltage measured between the plates of the multivibrator tubes was proportional to the deviation of the signal from the center frequency.

The plates of the multivibrator tubes were connected to the grids of push-pull cathode followers, which performed the operation of averaging the voltage difference between the multivibrator plates. The process of discrimination was thus a joint function of the multivibrator stage and the averaging stage.

Following the averaging stage was a push-pull cathode-follower stage, providing a balanced output having an effective source impedance of 330 ohms. Overload protection was incorporated in the output circuit, limiting the current output to 15 ma.

With the output load 330 ohms, the output current delivered to the load was 10 ma when the f-m signal deviated $7\frac{1}{2}$ per cent from its center frequency. Within this $7\frac{1}{2}$ per cent range of deviation, the output current was proportional to the deviation to within $\frac{1}{2}$ per cent.

When the input-signal level was within the correct limits, the input-level meter on the front panel read on the green marked sector of its scale. This green sector represented a variation in level of 20 db from its upper to lower limit. When the signal-level indicator dropped below the green sector, the discriminator became inoperative. When the signal level indicated above the green sector, the discriminator became nonlinear in its output-current-to-input-frequency relation.

The maximum allowable deviation of the chosen f-m signal was determined by the band-pass filter following the input stage. When the deviation exceeded 10 per cent, the attenuation of the filter caused the signal level to drop so much that the discriminator became inoperative. For a $7\frac{1}{2}$ per cent deviation, which was the limit imposed by the gauge, the variation in signal level was 3 db, and this was well within the allowable range of the discriminator — 10 db from the center of the green sector on the level meter.

The maximum allowable modulation frequency was specified by the manufacturer to be 15 per cent of the f-m carrier frequency. Since the maximum modulation frequency arising from the gauge was 500 cps and the f-m center frequency was 14.5 kc, this limitation was respected in this system.

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2.2.8 Final Pressure-Time Record Presentation

The final pressure-time record was made with a Hathaway S-8B oscillograph. The record was made on a moving strip of photographic paper or film by a vibrating galvanometer that had an impedance of approximately 7 ohms.

The galvanometer sensitivity was such that, when the f-m signal to the discriminator deviated $7\frac{1}{2}$ per cent, the light-beam deflection on the photographic paper was approximately 3 cm.

The resonant frequency of the galvanometer was approximately 1,100 cps, and its damping was somewhat greater than critical. The sensitivity of the galvanometer was uniform from direct current to 500 cps, where it was 95 per cent of its d-c value. The damping was induced by a fluid surrounding the moving mirror of the galvanometer. The electromechanical coupling constant of the galvanometer was so small that its damping was independent of the driving-circuit impedance, and its impedance was independent of the driving frequency.

2.2.9 Pressure-vs-Frequency Calibration

A static calibration of each gauge was performed by the manufacturer at the time the gauge was sealed. A sample calibration for a 60-psi gauge is shown in Fig. 2.21. The linearity of the pressure-frequency relation exhibited by this gauge is characteristic of the TTP-3A gauge. Note that zero overpressure corresponds to a frequency of 14.5 kc and that application of 60-psi overpressure will cause a frequency shift of 1,110 cps, or 7.6 per cent. In order to provide measurement of the negative or suction phase of the blast wave, the gauge was adjusted to permit response to pressures below atmospheric down to about 1 psia.

In order to confirm the satisfactory condition of the gauges and the validity of the original calibration curves, static calibrations were made on each gauge after installation in the field. A field pressure calibrator was designed to be bolted to the closure plate over the opening of the gauge inlet tube. The chamber section of the calibrator was fitted with a relief valve at one end and a length of tubing at the other end leading to a compressed-air bottle and pressure regulator. Figure 2.22 is a sketch of the calibration assembly. Figure 2.23 is a photograph of the calibrator mounted on a wall plate.

With the gauge oscillator tuned to 14.5 kc, several values of overpressure were applied to the gauges, and in all cases there was good agreement with the initial manufacturer's calibrations. This static test, in addition to checking the calibration, also checked the system transmission from the end instrument to the blast-hut recording apparatus.

2.2.10 Frequency-shift Calibration

It was also desired to calibrate the sensitivity of the electronic system to a frequency shift. This was done by substituting for the gauge signal two precisely known frequencies, one corresponding to the quiescent frequency of the gauge oscillator when exposed to atmospheric pressure and a second corresponding to the frequency to which the oscillator shifted with peak overpressure. These frequencies were added linearly across a resistor and were then sent through the system in exactly the same way as the pressure-time information. In playback, the two signals were separated and applied in sequence to the discriminator and recording oscillograph. The calibration measurement, therefore, consisted in comparing the deflection due to the data signal with the deflection due to these precisely known calibration frequencies. From this comparison it was possible to determine the instantaneous frequency of the gauge oscillator for any point on the pressure-time curve. The measured value of pressure at any instant was then determined by reference to the manufacturer's pressure-vs-frequency calibration curves described above.

The calibration frequencies were chosen to be 13,600, 14,500, and 14,800 cps, corresponding approximately to a −6 per cent deviation from center frequency for peak overpressure and a +2 per cent deviation for maximum negative pressure. In order to obtain the accuracy required, crystal oscillators were believed to be necessary for the generation of these frequencies. Because of the practical difficulties involved in grinding crystals for audio frequencies such as these, a mixing system was used to heterodyne higher frequency oscillator signals down to the desired frequencies.

Figure 2.24 is a schematic diagram of the calibration beat-frequency oscillator unit. The 100-kc oscillator shown at the bottom of the figure utilizes a GT cut crystal and provides a reference note against which are heterodyned the outputs of other crystal oscillators at 113.6 and 114.5 kc. The mixers which provide best frequency output at the desired frequencies are similar to the mixer described in Sec. 2.2.4, except that a parallel resonant circuit was placed in the mixer cathode to degenerate the undesired input frequencies and to emphasize the difference frequency output. The calibration frequencies were combined at the output of the calibration oscillator unit and fed into a prestorage mixer identical to those used for the data signals.

The output of the 117.1-kc crystal oscillator shown at the top of Fig. 2.24 was also heterodyned against the 100-kc oscillator to provide the 17.1-kc beat frequency desired, as mentioned in Sec. 2.2.4. The four crystals used to provide signals to beat against the 100-kc note were all CT cut and were mounted together in a temperature-controlled crystal oven.

The prestorage mixer for the calibration channel is shown in Fig. 2.25. It may be seen that the mixer circuit itself is identical to that of the data-channel mixers, and the only circuit changes are in the power supply which delivered power also to the calibration oscillator unit and was redesigned to provide the greater power drain required by the larger number of tubes in the calibration oscillators and mixers.

The output of the calibration prestorage mixer was recorded on the seventh channel of the tape recorder and consisted of a composite signal including a 3,500- and a 2,600-cps constant-frequency note applied simultaneously to the recorder head. These frequencies were obtained from heterodyning the calibration frequencies against the 17.1-kc signal. There was sufficient nonlinearity in the system throughout the mixing, recording, and reproducing stages so that a 900-cps heterodyne between the 2,600- and the 3,500-cps signals could be obtained in playback. This 900-cps signal was used for speed control, as described in Sec. 2.2.5.

The calibration signals themselves were fed together from the reproducer into the poststorage or playback mixer unit, shown in Fig. 2.20. The input circuit of this unit consisted of three narrow band-pass filters which separated the composite signal into its individual components. The output of each filter was used to drive a single-stage tuned amplifier consisting of a type 6SJ7 vacuum tube whose plate load was a parallel resonant circuit tuned to the desired frequency. This amplifier further purified the filter output.

During reproduction each data signal was sent, as were the separate calibration signals, into a sequence switching circuit, shown in Fig. 2.26. The motor-driven switches in this circuit coordinated the operation of the tape reproducer and the recording oscillograph with the recorded signal in such a way as to produce a useful graphical presentation of the results. For playback the tape was edited so that the desired pressure-time information was located about 2,000 in. from the leading end of the tape. Thus, at a 30-in./sec tape speed the information would be played back about 60 sec after starting the equipment. The sequence switching circuit started the recording oscillograph just before the arrival of the information and switched the input circuit of the poststorage mixer to each of the calibration signals successively and then to the data signal itself. After the data had been recorded, the calibration signals were each switched in again, providing a frequency-shift sensitivity calibration both before and after the recording of the pressure-time information. A typical record is shown in Fig. 2.27.

2.2.11 Power Generation and Distribution

Because no source of 110-v a-c power external to the blast huts could be guaranteed to operate throughout the time of each explosion, it was evident that power should be derived entirely from batteries located within each blast hut. However, operation of the tape recorder exclusively from d-c power would have required a revision of the commercially available tape recorders so extensive as to constitute a complete new design problem. In order to avoid the expense of such redesign, to

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retain the desirable features of the commercial tape recorders, and to simplify the problem of procuring equipment, 110-v 60-cps power was considered mandatory. It was therefore decided to power all equipment from battery-driven motor generators which deliver an a-c output. Such a choice seemed particularly desirable since this type of power source operated reliably on Operation Sandstone.

Preliminary estimates of power drain indicated that each tape recorder, with all the auxiliary equipment necessary to record six data signals and calibration, would require more than 1,500 watts. Therefore 2.5-kva motor generators were chosen. At full load this required 32 v at 90 amp, which was obtained from twelve 6-v 175-amp-hr lead-acid storage batteries arranged in two banks of six. A schematic diagram of the power distribution and control for a single tape recorder is shown in Fig. 2.28. In this circuit, switch S1 connected the batteries to the motor generator or to the battery charger. Switch S2 was used to connect the a-c load either to the motor-generator output during the time of the actual explosion being measured or to the utility power line for testing prior to the measurement.

Because the oscillator heater power had to be delivered to the heaters over long cable which also carried the data signal, a-c heater voltages were considered undesirable because of the likelihood of hum pickup. In order to reduce losses in the cable, the three heaters in each oscillator unit were connected in series so that the power required at the heater was 18.9 v at 0.45 amp for each unit. With this current drain the voltage drops in the longest cables were as much as 22 v, thus calling for a supply voltage of over 40 v. A series-parallel combination of four 24-v 11-amp-hr batteries provided 48 v to each set of six oscillators. Each filament circuit contained a potentiometer which permitted adjustment of the voltage at the heaters and also served to prevent a short circuit in any one oscillator from removing the power from all the others powered from the same batteries. Switch S3 served to switch the filament batteries either to a battery charger or to the load.

Thus it may be seen that all power, during the weapons tests, was obtained from batteries arranged in parallel banks so that the failure of any one battery never removed power completely from its load. Battery power ratings were considered in the choice of batteries so that under the expected loads the delivered voltages would not drop appreciably in an hour of operation.

A set of timing relays was provided for remote control of power. At 5 min before zero time for each explosion the closing of a relay started each motor generator and delivered a-c power to the entire system. This also activated the 10-min delay relay K1 and the filament relay K2 which closed the d-c power circuit to the gauge oscillator heaters. Ten minutes after being activated, the delay relay opened the motor-generator control circuit, stopping the generator and thus turning off all power, including the d-c heater power. All equipment was thus shut off about 5 min after zero time. Prior to this, at 1 min before zero time, a timing relay closed the tape-recorder "start" circuit, applying power to the drive motor and setting the tape in motion. At 30 sec before zero time the "record" circuit was similarly closed. From then until the delay relay turned off the power, all signals were continuously recorded.

2.3 ANALYSIS OF SYSTEM ERROR

2.3.1 Error Due to High-frequency-response Limitations

The error in the final record contributed by limitations in the high-frequency response of the system was approximated separately by considering the elements possessing limited high-frequency response. A functional block diagram appears in Fig. 2.29 which shows the elements that limit the high-frequency response and their interrelation. These elements when listed in the order of their importance in limiting response are as follows: gauge inlet tube, oscillograph galvanometer element, band-pass filter in the poststorage mixer, low-pass filter after the prestorage mixer, and the other elements shown in Fig. 2.29.

The electrical filters in the frequency changers were made sufficiently wide in the pass band to accommodate an f-m signal spectrum carrying 500 cycles of information. However, the gauge inlet tube was adjusted for each gauge range and represented a

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compromise between response and signal overshoot, as discussed in Sec. 2.2.1. These compromises were made under shock conditions to assure dynamic fidelity to approximately 500-cycle response. Clearly, the greatest limitation of the high-frequency response was due to the inlet tube.

2.3.2 Error Due to Flutter

The error in the pressure due to flutter in the tape-handling mechanisms during recording and reproducing appears as random fluctuations or noise in the final record. These fluctuations are the analogue of noise in amplitude-modulated systems and represent an uncertainty in the indicated value of the pressure throughout the final record. Since the overall maximum-flutter index is known for the machines used in recording and reproducing, it is possible to estimate the uncertainty in the pressure caused by this anomaly. The maximum flutter was measured and found to be less than 0.1 per cent rms. This means that an unmodulated stable volt of frequency F, when recorded and reproduced on the machines and demodulated by a Greenhouse discriminator that yields V volts for each cycle of frequency shift, will present an error or ripple voltage (on a d-c carrier) of magnitude $0.001 \times F \times V$ volts rms at the output of the discriminator. This error voltage can be expressed as a percentage of the measured peak pressure, provided the discriminator is linear in its voltage-vs-frequency shift characteristic. Assume the pressure exceeds atmospheric by an amount that causes the gauge oscillator to shift its center frequency 6 per cent. The frequency that is recorded is not the 14.5-kc f-m carrier but the intermediate-frequency carrier of 2.6 kc. The overpressure lowers the oscillator frequency; hence the peak pressure is recorded as $17.1 - 14.5 - 0.06 \times 14.5$ kc or 3,470 cps. The output of the discriminator yields $0.06 \times 14{,}500 \times V$ volts. The ratio of signal to rms value of noise is $(0.06 \times 14{,}500 \times V)/(0.001 \times 3{,}470 \times V) = 250$. If the noise is roughly sinusoidal in character, its peak value will have increased by a factor of 2×1.4 over its rms value, and hence the signal-to-peak-noise ratio will have become 250/2.8 or 89.28. This means that the maximum error in the indicated value of pressure due to flutter will have been 1.1 per cent.

In addition to the errors caused by limited high-frequency response and flutter, there are errors caused by nonlinearity. This nonlinearity is, for the most part, in the gauge and is known; and the final record can be corrected if necessary by use of the gauge calibration curves discussed in Sec. 2.2.9. There is a nonlinearity error in the discriminator which cannot be corrected for and must be considered in determining the overall measurement error.

2.4 PRELIMINARY SYSTEM TESTING

2.4.1 Shock-tube Experiments

The high- and low-pressure shock tubes at the Naval Ordnance Laboratory were used extensively during the design phase of the measuring system. As each portion of the system was developed, it was added to the test setup at the shock tube. The gauge was subjected to a pressure stop corresponding to a frequency deviation for the oscillator of about 6 per cent. The resulting signal was carried through the system as developed at that time, and the result was displayed on a cathode-ray tube for photographing and subsequent analysis.

Initially, the pre- and poststorage mixers were directly connected, eliminating the magnetic-tape recording and playback processes, thus saving considerable time. As the development of the system progressed, the recorder and playback units were included as well as the final recording unit, the Hathaway oscillograph. These tests were used as a basis for determining the satisfactory condition of the entire system to meet the requirements for Operation Greenhouse.

2.4.2 Small-scale Test Program

A small-scale test program was organized to determine the reliability of the measuring system under field operating conditions. Several 1,000-lb charges were made available at the Army Proving Ground, Aberdeen, Md., and tests were conducted there during the month of September, 1950. The short positive durations available from a 1,000-lb charge and the response characteristics of the system imposed errors in the measurement of peak

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pressures of the order of 30 per cent. Therefore the tests were not intended to demonstrate the accuracy of the system, but they were valid field tests for the signal transmission from gauge to final record.

Except for the source of power, the system described in Sec. 2.2 was set up in a blast hut on an Aberdeen test site. Line power was used for the operation of the system units, whereas batteries were used only to provide the filament voltage for the gauge oscillators.

A wall, described in Greenhouse Report, Annex 1.6, Part II, Sec. 1, was constructed on the field. Gauges were mounted in the wall and in ground stations as they would be for the Greenhouse tests. Five gauges were used at positions corresponding to peak pressures from the 1,000-lb charge of from 10 to 40 psi. The shock signal was transmitted to the blast hut, located about 1,200 ft from the gauges, by MCOS-4 cable; and the signal was recorded on magnetic tape. The tape was later played back on the reproducer through the playback portion of the system, and the pressure-time curves thus obtained were recorded on film and photographic paper.

The results of the program were most useful in that they suggested certain engineering changes which could be incorporated into the system to improve the quality of the final record. In the field, defects which could not be observed in the laboratory became apparent and, through minor design improvements, were eliminated in the final design of the system.

REFERENCES

1. Sandstone Report, Vol. 22, Annex 5, Chap. 13.
2. E. A. Guillemin, "Communication Networks," Vol. II, pp 479-480, John Wiley & Sons, Inc., New York, 1938.
3. August Hund, "Frequency Modulation," 1st ed., McGraw-Hill Book Company, Inc., New York, 1942.

Chapter 3

Experimental Procedure

3.1 MEASURING PROGRAM

The system as outlined in Chap. 2 is one which can be used for any test of atomic weapons in which the accuracy requirements are in accord with the system specifications. Specific variations of the system due to the requirements imposed by Operation Greenhouse were manifest in the selection of end instruments for the various stations. Greenhouse requirements were prescribed in the location of the measuring points.

The inductance gauges were used to obtain data from the Runit and first Engebi shots, Tests Dog and Easy. The Runit instrumentation was based on an estimated explosion maximum of 90-kt TNT equivalent and that for Engebi on an estimated explosion of 50-kt TNT equivalent.

3.1.1 Measurements To Be Made

The distances from zero which would yield the desired peak pressures at which measurements were to be made were specified during the early planning for the operation. On Runit, walls were built along a single line from zero to permit analysis of the parameters as they varied with distance. These walls were located at distances of 650, 750, 950, 1,250, 1,450, and 2,000 yd from zero. On Engebi, two lines of walls were constructed to permit analysis of the parameter variation with distance along two radii, permitting some estimate of the symmetry of the blast wave. The line on the lagoon side of the island had walls at 460, 560, 700, 900, 1,300, and 1,550 yd from zero. The line on the ocean side had walls at 900, 1,000, and 1,250 yd from zero. In addition, the lagoon line had a pylon with an associated ground station at 1,430 yd from zero, and the ocean line had pylons and associated ground stations at 700 and 950 yd from zero, to permit analysis of the variation of the parameters with height above ground level.

The details of the wall, pylon, and ground-station structures are described in Greenhouse Report, Annex 1.6, Part II, Sec. 1. Figures 3.1 to 3.6 are photographs of these stations. The walls were 1 ft thick, 5 ft high, and 29 ft long. They were made up of a steel section 8 ft long between two concrete sections each 10.5 ft long. An inductance gauge was located on both sides of each wall 3.5 ft above ground and 12.6 ft from the end of the wall nearest zero. The pylons were steel walls 6.5 in. thick, 15 ft high, and 15 ft long. Inductance gauges were located 7.5 ft from the end nearest zero at heights above ground of 3.5, 7, 10, and 14 ft. Two gauges in each associated ground station provided data for ground measurements.

3.1.2 Selection of Gauges

The gauges had a specified calibrated range corresponding to a shift from a frequency of 14.5 kc to a frequency of 7.5 per cent of 14.5 kc for full range of rated pressure. Hence it was necessary to determine as accurately as possible the peak pressures to be expected at the various measuring points before gauges of specific rated pressures could be properly assigned. By choosing gauges which would provide the full frequency deviation on application of the expected peak pressure, maximum signal amplitude would be obtained; and, since the gauge inlet tubes were designed for definite operating pressures on the gauge, best response would also be obtained.

In order to maintain the procurement program and the test and design programs within reasonable limits, gauges at selected levels to cover the entire range from very high to very low pressures were chosen for application to the system. The rated pressures chosen were 150, 100, 60, 30, 20, 15, and 10 psi. Thus the gauges selected for the various measuring points were those which would give the best frequency deviation for the expected pressures, and these gauges represented a compromise to the procurement and testing programs.

In all cases gauges were chosen for frequency deviations somewhat less than the maximum. This provided a safety factor in the event that the actual kiloton equivalent of the weapon had been underestimated. The record obtained from an explosion in which the kiloton equivalent had been overestimated would be perfectly usable, although the signal amplitude would be reduced.

Information on pressures and durations to be measured at the various distances from zero was obtained from previous Sandstone reports[1] for the 50-kt measurement. Using the basic values from these reports together with suitable scaling equations,[2] similar information was obtained for the 90-kt measurement.

The expected peak pressure was determined for each of the gauge stations, and, by computing the frequency deviations for the several gauges from the manufacturer's calibration curves for these pressures, gauges were selected for the

TABLE 3.1 SELECTION OF GAUGES FOR TEST DOG

Distance from Zero (yd)	Expected Peak Pressure (psi)	Gauge Full Scale (psi)	Frequency Deviation (%)
650	67	100	4.69
750	47	60	5.65
950	28	30	7.05
1,250	16.4	20	5.93
1,450	12.3	15	5.96
2,000	6.8	10	4.69

TABLE 3.2 SELECTION OF GAUGES FOR TEST EASY

Distance from Zero (yd)	Expected Peak Pressure (psi)	Gauge Selected (psi)	Frequency Deviation (%)
	Lagoon Line		
460	106	150	5.15
560	60	100	4.17
700	35.5	60	4.2
900	21	30	4.9
1,300	10.5	15	5.15
1,430	8.7	10	6.38
1,550	7.6	10	5.45
	Ocean Line		
700	35.5	60	4.2
900	21	30	4.9
950	18.5	30	4.4
1,000	17	20	6.21
1,250	11	15	5.25

measurement lines. Tables 3.1 and 3.2 are summaries of the distance of the stations from zero, the expected peak pressures, the gauges selected, and the frequency deviations due to the expected peak pressures.

3.2 FIELD INSTALLATION

3.2.1 Gauge Housing

All the gauges and gauge oscillators were mounted in three assemblies, which were similar in general design but differed slightly due to the type of structure in which they were mounted. The three structures (wall, pylon, and ground) are described in Greenhouse Report, Annex 1.6, Part II, Sec. 1.

The gauge inlet tube was shock-mounted in rubber in a $\frac{1}{2}$-in. hole drilled in each closure plate. The gauge oscillator was placed in a metal container attached to the inner face of the plate, and the container was lined with foam rubber to shock-mount the oscillator. Sufficient foam rubber was used to hold the oscillator assembly firmly when the container cover was pressed in place. A multiconductor cable carried power to the oscillator and the signal from it. This cable was led out through an opening in the cover, into a conduit set in the mounting structure, and down into the cable trench leading back to the blast hut. The outer face of the closure plates were drilled to receive two carrying handles and to mount the clamping bar of the field pressure calibrator.

Different size closure plates were required for the wall, pylon, and ground stations. Further, the attitude of the gauge inlet tube was different for each type of installation since the closure plate accesses were vertical for the walls and pylons but horizontal for the ground stations.

The holes in the wall and pylon closure plates were drilled at an angle of 15° and oriented so that, in position, the air chamber of the gauges would be higher than the inlet-tube openings with the diaphragms uppermost. This tended to eliminate contamination of the air space in the chamber by rain water and dirt. At the horizontal ground-station plates, the holes were drilled perpendicular to the plane of the plate. The inlet tubes for these stations were covered until test time to prevent entry of water and dirt.

One gauge was mounted on each side of a wall station, one gauge per closure plate. The gauges were mounted at the center of these plates, but the inside surfaces of opposite plates were drilled to mount opposite oscillator containers on the upper and lower semicircles of the plates, thereby using the entire space in the wall between the plates.

There was less room available in the pylons, and the closure plates at these stations were smaller. The oscillator containers were therefore relatively larger than a semicircle of the plate. Hence, the $\frac{1}{2}$-in. hole was drilled off-center for the pylon plates.

Two gauges were mounted at each ground station. The $\frac{1}{2}$-in. holes were drilled along a diameter of the plate, equidistant from the center. Both oscillator containers were attached to the plate on opposite semicircles.

A sketch of the three assembly types is shown in Fig. 3.7. Figures 3.8 to 3.10 are photographs of the three assemblies.

3.2.2 Cable Considerations

In estimating the length of cable, 10 per cent was added to the distance of each site from its blast hut, plus 40 yd for lead-in lengths. A safety factor of 20 per cent was added to the total cable length of 37,963 yd, giving the total of 45,556 yd, the amount ordered.

Each pylon, ground station, wall, and hut was provided with a metal conduit leading to the trench in which the cable was buried. In this manner the cable was covered and protected for its entire length.

Type MCOS-4 cable was used. Sections of the cable were spliced together with solderless connections.

REFERENCES

1. Sandstone Report, Vol. 22, Annex 5.
2. "The Effects of Atomic Weapons," Shock from Air Burst, Chap. III, Los Alamos Scientific Laboratory and U. S. Government Printing Office, Washington, D. C., 1950.

Chapter 4

Test Results

4.1 INTRODUCTION

The inductance-gauge measurement program was presented in Secs. 3.1 and 3.2. Twelve gauges were placed on Runit for Test Dog, and 36 gauges were placed on Engebi for Test Easy. The two lines on Engebi were identified as "lagoon line" and "ocean line." The positions of the lines and stations for both tests are shown in Figs. 4.1 and 4.2. Photographs of typical mounting structures and assemblies are shown in Chap. 3. Figures 4.3 to 4.6 are photographs of the Runit blast-hut installation.

The over-all instrumentation program described in this report operated satisfactorily in the field. On Test Dog one of the 12 gauges failed to produce a record because of an electrical failure in the recording apparatus. On Test Easy there was an electrical failure of very short interval at one gauge oscillator during the passage of the pressure wave. In addition, severe damage to several mounting structures, resulting in severed transmission cables, caused the loss or partial loss of the records from six gauges.

4.2 TEST DOG RESULTS

The results obtained from the 12 gauges used on Test Dog are outlined in Tables 4.1 and 4.2 and in Figs. 4.7 to 4.14. The actual pressure-time records obtained are shown in Figs. 4.39 and 4.40.

When these records were examined, there appeared on each one a sharp pulse which corresponded in time to the time of the explosion. The elapsed time between this pulse and the arrival of the blast at each gauge was included in the measurements. Table 4.1 summarizes the following blast measurements: shock-arrival time, positive peak pressure, decay time constant from the positive peak pressure, maximum negative pressure, durations of the positive and negative phases, and the positive and negative impulses. All these measurements are shown plotted against distance from zero in Figs. 4.7 to 4.14. It was observed that the measured value of the time of rise to the initial peak pressure was greater than the resolving time of the measuring system. Moreover, on the measurements closest to zero the rise was characterized by intermediate peaks. These intermediate peaks (where significant), the rise time to the initial peak, and the time of occurrence of the maximum pressure have been included in Table 4.1. The average of the pressures, decay time constants, durations, and impulse values of both sides of each wall are given in Table 4.2.

The three walls closest to zero were damaged by the blast. The first wall, Station 20a, sustained no permanent displacement, but part of the concrete air foil at the rear of the wall was broken off. The second wall, Station 20b, sustained considerable damage. The forward concrete section above ground was almost completely broken off, and the remainder of the wall inclined approximately 12° from the vertical toward the lagoon. The third wall, Station 20c, was left inclined about the same amount, but toward the ocean side of the island. Photographs of the damage to these walls are shown in Figs. 4.31 to 4.34.

No record was obtained from the ocean side of the second wall because of an electrical failure.

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TABLE 4.1 TEST DOG, SUMMARY OF RESULTS

Station	Distance from Ground Zero (yd)	Shock-arrival Time (sec)	Initial Peak Pressure (psi)	Rise Time to Initial Peak (sec)	Positive Peak Pressure (psi)	Time* of Occurrence of Maximum Pressure (sec)	Time Constant of Decay from Maximum Pressure (sec)	Positive Duration (sec)	Positive Impulse (psi-sec)	Maximum Negative Pressure (psi)	Negative Duration (sec)	Negative Impulse (psi-sec)
						Ocean Side						
20a	650	0.360	20.8		55.3		0.058	0.593	6.29	3.15	4.290	12.35
20b	750	0.480	11.8†		31.0		0.065	0.651	5.40	3.70	4.084	6.27
20c	950	0.770	10.7		20.0		0.201	0.841	5.26	2.0	4.625	5.87
20d	1,250	1.407	11.7	0.004	11.7	0.012	0.298	0.853	3.84	1.5	4.605	3.26
20e	1,450	1.820	10.5	0.00125	10.5		0.378	1.028	3.64	1.4	4.440	3.34
20f	2,000	3.015	6.6		6.6		0.470	1.167	2.86	1.2	5.130	3.40
						Lagoon Side						
20a	650	0.360	19.0		46.5		0.054	0.564	5.91	4.3	3.664	10.16
20b	750‡											
20c	950	0.770	8.7		11.9		0.205	0.815	3.18	2.0	4.006	4.81
20d	1,250	1.407	12.0		12.0		0.352	0.869	4.12	1.8	4.470	4.81
20e	1,450	1.820	9.7		9.7		0.320	0.982	3.55	1.5	4.319	3.44
20f	2,000	3.015	6.4		6.4		0.520	1.216	2.76	1.2	4.680	3.50

*Occurrence times are referred to the time of the initial pressure disturbance at the gauge.

†The record from the ocean side of the 750-yd wall shows an intermediate pressure peak of amplitude 20.5 psi.

‡Because of electrical failure, no record was obtained from the lagoon side of the 750-yd wall.

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TABLE 4.2 TEST DOG, AVERAGE VALUES OF RESULTS FROM BOTH SIDES OF EACH WALL

Station	Distance from Ground Zero (yd)	Positive Peak Pressure P_m (psi)	Decay Time Constant (sec)	Positive Duration (sec)	Impulse (psi-sec) Positive	Impulse (psi-sec) Negative
20a	650	50.9	0.056	0.579	6.10	11.26
20b	750	31.0	0.065	0.651	5.40	6.27
20c	950	16.0	0.203	0.828	4.22	5.34
20d	1,250	11.9	0.325	0.861	3.98	4.04
20e	1,450	10.1	0.349	1.005	3.60	3.39
20f	2,000	6.5	0.495	1.192	2.81	3.45

4.3 TEST EASY RESULTS

The results obtained from the 36 gauges used on Test Easy are outlined in Tables 4.3 to 4.6 and in Figs. 4.15 to 4.30. The actual pressure-time records obtained are shown in Figs. 4.41 to 4.46.

The measurements made on the Test Easy records are the same as those made for Test Dog, except that the sharp pulse corresponding to the time of explosion was not evident on all records.

The walls on the ocean line were undamaged. On the lagoon line, however, the second wall, Station 20b, was found broken and lying flat on the ground on the lagoon side with both cables cut. Incomplete data were obtained from this wall. In addition, there was a brief electrical failure of the land-side system at the first wall. This occurred at the time of peak pressure and prevented the recording of maximum pressure at that station.

The two pylons along the ocean line were damaged. Portions of the one closest to zero, pylon 37a, were found on the land side of the line at various distances from its original position. Very little data were obtained from the records taken at this station. The second pylon at Station 37b was found lying flat at its footing on the ocean side of the line with one of the four cables severed. Except for this channel, complete data were obtained from this station. The pylon on the lagoon line, 37c, was undamaged.

Photographs of the damaged stations are shown in Figs. 4.35 to 4.37.

4.4 CONCLUSIONS

The pressure-time records on both tests indicate that the formation of the pressure wave into a shock front takes place at distances much farther from the zero point than expected. Within approximately 1,000 yd the records have the appearance of several relatively slow-rising pressure fronts of various magnitudes. Beyond 1,000 yd the fronts appear to unite gradually into the conventional pressure-time curve, rising abruptly to a single maximum.

Comparison of the values of the blast parameters, particularly between the two lines on Test Easy, indicates that the pressure wave from the atomic explosion did not proceed outward with radial symmetry from the zero point. Figure 4.38 is a comparison of the average peak pressures at the walls on both the Test Easy lines. The average values of the vertical-pylon measurements have been included. There is a very marked difference over the region of comparison. The differences in the pressure measurements on both sides of all the walls also indicate the nonsymmetric nature of the blast wave. The damage to the mounting structures was believed due primarily to this asymmetry.

Data from the pylons indicated no consistent variations with height in the several blast parameters. It was noted, however, that at Stations 37a and 37b, both within 1,000 yd, the ground-station peak pressures were consistently lower than the average pylon pressures, whereas at Station 37c, located at 1,430 yd, the

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TABLE 4.3 TEST EASY, LAGOON LINE; SUMMARY OF RESULTS

Station	Distance from Ground Zero (yd)	Shock-arrival Time (sec)	Initial Peak Pressure (psi)	Rise Time to Initial Peak (sec)	Positive Peak Pressure (psi)	Time of Occurrence of Maximum Pressure (sec)	Time Constant of Decay from Maximum Pressure (sec)	Positive Duration (sec)	Positive Impulse (psi-sec)	Maximum Negative Pressure (psi)	Negative Duration (sec)	Negative Impulse (psi-sec)
						Lagoon Side						
20a	460	0.194	16.5	0.040	66.0	0.098	*	0.561	7.3	4.05	2.28	5.18
20b†	560	0.312	13.5	0.024	38.4	0.143	0.077					
20c	700	0.536	12.5	0.122	23.0	0.193	*	0.758	5.19	2.23	2.27	3.59
20d	900	0.850	7.8		15.1	0.067	0.266	0.784	4.43	2.50	4.06	6.07
20e	1,300	1.734	9.51		9.51		0.320	0.916	3.54	1.83	4.23	4.10
20f	1,550	2.274	7.00		7.00		0.380	0.996	2.96	1.2	4.26	2.86
						Land Side						
20a	460	0.194	14.0	0.033	‡	0.094	*	0.896	10.5	2.25	1.98	2.81
20b†	560	0.312	14.3	0.030	61.8	0.122						
20c	700	0.536	13.0	0.081	20.7	0.204	*	0.631	4.9	3.5	3.37	7.87
20d	900	0.850	8.8	0.034	15.0	0.052	0.230	0.757	4.74	2.12	3.94	4.18
20e	1,300	1.734	9.52		9.52		0.335	0.877	3.36	1.6	4.21	3.18
20f	1,550	2.274	7.90		7.90		0.364	0.951	2.8	1.36	4.29	2.88

*Irregularities in the decay made it impossible to measure reliably the decay time constant.
†Incomplete data were obtained from this station because the wall was torn loose from the footing.
‡Brief electrical failure.

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TABLE 4.4 TEST EASY, OCEAN LINE; SUMMARY OF RESULTS

Station	Distance from Ground Zero (yd)	Shock-arrival Time (sec)	Initial Peak Pressure (psi)	Rise Time to Initial Peak (sec)	Positive Peak Pressure (psi)	Time of Occurrence of Maximum Pressure (sec)	Time Constant of Decay from Maximum Pressure (sec)	Positive Duration (sec)	Positive Impulse (psi-sec)	Maximum Negative Pressure (psi)	Negative Duration (sec)	Negative Impulse (psi-sec)
						Ocean Side						
21a	900	0.745	4.55	0.0515	9.55	0.168	*	0.902	3.53	2.45	3.43	4.44
21b	1,000	0.986	9.15	0.179	9.40	0.301	0.28[illegible]	0.917	4.09	1.85	4.01	3.47
21c	1,250	†	7.30		7.9	0.103	0.450	0.952	3.18	1.55	3.91	3.32
						Land Side						
21a	900	0.745	4.60	0.036	11.9	0.216	*	0.825	4.12	2.2	3.69	4.22
21b	1,000	0.986	4.50	0.058	8.04	0.303	0.265	0.927	3.63	1.85	4.12	3.85
21c	1,250	†	7.1		8.0	0.105	0.370	0.943	3.23	1.5	3.85	3.32

*Irregularities in the decay made it impossible to measure reliably the decay time constant.
†No zero-time pulse was discernible on this record.

TABLE 4.5 TEST EASY PYLONS, SUMMARY OF RESULTS

Station	Height above Ground (ft)	Distance from Zero (yd)	Shock-arrival Time (sec)	Initial Peak Pressure (psi)	Rise Time to Initial Peak (sec)	Positive Peak Pressure (psi)	Time of Occurrence of Maximum Pressure (sec)	Time Constant of Decay from Maximum Pressure (sec)	Positive Duration (sec)	Positive Impulse (psi-sec)	Maximum Negative Pressure (psi)	Negative Duration (sec)	Negative Impulse (psi-sec)
						Pylon 37a*							
37a-1	14	700											
37a-2	10	700	0.426			22.8							
37a-3	7	700	0.426			22.7							
37a-4	3.5	700	0.426			24.6							
37d-1	0	700	0.411	14.3		17.3		0.12	0.804	5.70	2.9	3.72	6.75
37d-2	0	700	0.411	15.4		17.35			0.855	5.99	2.15	2.81	3.43
						Pylon 37b							
37b-1	14	950	0.879	9.4		12.32		0.305	0.786	3.87	2.45	4.75	5.03
37b-2	10	950	0.879	8.92		13.15		0.382	0.841	3.61	2.2	4.72	4.99
37b-3	7	950	0.879	9.35		12.77		0.257	0.865	3.91	†	†	†
37b-4	3.5	950	0.879	10.35		12.8		0.280	0.867	4.16	2.3	4.04	4.86
37e-1	0	950	0.852	7.9		10.42		0.377	0.868	3.73	2.1	3.56	4.99
37e-2	0	950	0.852	8.2		10.9		0.387	0.847	3.68	2.1	4.86	4.49
						Pylon 37c							
37c-1	14	1,430	1.995	8.69	0.0014	8.69		0.31	0.938	3.17	1.53	4.44	3.30
37c-2	10	1,430	1.995	8.27		8.27		0.295	0.928	3.26	1.43	4.44	2.86
37c-3	7	1,430	1.995	8.71		8.71		0.36	0.925	3.23	1.69	4.45	3.60
37c-4	3.5	1,430	1.995	7.23	0.0018	7.23		0.38	0.931	2.86	1.22	4.28	2.50
37f-1	0	1,430	1.995	8.51	0.00275	8.51		0.35	0.939	3.27	1.52	4.71	2.98
37f-2	0	1,430	1.995	8.23	0.00275	8.23		0.33	0.915	2.94	1.45	4.36	3.41

*This pylon was blown away; hence no data were obtained other than those listed.

†This pylon was knocked over, and a cable to a gauge assembly was broken; hence no data on the negative phase were obtained from Station 37b-3.

TABLE 4.6 TEST EASY, AVERAGE VALUES OF RESULTS FROM BOTH SIDES OF EACH WALL

Station	Distance from Ground Zero (yd)	Positive Peak Pressure P_m (psi)	Decay Time Constant (sec)	Positive Duration (sec)	Impulse (psi-sec) Positive	Impulse (psi-sec) Negative
			Lagoon Line			
20a	460	66.0*	†	0.729	8.9	3.99
20b‡	460	50.1	0.077*			
20c	700	21.8	†	0.695	5.05	5.73
20d	900	15.05	0.248	0.771	4.58	5.11
20e	1,300	9.51	0.328	0.897	3.45	3.64
20f	1,550	7.45	0.372	0.973	2.88	2.87
			Ocean Line			
21a	900	11.07	†	0.863	3.83	4.33
21b	1,000	8.8	0.273	0.922	3.86	3.66
21c	1,250	8.0	0.410	0.948	3.21	3.32

*Reading is for lagoon side of lagoon line.

†Irregularities in decay made it impossible to measure reliably the decay time constant.

‡Incomplete data were obtained from this station because the wall was torn loose from the footing.

ground-station pressures were very nearly equal to the average pylon pressure.

Because of the inaccuracies present in the method of integration, owing to the uncertainty of where the pressure-time curve returns to the base line, the negative durations and impulses are not so accurate as the other tabulated parameters.

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Chapter 5

Conclusions and Recommendations

5.1 EVALUATION OF INSTRUMENTATION

5.1.1 Performance of Equipment in the Field

The instrumentation system described in Chap. 2 performed satisfactorily in the field. Only one record of the 48 installations was lost because of electrical failure in the instrumentation. Incomplete records were obtained in a few instances where walls and pylons were moved by the blast to the extent of breaking cables connecting the end instruments to the recording equipment.

Prior to the tests, there were some reservations about the unattended operation of magnetic-tape recorders powered from battery-driven motor generators. These components performed extremely well, however, and at no time was there any indication that they were not completely reliable under the test conditions. The effects of extreme temperature rise on this equipment are still unknown, since the recorded temperatures in the sealed blast huts never rose more than 5°F from an 80°F ambient in a 24-hr period.

The pressure entry system for the end instruments operated satisfactorily. It did not introduce any overshoot in the record and allowed a rapid rise when there was one to be observed.

Although no end instruments were installed to detect shock-arrival times, they were observed on the records. This was believed due to electromagnetic pickup on the cables connecting the end instruments to the blast huts. The durations of these zero pulses were quite short and did not interfere with the pressure-time curves.

The over-all accuracy of the peak-pressure measurements was 2 per cent except at the first wall on Dog Shot and the first wall of the lagoon line on Easy Shot, where it was approximately 4 per cent. These accuracy figures were arrived at by analyzing, cycle by cycle, the recorded frequency modulation in the region of occurrence of the peak pressure.

5.1.2 Comparison with Other Measurement Systems

Pressure-time measurements in the Mach region were made by two other independent systems of different design. One of these systems was a mechanical spring-piston gauge, and the other was an interferometer gauge.[1] The spring-piston gauges were not installed at the pylons, but they were installed at all the walls. Some interferometer gauges were mounted in the ground near but not on the NOBL blast lines on both Easy and Dog Shots. Figures 5.1 to 5.8 show the comparison between the systems. The resolving times for the three systems were approximately as follows: interferometer gauge, 0.2 msec; inductance gauge, 1 msec; spring-piston gauge, 8 to 20 msec.

5.2 RECOMMENDATIONS FOR FUTURE USE OF THE DIAPHRAGM-TYPE INDUCTANCE-GAUGE MEASURING SYSTEM

It is believed that a system in which the data are carried as frequency modulation, stored on magnetic recording tape at the time of the explosion, and reduced under laboratory conditions to final form for analysis is the best electronic system for pressure-time measurements on atomic explosions. However, in view of field experience with a system of this

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design, certain modifications are recommended (1) to reduce the number of low reliability elements operating at the time of the explosion and (2) to improve the system accuracy and data-handling capabilities.

In the system used, the flutter in the tape-handling mechanisms was compensated by a frequency conversion of the gauge signal to a lower frequency for recording. It is suggested that the system can be simplified by eliminating this conversion and using a compensation circuit in the playback to reduce the effect of flutter. (The Raymond Rosen Co. of Philadelphia, Pa., has such a system in production for one model of the Ampex recorder.) Also, the tape speed can be increased considerably to reduce the flutter without interfering with the amount of data that must be recorded.

On the basis of the demonstrated reliability of the magnetic-tape recorder under field conditions, it seems advisable to increase the amount of data that one recorder should handle. This can be accomplished by frequency-division multiplexing and can be achieved by recording simultaneously more than one oscillator frequency on the same recording head.

The Bendix diaphragm-type inductance gauge should be replaced with a gauge designed for greater frequency response and larger dynamic range in the linear region of operation. This is a natural change even though the Bendix gauge gave excellent results on two nuclear explosion tests. Its use on Greenhouse necessitated a design compromise in pressure entry and limited the use of its dynamic range to preserve linearity.

The gauge oscillators installed in the wall were rugged and shock-mounted. At pressures above 60 psi, however, they did not operate continuously through the positive phase. Of the two units that were installed at this range, both put breaks in the pressure-time curves for a period of approximately 10 msec.

Tests made on the recording apparatus at the time of the Greenhouse tests and not reported here indicated that this equipment was not subjected to any significant ground shock. Hence, any elaborate shock-mounting of equipment in the blast hut is unnecessary.

In a few instances where it was desired to know the rise times and initial peak pressures very accurately, a method of analysis different from the one described in Sec. 2.2 was used. This method consisted in measuring, cycle by cycle, the frequency that was recorded on the magnetic tape. The output of the reproducer was photographed together with a timing trace by means of a dual-beam recording cathode-ray oscillograph, and measurements were made on the film with a "traveling" microscope. This method of data analysis resolved the entire response of the end instrument, and nothing was lost in discrimination or the final recording process.

REFERENCE

1. "Interferometer Gauge Pressure-Time Measurements," Greenhouse Report, Annex 8.2B.

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Section 2

MEASUREMENT WITH SPRING-PISTON GAUGE

by

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Chapter 6

Description of the Spring-piston Gauge

6.1 INTRODUCTION

During the initial planning stages of Greenhouse it was decided to obtain measurements of pressure vs time in the Mach region of the blast wave between 5 and 100 psi peak pressure. From these measurements the following blast parameters were desired: (1) peak pressure, (2) duration, and (3) impulse.

It was apparent that it would be advantageous to develop a mechanical-damped spring-piston gauge to obtain these measurements; accuracy and fidelity were to be commensurate with reliability and simplicity. A gauge of this type was desirable for two reasons: (1) to serve as a backup method and independent check on the diaphragm-type variable-inductance gauge (see Chaps. 1 to 5), a much more highly refined, although complex, pressure-time instrument, and (2) to act as a possible prototype for future blast measurement.

This is a report on the design, construction, and use of such a mechanical gauge. It is believed that this report represents the first time a mechanical-damped spring-piston gauge has been used to measure air-blast pressure-time phenomena. A few sentences are devoted to a critically damped spring-piston gauge in a report by W. E. Gordon and P. E. Shafer.[1] However, the construction or testing of a real instrument is not mentioned.

6.2 GENERAL INFORMATION

A mechanical pressure-time gauge records pressure directly without the help of electronic circuits. Its dynamic response is somewhat slower than that of an electronic gauge because large deflections, resulting in increased mass and decreased spring constant, are necessary to produce a readable signal. However, the blast wave from a very large charge, such as an atomic bomb, is of sufficient duration to allow the use of a mechanical gauge without too serious a loss in signal fidelity.

6.3 SYSTEM DESCRIPTION

The system described in this report consisted of two units—the gauge proper and the recorder. Both instruments were of a rather highly specialized nature. The gauge itself was composed of a piston coupled by an oil channel to a spring restoring force. A stylus was attached to the piston. This stylus scribed a mark in an opaque coating on a revolving transparent plastic drum, whose axis of rotation was parallel to the motion of the stylus. The speed of revolution of the drum was obtained by recording 1-sec timing marks on it. The piston was actuated by the blast wave, and its displacement furnished a measure of the pressure, while the revolving drum developed the time coordinate. The drum was similar to a cylindrical photographic negative, and the record was removed and enlarged by photographic techniques.

6.4 GAUGE PROPER

6.4.1 Principles of Operation

The operation of the gauge can best be understood by referring to Fig. 6.1. The spring piston was suspended between two extension springs of equal force constants by means of

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a ball joint. The springs were prestressed 50 per cent farther than the expected deflection. When the face of the main piston was subjected to an excess pressure, the force was coupled to the spring piston through the oil channel. The spring piston then deflected until the spring restoring force balanced the force on the spring piston which had been caused by the pressure in the oil. This deflection of the spring piston resulted in a deflection of the main piston, since the oil volume remained essentially constant. The magnitude of the deflection of the main piston depended on the area ratio of the two pistons and the spring constants. When the excess pressure was removed from the face of the main piston, the spring restoring force returned both pistons to their original zero positions. This mass-spring system was damped by viscous shear of the oil present in the bearing clearances of the main and spring pistons.

6.4.2 Construction

In order to obtain the desired main-piston deflection for the wide range of expected pressures, it was necessary to use two different gauge sizes, one for the region of 5 to 25 psi and another for the region of 25 to 100 psi. The gauges were further adjusted within each range by changing the spring constants and oil viscosity. An exploded low-pressure (5 to 25 psi) gauge is shown in Fig. 6.2, and a high-pressure (25 to 100 psi) gauge is shown in Fig. 6.3. The essential differences were the size of the main and spring pistons, and the internal-area ratios.

An assembled high-pressure gauge is shown in Fig. 6.4. As may be readily noted from the photographs, the spring cylinder and main cylinder were separate pieces bolted together. The spring-piston motion was at right angles to the motion of the main piston. The main piston by itself was free to rotate. In order to prevent rotation and to maintain the alignment of the stylus point on the record drum, a short piece of music wire was soldered to the stylus shank. This wire rode on two parallel bars that were fastened to the main-cylinder block. The spring-piston ball joint is shown disassembled in Fig. 6.2. The loops into which the springs hooked had not been silver-soldered to the ball when the photograph was taken.

The main-cylinder block, the spring-cylinder block and end caps, and the stylus and guides were brass. The main and spring pistons were aluminum, and the spring-piston ball-and-socket joint was steel. The springs were high-grade spring-steel music wire. The main-cylinder block was 3 in. in diameter by $2\frac{1}{2}$ in. long, and the spring cylinders were about 6 in. long. For the low-pressure design the main-piston face and the spring piston were both 1 in. in diameter. In the high-pressure design they were $\frac{1}{2}$ and $\frac{3}{4}$ in., respectively.

The stylus point was a Jensen type W-16 replacement phonograph needle with the heavy shank removed. The tip was osmium with a so-called "standard" (0.003-in.) radius. This particular needle was used because it was cheap; the lines it scribed were consistently sharp and clear, of about 0.004-in. width; the rounded point did not scratch the plastic drum; the mass was extremely small; and it was easily soldered. The cantilever spring to which the needle was attached was made from a phosphor bronze strip 0.010 in. thick, $\frac{3}{16}$ in. wide, and 1 in. long.

The gauge was filled with D-C 200 silicone oil produced by the Dow Corning Corp. This oil did not attack any of the surfaces and had a small variation of viscosity with temperature. It was commercially available in any viscosity between 0.65 and 1,000,000 centistokes.

6.4.3 Method of Assembly

The only problem in assembly consisted in removing all traces of air in the oil channels. The hole visible in the bottom of the main-cylinder block was used for filling. With the entire gauge assembled, a special funnel was screwed into the threaded filling hole, and oil was poured into the gauge with some excess left in the funnel. The gauge was then placed in a vacuum system until all air bubbles had escaped, the oil in the funnel having taken their place. The funnel was removed, and the hole was sealed with a soft-copper washer and a $\frac{1}{4}$-28 NF cap screw.

6.5 RECORDER

A photograph of the recorder is shown in Fig. 6.5. The writing surface was formed by a piece of transparent plastic tubing 3 in. in diameter

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by 4 in. long coated with an opaque film of specially prepared Aquadag. This drum was driven at a surface speed of from 1.8 to 4 in./sec by a 60-v d-c shunt-wound motor. A standard packing O ring was used for belt drive. In order to furnish a helical advance, one of the drum bearings was an accurately machined $\frac{1}{4}$-20 NC screw thread. After approximately 12 revolutions of the drum, the motor was cut off by a limit switch. Power was supplied by batteries mounted in a blast-proof structure (blast hut) somewhat removed from the gauge positions. A hinged cover was attached to the recorder to provide protection for the record drum during handling. One recorder served two gauges.

6.5.1 Reasons for Choice of Design

Since only a short running time (30 to 60 sec) was necessary, a drum-type recorder was used because of its inherently small zero drift. The opaque coating etched by a stylus combined a high-resolution high-contrast record with a very convenient means of reproduction. It also provided a jointless low-friction writing surface. Three-inch plastic tubing was used because of its commercial availability and ease of machining and handling. Because an electrical signal was available to start the recorder, it was felt that an electric motor was just as reliable, if not more so, than a relay-actuated clock-drive mechanism. The case design was primarily dictated by available space and recovery considerations. Welded aluminum was used to furnish the required rigidity without excess weight.

6.5.2 Timing System

In order to provide timing marks on the record, standard U. S. Navy deck clocks were modified at the U. S. Navy Navigational Aids Repair Facility, Washington, D. C., to actuate a sensitive relay once each second. A picture of the clock and relay is shown in Fig. 6.6. These clocks were operated in the blast huts, and one clock served six recorders. A modified 24-v relay with a stylus attached to the armature was mounted in each recorder and was actuated by the clock relay.

6.5.3 Application and Reproduction of Writing Surface

Aquadag is the trade name of a colloidal suspension of graphite in water produced by the Acheson Colloids Corp., Port Huron, Mich. In concentrated form it is a thick paste. The opaque paint used to coat the record drums was prepared by thinning the Aquadag to the consistency of thick cream with distilled water to which a small amount of aerosol O. S. wetting agent had been added.

The surface of the plastic tubing as supplied commercially was sufficiently smooth to be used without polishing. In order for the Aquadag paint to wet the surface, the drum was carefully cleaned. All grease and oil was first removed with carbon tetrachloride (plastic, if acrylic, is insoluble in CCl_4). The drum was then scrubbed with a clean cloth wet with the prepared paint. After scrubbing, the drum was wiped clean before the paint dried. The final coating was applied with a high-grade artist's brush. Spraying was not satisfactory, because considerably greater force had to be applied to the stylus in order to scratch through the sprayed graphite film. The paint dried in about 20 min and was quite rugged; of course, it could be rubbed off with the fingers if anything other than very light pressure was applied.

After a record had been obtained, the drum was removed from the recorder and sprayed with a thin coating of transparent plastic to facilitate handling. Sheet film, in this case, Kodak Commercial Ortho, was wrapped around the drum and held in close contact by a continuous wrapping of a long rubber band. The film was exposed by a special light source (see Fig. 6.7) over which the drum was placed. Once the record had been transferred to the flat film it could be handled in any conventional manner.

REFERENCE

1. W. E. Gordon and P. E. Shafer, Mechanical Air-blast Gauges, WHOI, Division 2, NDRC, March 1945; NDRC Report No. A-371; OSRD Report No. 6249, p 13.

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Chapter 7

Design of the Spring-piston Gauge

7.1 GENERAL CONSIDERATIONS

For a simple mass-spring oscillatory system,

$$T_0 = 2\pi \sqrt{\frac{M}{K}} \qquad (7.1)$$

where T_0 = natural period
K = spring constant
M = mass.

For a damped mass-spring system there is in reality no "natural period." However, the undamped natural period, or so-called "free period," can be used for a rise-time criterion, as will be shown later. That is to say, the shorter the free period, the more rapid will be the response to a step function. A blast wave consists essentially of a step pressure front followed by a decay. Therefore, in the design of any spring-piston gauge for pressure-time measurements, the first consideration is to keep the mass as small as possible and the spring constant as large as possible, in order for the system to respond rapidly to the pressure step before the decay introduces a serious error in the observed peak pressure.

7.1.1 Bore and Stroke

The reduction in mass and the increase in spring constant can be carried only to certain limits in a gauge. If the bore is made large, the spring constant required for a given stroke is increased, but so is the mass of the piston and spring; and there may or may not be a decrease in rise time, depending on the construction. Bore size for a given deflection will be limited by physically realizable springs and damping media. The converse is true as bore diameter is reduced. It must not be reduced too far, however, because friction forces will approach the force on the piston due to the blast wave and result in serious errors. As the stroke is reduced, rise time for a given pressure decreases because of reduced piston mass and increased spring constant; however, rise time must be fixed at some minimum, depending on the resolution of the recording system.

7.1.2 Spring Suspension

A pressure-time record consists of both positive and negative phases; hence, it is desirable to incorporate a spring suspension linear through zero. The machine work necessary to mount a single spring linear through zero is unduly complicated. The incorporation of two series springs prestressed an amount greater than the expected deflection in either direction results in a much simpler system. Compression springs are not satisfactory for series use because they form a system in unstable equilibrium, and, in addition, any slight error in squaring of the spring ends tends to cock the spring piston and create large friction forces. By nature, an extension-spring system is one of stable equilibrium, and this, coupled with a ball-and-socket spring-piston joint, reduces friction errors to a minimum.

7.1.3 Air and Oil Leakage

In any piston gauge the problem of air leakage must be considered, since any passage of air around the piston will result in errors in pressure. This problem is minimized by utilizing a

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differential piston with oil coupling to the springs, since the internal oil pressure will be greater than the external air pressure for the positive duration of the blast wave. Oil will leak out under these conditions, but by proper choice of clearances and viscosity the leakage can be made extremely small. During the negative phase the internal oil pressure is less than the external air pressure, and air will tend to leak in. However, if the bearings are designed to include small reservoirs of oil that must be forced into the gauge before the entry of air, the system can be made to function with negligible leakage error during the negative phase also. Care must be taken in the choice of the differential-piston areas to ensure that the pressure in the oil does not drop low enough to cause cavitation during the negative phase of the blast wave.

7.1.4 Oil Coupling to Springs

In addition to minimizing leakage errors, the differential-piston oil-coupling system has several other advantages. A short-stroke stiff spring has a greater force-constant-to-mass ratio than a long-stroke soft spring. This fact can be utilized to decrease the over-all free period of the gauge by proper choice of the internal-area ratio. The problem of recording the deflection of a piston to which a spring is directly attached is quite formidable because the torque developed as a result of deflection of the spring tends to rotate the stylus off the writing surface. This torque is eliminated by oil coupling. With oil coupling there is a slight flow of oil through the bearings; hence, positive lubrication is maintained and metal-to-metal friction is minimized. The system also provides a method for easily obtained damping.

7.1.5 Methods of Damping

In order not to lead to signal distortion, the damping force must be directly proportional to piston velocity. With oil, such a force may be obtained by laminar flow through a channel or by viscous shear in oil separating two sliding surfaces. In order to obtain damping by flow through a channel, the channel cross section must be quite small for a gauge of the size used here. This results in high oil velocities, and, as will be shown later, the effective mass of the oil increases by the square of the velocity. This leads to an unreasonable increase in total system mass and a consequent increase in rise time. Damping by viscous shear in the clearances of the piston bearings can be obtained with reasonable clearances, easily handled oil viscosities, and tolerable oil leakage, with no increase in mass.

7.2 ANALYSIS OF DESIGN

As may be readily noted from the preceding paragraphs the design of a gauge is not a simple matter of calculating each parameter for optimum performance and then combining them in a single instrument; rather, it is more of a compromising process. Not the least of the design problems is the judicious choice of physical dimensions that affords simple and economical machine work. The general form of the gauge described in this report was the result of all these considerations.

7.2.1 Simplified Mechanical Circuit

The equivalent mechanical circuit for the gauge can be reduced to that of Fig. 7.1. The force equation for this system is

$$M \frac{d^2x}{dt^2} + R \frac{dx}{dt} + KX = 0, \qquad (7.2)$$

and the solution has the form

$$X = C_1 e^{m_1 t} + C_2 e^{m_2 t} \qquad (7.3)$$

where

$$m_{1,2} = -\frac{R}{2M} \pm \sqrt{\left(\frac{R}{2M}\right)^2 - \frac{K}{M}} \qquad (7.4)$$

and C_1 and C_2 are constants depending upon initial conditions. Three distinct cases arise: when the quantity under the radical is less than zero, equal to zero, or greater than zero. If it is less than zero, m_1 and m_2 will contain real and imaginary parts, and the motion will be oscillatory. If, in the limit, R equals zero (no damping), m_1 and m_2 will be purely imaginary, and the general solution is

$$X = C_1 e^{i\omega_0 t} + C_2 e^{-i\omega_0 t}, \qquad (7.5)$$

or it can be expressed as

$$X = C_3 \cos(\omega_0 t + \alpha) \tag{7.6}$$

where $\omega_0 = \sqrt{K/M}$. This ω_0 is the natural or undamped frequency of oscillation expressed in radians per second. Equation 7.1 follows from it.

If the quantity

$$\left(\frac{R}{2M}\right)^2 - \frac{K}{M} = 0, \tag{7.7}$$

the general solution becomes

$$X = (C_1 + C_2 t)e^{-Rt/2M}, \tag{7.8}$$

and the system is critically damped. This is the case of particular interest here. It can be easily shown that the system has the most rapid response to a step function without overshoot (oscillation) when it is critically damped. Solving Eq. 7.7 for critical damping,

$$R = 2\sqrt{KM}, \tag{7.9}$$

and Eq. 7.8 becomes

$$X = (C_1 + C_2 t)e^{-\omega_0 t}. \tag{7.10}$$

If in Eq. 7.4 the quantity under the radical is greater than zero, m_1 and m_2 will be real and distinct, and the response to a step will be slower than that for critical damping. This latter case is called overdamping and will be treated further in Chap. 9.

7.2.2 Consideration of Area Ratios

If the spring constant K and the mass M for the simple system discussed in the previous section are known, the damping coefficient R is determined by Eq. 7.9, and the motion of the desired critically damped system is described by Eq. 7.10. However, in the actual gauge, the components of K, M, and R exist at different levels and must be referred to one coordinate system before the simplified circuit analysis can be used. In order to do this, consider the consequences of the oil coupling, Fig. 7.2. Since the change in oil volume can be considered negligible,

$$X_1 A_1 = X_2 A_2 \tag{7.11}$$

or

$$X_2 = \frac{X_1}{a}. \tag{7.12}$$

By definition

$$K_s = \frac{P_0 A_2}{X_2}, \tag{7.13}$$

and substituting for A_2 and X_2,

$$K_s = a^2 \frac{P_0 A_1}{X_1}. \tag{7.14}$$

For steady-state conditions,

$$P_0 A_1 = P_a A_a; \tag{7.15}$$

therefore

$$K_s = a^2 \frac{P_a A_a}{X_1}. \tag{7.16}$$

Now by definition

$$K_{eff} = \frac{P_a A_a}{X_1}, \tag{7.17}$$

whence

$$K_{eff} = \frac{K_s}{a^2}. \tag{7.18}$$

In like manner it can be shown that the mass M and the damping coefficient R of the spring piston can be referred to the main piston by dividing by a^2. For analysis it is convenient to refer all quantities to the main piston, because it is the motion of the main piston that is recorded.

7.2.3 Development of Damping Formula

Maxwell defined viscosity as "the tangential force on unit area of either of two horizontal planes of indefinite extent at unit distance apart, one of which is fixed, while the other moves with unit velocity, the space between being filled with the viscous fluid." For the cylindrical bearings of the spring-piston gauge this definition can be approximated by

$$\mu \cong \frac{R\Delta}{2\pi r l} \tag{7.19}$$

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where μ = viscosity
Δ = bearing clearance
r = radius of bearing
l = length of bearing,

since $\Delta \ll r$. In the gauge, three bearings contributed to the total effective damping coefficient, or

$$R_{eff} = R_1 + R_2 + R_3 \qquad (7.20)$$

where the subscripts 1, 2, and 3 refer to the front bearing of the main piston, the rear bearing of the main piston, and the spring-piston bearing, respectively. The effective damping coefficient can then be written as follows:

$$R_{eff} = 2\pi\mu\left(\frac{r_1 l_1}{\Delta_1} + \frac{r_2 l_2}{\Delta_2} + \frac{r_3 l_3}{a^2\Delta_3}\right). \qquad (7.21)$$

Since for critical damping $R = 2\sqrt{KM}$, the oil viscosity required to give proper damping is

$$\mu = \frac{\sqrt{KM}}{\pi\left(\frac{r_1 l_1}{\Delta_1} + \frac{r_2 l_2}{\Delta_2} + \frac{r_3 l_3}{a^2\Delta_3}\right)}. \qquad (7.22)$$

7.2.4 Leakage

The volume rate of oil flow through the bearings can be expressed in terms of the bearing parameters from a formula for flow between two concentric pipes developed by Leigh Page[1] as

$$\frac{\pi(2\Delta r + \Delta^2)(P_1 - P_2)}{8\mu l}\left[(2r^2 + 2\Delta r + \Delta^2) - \frac{2\Delta r + \Delta^2}{\log\left(l + \frac{\Delta}{r}\right)}\right] \qquad (7.23)$$

where $P_1 - P_2$ is the pressure differential across the bearing. By expanding $\log[l + (\Delta/r)]$ in a series and neglecting all insignificant terms, the expression reduces to

$$\text{Volume rate of flow} = V_f = \frac{\pi(P_1 - P_2)\Delta^3 r}{6\mu l}. \qquad (7.24)$$

If external pressure is zero gauge, then $(P_1 - P_2) = P_0$, and, since

$$P_0 = \frac{K_{eff}X}{A_1}, \qquad (7.25)$$

then

$$V_f = \frac{\pi\Delta^3 r\, K_{eff}X}{6\mu l A_1}. \qquad (7.26)$$

If leakage error E is defined as

$$E = \frac{\int V_f\, dt}{X_0 A_1} \qquad (7.27)$$

where X_0 = peak displacement, then

$$E = \frac{\pi\Delta^3 r\, K_{eff}}{6\mu l A_1^2 X_0}\int X\, dt. \qquad (7.28)$$

In order to approximate the leakage error during the positive duration of a blast wave, assume that the average value of the decay is one-third the maximum, or

$$\int_0^{t_0} X\, dt \cong \frac{X_0}{3}\, t_0, \qquad (7.29)$$

whence

$$E = \frac{\pi\Delta^3 r\, K_{eff} t_0}{18\mu l A_1^2}. \qquad (7.30)$$

The total leakage error is the sum of the errors introduced by each of the three bearings. However, in calculating the leakage for the front bearing during a blast wave, the external pressure is not zero. In the case of the low-pressure gauge it is $\frac{1}{2}P_0$. For the high-pressure gauge it is $\frac{3}{4}P_0$. Therefore, the leakage errors for these front bearings are, respectively, one-half and one-fourth of that computed by Eq. 7.30. The total leakage errors for each design are then

$$E_{LP} = \frac{\pi K_{eff} t_0}{18\mu A_1^2}\left(\frac{\Delta_1^3 r_1}{2l_1} + \frac{\Delta_2^3 r_2}{l_2} + \frac{\Delta_3^3 r_3}{l_3}\right) \qquad (7.31)$$

and

$$E_{HP} = \frac{\pi K_{eff} t_0}{18\mu A_1^2}\left(\frac{\Delta_1^3 r_1}{4l_1} + \frac{\Delta_2^3 r_2}{l_2} + \frac{\Delta_3^3 r_3}{l_3}\right). \qquad (7.32)$$

By definition the leakage error is the shift in gauge zero at the end of the positive duration of a blast wave, expressed in percentage of peak pressure.

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7.2.5 Bandwidth

Another useful quantity in the design of the gauge is bandwidth. For practical purposes the response may be considered good to zero frequency, even though there is slight oil leakage. Bandwidth is used here in the normal sense of the word, namely, the frequency to which the response has fallen to 0.707 of maximum (the upper half-power frequency). A rough guide to rise time may be obtained by taking one-half the period of the upper half-power frequency, f_2. By setting the system force equation, Eq. 7.2, equal to a sinusoidal driving function and solving the steady-state integral for the case of critical damping, the following relation is obtained:

$$f_2 = \left(\sqrt{2} - 1\right)^{1/2} f_0 = 0.644 f_0 \qquad (7.33)$$

where f_0 is the natural undamped frequency of the system.

7.3 CALCULATION OF GAUGE PARAMETERS

In order to choose the best compromise of the various gauge parameters, it was necessary to estimate the characteristics of the shock wave to be measured. For Greenhouse the expected peak pressures and positive durations at each of the stations assigned to the spring-piston gauges were calculated in exactly the same manner, and from the same Sandstone data, as described in Chaps. 1 to 5 of this

TABLE 7.1 PHYSICAL DIMENSIONS OF SPRING-PISTON GAUGES

Quantity	Low-pressure Gauges (5 to 25 psi)	High-pressure Gauges (25 to 100 psi)
Total effective mass, M	44.2 g	15.3 g
Peak deflection, X_0	0.50 in.	0.50 in.
Maximum linear deflection, X	0.75 in.	0.75 in.
Radius of front main bearing, r_1	0.50 in.	0.25 in.
Radius of rear main bearing, r_2	0.35 in.	0.125 in.
Radius of spring-piston bearing, r_3	0.50 in.	0.375 in.
Area ratio, a	2	3
Main-piston radial clearances, Δ_1 and Δ_2	0.001 ± 0.0001 in.	0.001 ± 0.0001 in.
Spring-piston radial clearance, Δ_3	0.0006 ± 0.0001 in.	0.0006 ± 0.0001 in.
Length of bearings, l_1, l_2	0.25 in.	0.25 in.
Length of bearings, l_3	0.50 in.	0.50 in.

TABLE 7.2 PERFORMANCE CHARACTERISTICS OF SPRING-PISTON GAUGES

Gauge Design Pressure (psi)	Spring Constant K_{eff} (dynes/cm)	Natural Frequency f_0 (cps)	Rise Time $\simeq 1/2f_2$ (msec)	Viscosity for Critical Damping, μ (centipoises)	Estimated Leakage Error, E (%)
7.5	2.2×10^6	35.5	22	390	0.06
11	3.3×10^6	43.5	18	480	0.08
17	4.44×10^6	50.3	15	560	0.09
23	6.38×10^6	60.5	13	670	0.10
38	2.78×10^6	68	11.5	640	0.06
70	5.02×10^6	91.5	8.5	850	0.08
105	7.54×10^6	112	7	1,050	0.10

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report. For the sake of brevity these characteristics are not repeated. Once they were known, the physical dimensions and performance characteristics of the gauges could be calculated by means of the formulas developed in the preceding discussion. In the interest of economy it was possible to compromise somewhat and cover the entire range of desired data with two different size gauges and seven different spring constants.

7.4 SUMMARY OF GAUGE PARAMETERS

The physical dimensions and performance characteristics of the Greenhouse spring-piston gauges are given in Tables 7.1 and 7.2.

REFERENCE

1. Leigh Page, "Introduction to Theoretical Physics," 2nd ed., p 260, D. Van Nostrand Co., Inc., New York, 1935.

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Chapter 8

Laboratory Tests

8.1 DIFFICULTIES IN CALIBRATION

Because of the relatively long rise time of the spring-piston gauge, calibration by means of shock waves would be very difficult and expensive. Only the very largest shock tubes or very large charges of TNT are capable of generating shock waves of long enough duration for the range of pressures of interest. It was necessary, therefore, to resort to the design of a special system in order to check the dynamic response and calibrate the gauge.

8.2 DESCRIPTION OF TEST POT

The unit shown in Fig. 8.1 was used to measure the dynamic response and calibrate the gauges. It consisted essentially of a large chamber containing air under pressure separated from the face of the gauge piston by a quick-opening valve. The valve was a flat mushroom type that was held against an O-ring seat by the air pressure in the chamber. The valve stem passed through an O-ring packing in the rear of the chamber and terminated in a shoulder. A free-sliding mass was held against a compressed spring by a sear. When the sear was tripped, the mass accelerated freely until it contacted the valve shoulder and carried the valve with it. The spring and mass were designed so that the valve opened with a velocity of about 100 in./sec. The volume of the air chamber was 100 times the volume on the gauge side of the valve; therefore, a Bourdon gauge reading of the test-chamber pressure before the valve was tripped was within 1 per cent of the final pressure and could be used for calibration. Specially calibrated Ashcroft precision gauges were used.

8.2.1 Performance

In order to measure the rise time of the pressure pulse generated by the test pot, an inductance gauge was used as a pressure sensing element. A photograph of the output is shown in Fig. 8.2. The frequency of the timing signal was 1,000 cps. It may be noted that the rise time was approximately 1.5 msec. Several shots at the same pressure level (60 psi) indicated that the rise in pressure was very reproducible. There is reason to believe that the oscillations on the top of the trace were due to ringing in the inductance gauge; however, even if they were a real part of the pressure pulse, they were unimportant, since they were about 855 cps and far outside the bandwidth of the spring-piston gauge.

8.2.2 Method of Use

The bench setup used for calibrating the gauges is shown in Fig. 8.3. The valve-opening mechanism of the test pot in this figure was of different mechanical construction; nevertheless, it functioned in the same manner as the one shown in Fig. 8.1.

8.3 RESULTS OF CALIBRATION USING TEST POT

8.3.1 Calibration Curves

Sample calibration curves for each of the seven pressure designs are presented in Figs. 8.4 and 8.5. These curves are noteworthy because (1) they show the excellent linearity of the gauges and (2) it may be noted that all but one curve intersects the zero-displacement axis at a slight positive pressure. This zero-

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displacement pressure is equal to twice the gauge friction because of the manner in which the data were obtained. The greatest friction error in this group occurred in the 7.5-psi gauge. For this gauge, the maximum error in measured peak pressure due to friction was –5.0 per cent.

8.3.2 Rise Time

Because the rise time of the pressure pulse was short compared to that of the gauge, the pulse could be considered a step function for gauge rise-time analysis. Portions of two sample records obtained with the test pot are shown in Figs. 8.6 and 8.7. The pulse from the pot was bled off by a controlled leak, which was necessary to ensure that any valve leakage would not result in a false zero reading. In order to give some measure of rise time, the time to 90 per cent of the final value was taken as a criterion. Table 8.1 is a comparison of these measured times with the calculated half-period rise times. The measured response to 90 per cent of final value should be somewhat less than the computed half-period times if the systems are critically damped. Table 8.1 indicates that the higher pressure gauges were very near critical damping but that the low-pressure gauges were slightly overdamped. No evidence of any overshoot was present on any of the records.

TABLE 8.1 COMPARISON OF RISE TIMES

Gauge Design Pressure (psi)	Measured Rise Time to 90 Per Cent (msec)	Calculated Half-period Rise Time (msec)
7.5	22	22
11	20.5	18
17	14.2	15
23	9	13
38	7	11.5
70	5.7	8.5
105	5.2	7

Chapter 9

Results

9.1 FIELD INSTALLATION

Spring-piston gauges were mounted in all blast walls adjacent to the inductance gauges on both Runit and Engebi (Tests Dog and Easy). No gauges were mounted in the ground or pylons. A total of 12 gauges was used on Dog and 18 on Easy. A brief description of the walls is given in Chap. 3.

In order to facilitate installation and testing of the gauges and recorders in the walls, one of the cover plates was split. A close-up of a typical complete installation with half of the cover plate removed is shown in Fig. 9.1. The entire mounting chamber was sealed at atmospheric pressure after the gauges were installed. The tip of a latex prophylactic was mounted loosely to the face of the gauge by a brass ring to provide protection from the sand without interfering with the operation of the gauge. Battery power and timing signals were supplied to the wall stations by MCOS-4 cable from the blast huts. Figures 9.2 and 9.3 show the clock and junction box and the battery racks that were mounted in the blast huts. All blast huts were similar in arrangement. The recorders and timing signals were started at zero minus 15 sec.

Figures 4.1 and 4.2 show the layout of the blast line for both shots. Damage to the walls is discussed in Chap. 4.

9.2 TEST DOG RESULTS

The results of Test Dog are summarized in Tables 9.1 and 9.2. Positive peak pressures are plotted in Fig. 9.4. The actual pressure-time records are reproduced in Figs. 9.5 and 9.6.

The air seal at the cable exit hole below ground at each station proved ineffective, and the gauges were subjected to an unknown amount of back pressure. For this reason all quantities except peak pressure are in error by an unknown amount, most of them seriously. Peak pressures should not have been affected to any great extent by this leakage because of the long filling time of the gauge mounting chamber. The gauge covers were burnt off out to 1,250 yd, and the gauges at the first two walls were subjected to considerable sandblasting. The shock of wall 20b breaking up was sufficient to cause a momentary reversal of the recorder drum and the apparent multivalued pressure-time function. This sensitivity to shock was probably due to unbalance of the drum and the fact that the O-ring drive belt was somewhat elastic. The rise and decay of the blast wave at Station 20f was steep enough to require extrapolation of the record for peak pressure. The extrapolated pressure was taken to be that pressure at the intersection of a line drawn tangent to the rise and a line drawn tangent to the decay. It can be shown that this point is theoretically within 5 per cent of the true peak for these stations. The extrapolated pressure on the lagoon side of Station 20f is higher than the true value because the excessive gauge friction and air leakage introduced considerable error in the extrapolation.

9.3 TEST EASY RESULTS

Tables 9.3 and 9.4 contain the data obtained from the lagoon line, E_1, and Table 9.5 contains the data from the ocean line, E_2. These data are presented as functions of distance from

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TABLE 9.1 TEST DOG RESULTS, OCEAN SIDE*

Station	Distance (yd)	Gauge Serial No.	Gauge Force Constant (psi/in.)	First Peak Pressure (psi)	Second Peak Pressure (psi)	Negative Peak Pressure (psi)	Positive Duration (msec)	Negative Duration (msec)	Positive Impulse (psi-sec)
20a	650	7H	152	17.5	56.1		660		7.50
20b	750	10H	152	12.7	36.2		550		5.30
20c†	950	14H	88	20.8	38.2		1,735		
20d	1,250	10L	33.8	12.1	None	1.66	488	2,375	2.92
20e	1,450	6L	23.2	10.3	None	1.78	657	3,683	3.08
20f‡	2,000	4L	16	6.2	None	0.59	511	3,835	1.43

*Air leakage into wall chambers was considered serious enough to cause unknown errors in all quantities except peak pressure.

†There was evidence that this gauge contained air in the oil channel; hence all measurements are open to question.

‡Peak pressure is extrapolated.

TABLE 9.2 TEST DOG RESULTS, LAGOON SIDE*

Station	Distance (yd)	Gauge Serial No.	Gauge Force Constant (psi/in.)	First Peak Pressure (psi)	Second Peak Pressure (psi)	Negative Peak Pressure (psi)	Positive Duration (msec)	Negative Duration (msec)	Positive Impulse (psi-sec)
20a	650	6H	151.6	22.4	67.6	5.57	620	4,830	10.65
20b	750	8H	152	24.7	67		790		13.00
20c†	950	12H	86	15.9			965		
20d	1,250	9L	33.9	12.6	None	1.67	500	3,220	2.98
20e	1,450	5L	24.6	10.3	None	1.36	650	3,635	2.97
20f‡	2,000	2L	16.2	7.4	None	0.65	553	3,730	1.57

*Air leakage into wall chambers was considered serious enough to cause unknown errors in all quantities except peak pressure.

†There was evidence that this gauge contained air in the oil channel; hence all measurements are open to question.

‡Peak pressure is extrapolated, but it is too high because of large gauge friction.

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TABLE 9.3 TEST EASY RESULTS, LAGOON LINE, LAGOON SIDE

Station	Distance (yd)	Gauge Serial No.	Gauge Force Constant (psi/in.)	Measurement of Peak Pressure (psi)	Extrapolated Peak Pressure (psi)	Negative Peak Pressure (psi)	Positive Duration (msec)	Negative Duration (msec)	Positive Impulse (psi-sec)	Negative Impulse (psi-sec)
20a	460	1H	226	90.4			508	3,788	14.1	
20b	560	5H	150.4	68.7						
20c*	700	11H	82	37.9			742		13.28	
20d	900	13L	50	19.4		4.5	874	4,116	6.88	12.6
20e	1,300	5L	24.6	9.72		1.72	881	4,105	3.42	4.16
20f	1,550	3L	16.2	6.97	7.79	0.81	1,041	3,655	3.16	2.72

*This gauge probably contained air in the oil channel.

TABLE 9.4 TEST EASY RESULTS, LAGOON LINE, LAND SIDE

Station	Distance (yd)	Gauge Serial No.	Gauge Force Constant (psi/in.)	Measurement of Peak Pressure (psi)	Extrapolated Peak Pressure (psi)	Negative Peak Pressure (psi)	Positive Duration (msec)	Negative Duration (msec)	Positive Impulse (psi-sec)	Negative Impulse (psi-sec)
20a	460	2H	218	83.8		6.5	527	3,372	9.70	11.7
20b	560	9H	149	75.2						
20c*	700	13H	83.8	26.2			734		7.59	
20d	900	14L	50	14.0		2.3	910	3,632	4.97	4.91
20e	1,300	8L	23.6	10.1		1.80	958	4,092	3.94	4.23
20f	1,550	19L	15.5	6.64	7.48	0.88	1,054	3,100	3.09	1.92

*This gauge probably contained air in the oil channel.

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TABLE 9.5 TEST EASY RESULTS, OCEAN LINE

Station	Distance (yd)	Gauge Serial No.	Force Constant (psi/in.)	Measurement of Peak Pressure (psi)	Extrapolated Peak Pressure (psi)	Negative Peak Pressure (psi)	Positive Duration (msec)	Negative Duration (msec)	Positive Impulse (psi-sec)	Negative Impulse (psi-sec)
Land Side										
21a	900	15L	50.8	11.35		2.03	871	3,082	4.08	4.07
21b	1,000	17L	50.1	7.96		1.70	938	3,555	3.86	3.96
21c	1,233	11L	35.4	8.34		1.28	948	3,780	3.30	3.36
Ocean Side										
21a	900	16L	48.1	8.32			1,400		4.36	
21b	1,000	18L	48.1	9.42		1.64	990	3,445	4.03	3.78
21c	1,233	12L	33.3	8.26		1.43	968	3,770	3.38	3.17

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ground zero in Figs. 9.7 to 9.12. The pressure-time records are reproduced in Figs. 9.13 to 9.15.

The mounting-chamber air seal proved effective on this test, and no data were lost due to air leakage. The gauge covers were burnt off out to 1,300 yd on line E_1 and 1,000 yd on line E_2. The gauges at the close-in stations were again subjected to considerable sandblasting. The recorder at Station 20a suffered a momentary time reversal when the blast hit the wall. All data except peak pressures were lost at Station 20b because of severe damage to the wall. The cables were broken when the wall was blown over, and the recorder stopped. Peak pressures were extrapolated at Station 20f only. The blast wave was slow enough to allow the gauges to reach full response at all other stations.

9.4 ESTIMATE OF ERRORS

It is difficult to estimate the errors present in the data because of such unknown and unpredictable effects as sandblasting, air leakage into the oil channel, and air leakage into the gauge chamber. Very good agreement with the inductance gauge was obtained on both tests at distances over 1,000 yd. Closer than this the spring-piston pressures were higher in almost every case. At Station 20c on both tests this could be attributed to air in the oil channels of the gauges. At the other stations it is possible that the sand striking the faces of the pistons could have caused the higher apparent pressures. The blast wave was far from being symmetrical and smooth on both tests, and this could have led to considerable turbulence. Since the maximum pressure at the close-in stations was not reached until some time after initial arrival, it is conceivable that very high-velocity sand could have impinged on the piston faces and created a higher false pressure indication. Because of the type of construction used for the inductance gauge, this effect would have been negligible in its case.

In order to gain some idea as to the worth of the spring-piston data, Table 9.6 contains an estimate of errors. This table applies only to those gauges not subjected to sandblasting, air leakage, or excessive gauge friction.

TABLE 9.6 ESTIMATE OF ERRORS

Quantity	Per Cent
Positive peak pressure	5
Negative peak pressure	50
Positive duration	10
Negative duration	50
Positive impulse	5
Negative impulse	50

Chapter 10

Recommendations

10.1 SUCCESS OF PROGRAM

The spring-piston gauge successfully did the job it was designed to do. Although the loss of data on Dog Shot was considerable, the gauge provided an excellent independent qualitative correlation for the more precise data obtained by the inductance gauge, and it accomplished this purpose reliably and economically.

10.2 FAULTS OF SPRING-PISTON GAUGE

Although the gauge worked well, the problems brought to light during its design, construction, and use could be profitably discussed for any future programs. In the authors' opinion, a piston-type gauge is unsuitable for field measurements. Almost all the undesirable characteristics of the gauge and the loss of data can be directly attributed to the fact that it was a piston-type instrument. An atomic blast is, after all, quite violent, with sand, dirt, and miscellaneous missiles being accelerated to high velocities. Furthermore, the field conditions are far from ideal. To maintain proper functioning of a precision sliding bearing before and during the blast is nearly impossible. Most of the design time was spent in trying to create the most effective seal at the sliding bearing. The actual physical form of the gauge was a result of this problem.

10.3 SUPERIORITY OF RECORDER

Because of the limited time available and the amount of machine work required on the gauges, it was necessary to estimate the probable recorder resolution, settle the gauge design, and get the gauges into production before any recorders were built. The finished recorder had far greater resolution than was estimated. This could have been used to advantage by reducing the stroke of the piston with a consequent reduction in rise time and machining costs. During the search for a suitable recording surface, an article describing a soot system for high-resolution recording was discovered.[1] This system was tried with excellent results, but it was discarded because its high resolution was not required. Also, it was unnecessarily fragile and delicate to handle under the field conditions. The soot system does, however, appear to be an excellent recording system for a different mechanical pressure-time gauge. Its resolution is so high that a direct-recording linear diaphragm gauge could be used.

10.4 A PROPOSED MECHANICAL DIAPHRAGM-TYPE GAUGE

By its very nature, a diaphragm gauge has none of the inherent disadvantages of a piston type. It can be made completely sealed with no sand or dust problems. Preliminary rough calculations indicate that diaphragms with sufficient linear deflection for direct soot recording can be constructed to operate over the range of pressures measured on Greenhouse. It also seems feasible to critically damp such a diaphragm. The recorder could be a soot-coated glass disk mounted on a turntable driven directly by a powerful clock-type spring. Rapid starting and constant angular velocity could be obtained by mounting a rotary-type dash pot on the shaft. Timing could be furnished by a direct-recording clock-type balance wheel. Such a system could be made small, self-contained, and, if desired, actuated by the heat flash instead of a start relay. The response time should be of the order of 1 msec with a signal-to-noise ratio of at least 100 to 1. The authors are preparing a memorandum on such a gauge for release in the immediate future.

REFERENCE

1. K. R. Eldredge, High Resolution Recording with Soot, Rev. Sci. Instruments, 21: 199 (1950).

[redacted]

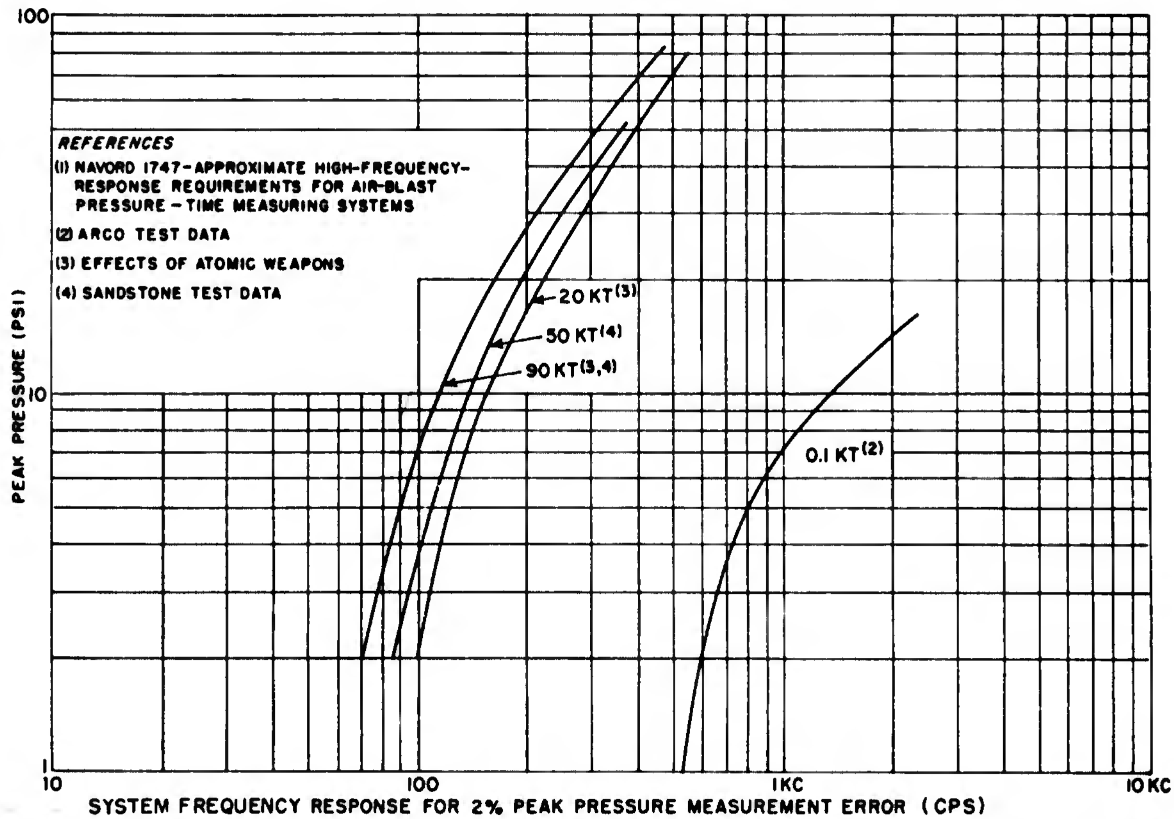

Fig. 1.1 System Response Requirements for 2 Per Cent Error in Peak-pressure Measurement

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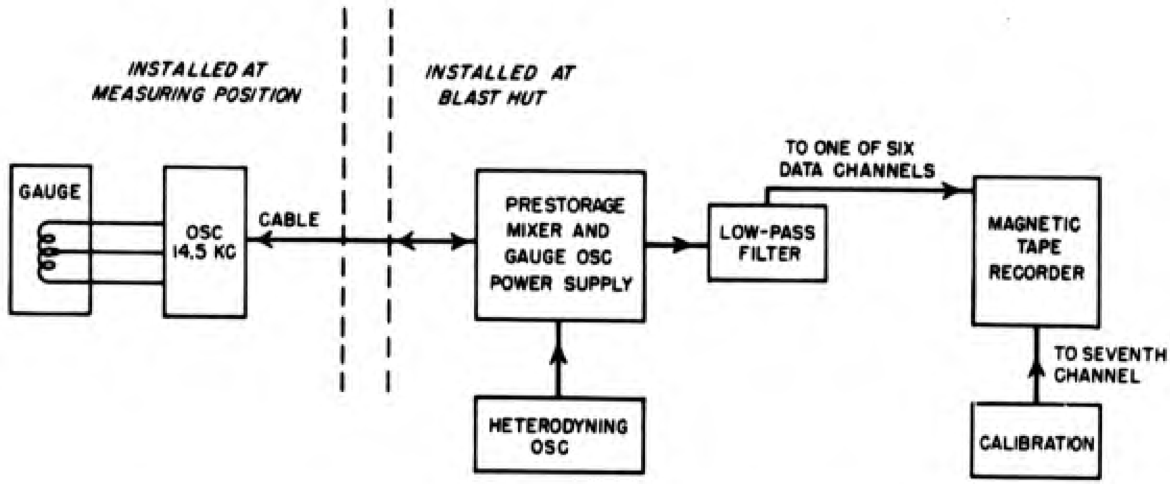

Fig. 2.1 Functional Diagram of Pressure-Time Recording System; Field Installation

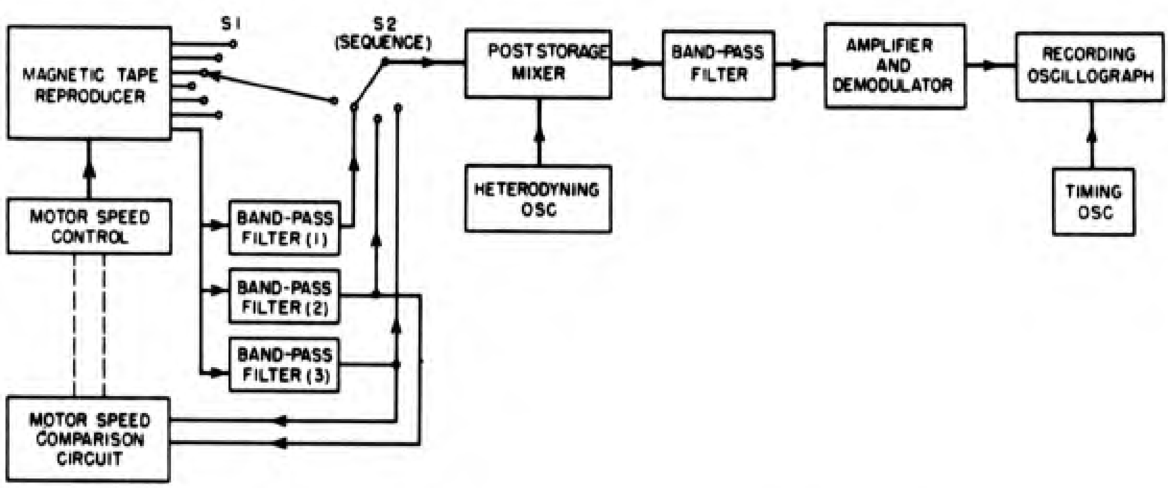

Fig. 2.2 Functional Diagram of Data-recovery System for Pressure-Time Recording System

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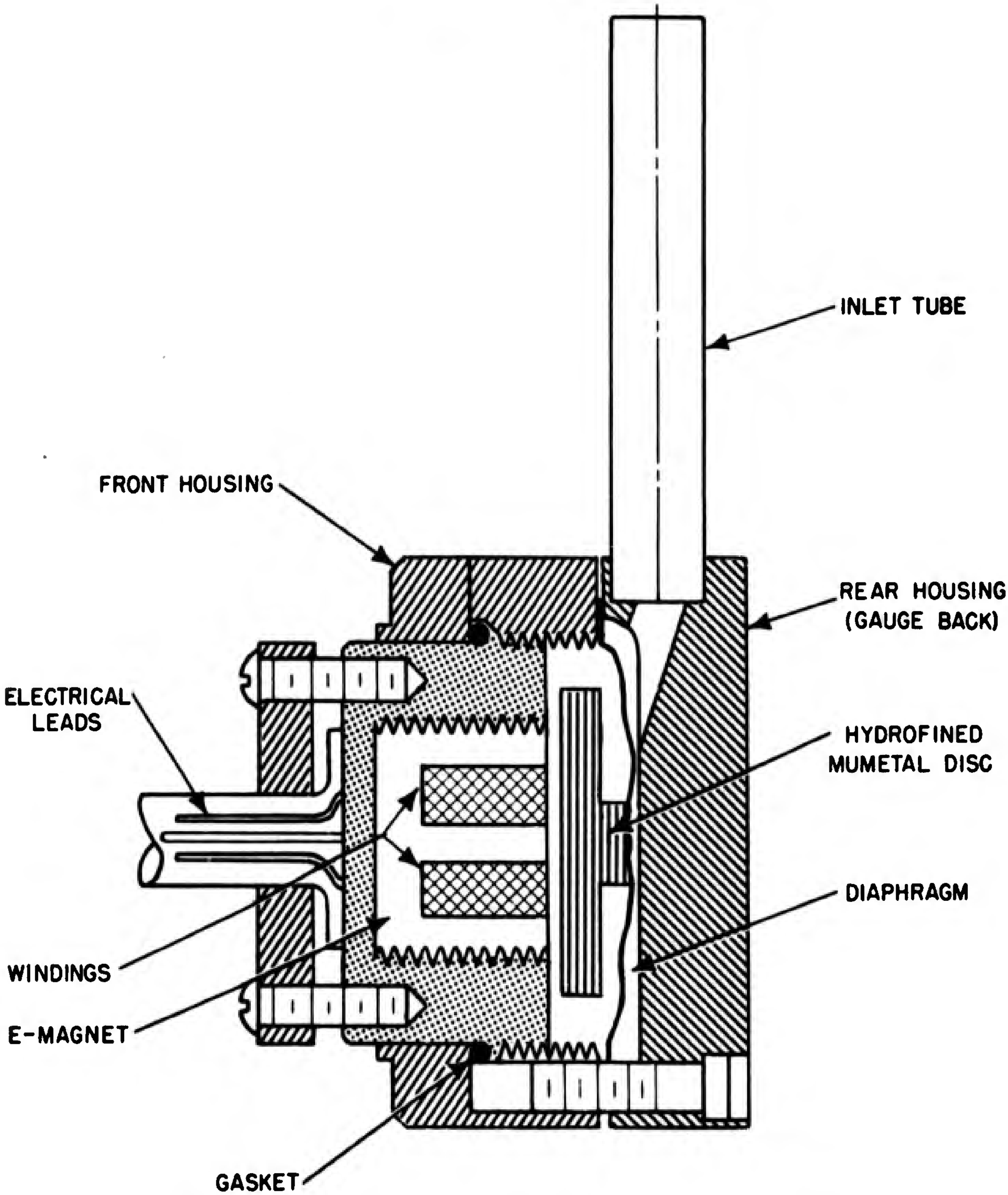

Fig. 2.3 Basic Features of Mark 5 Inductance Gauge with Modified Back

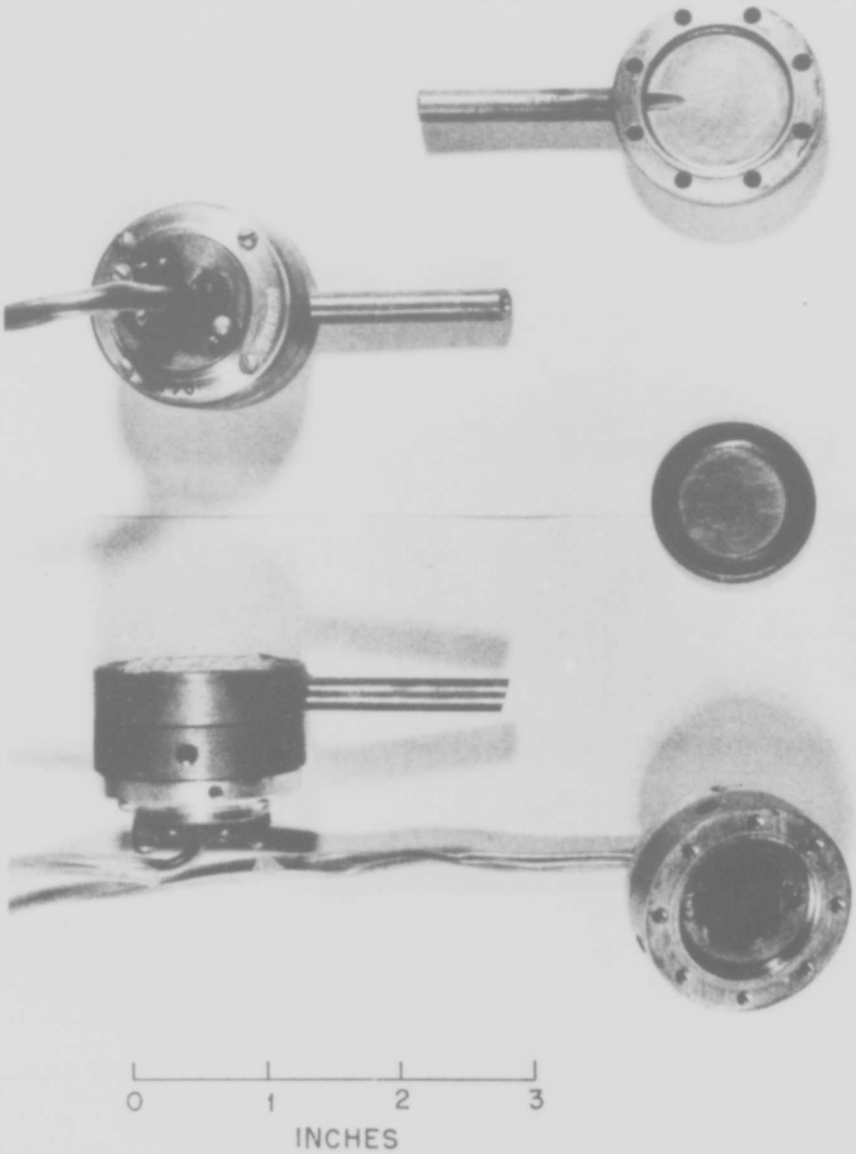

Fig. 2.4 Mark 5 Inductance Gauge

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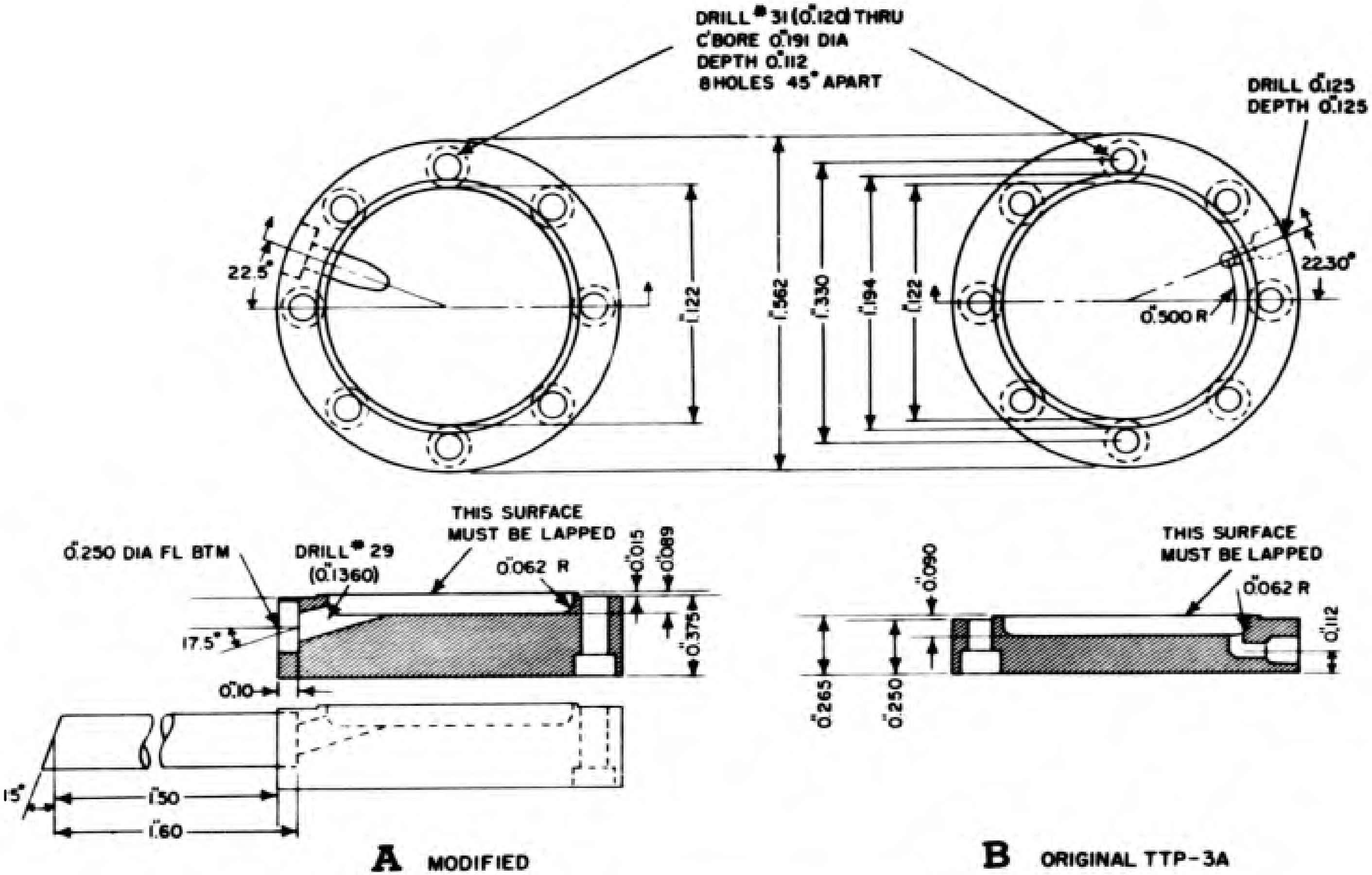

Fig. 2.5 Original and Modified Gauge Backs

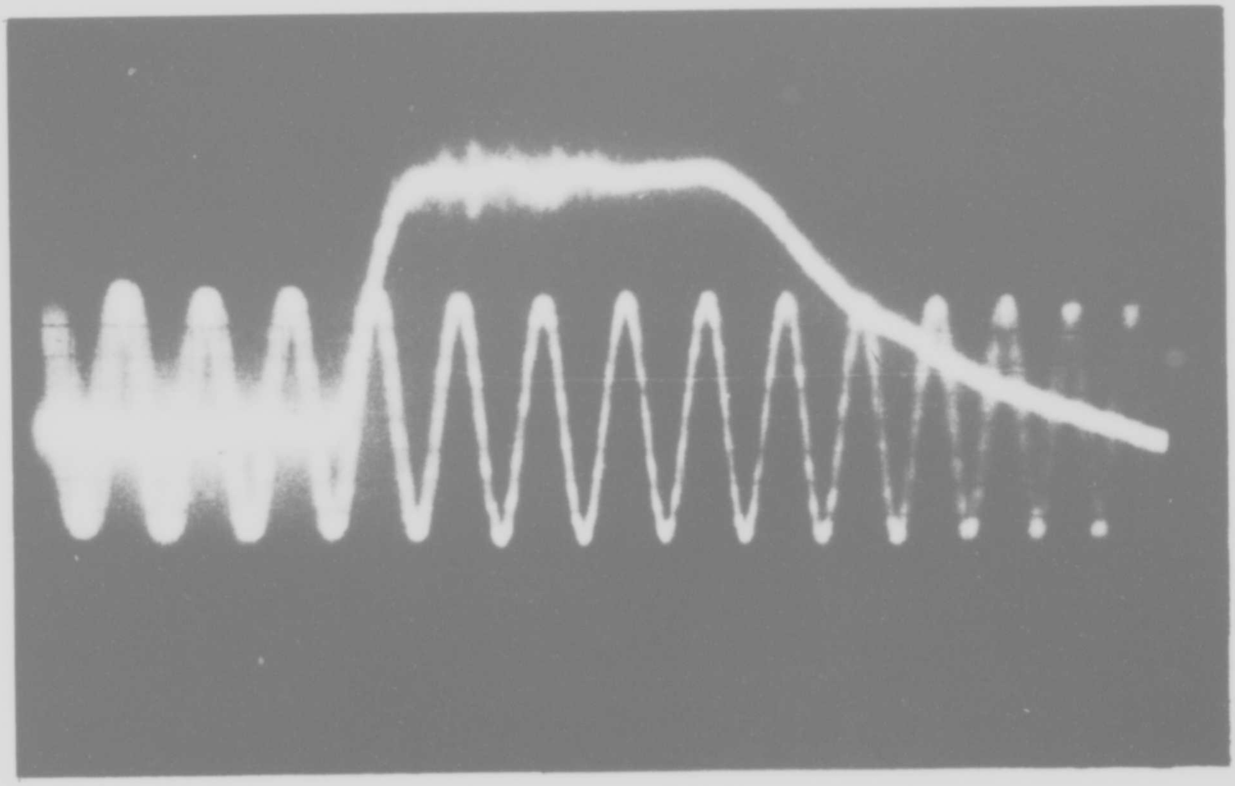

Fig. 2.6 Sample Gauge Test Record

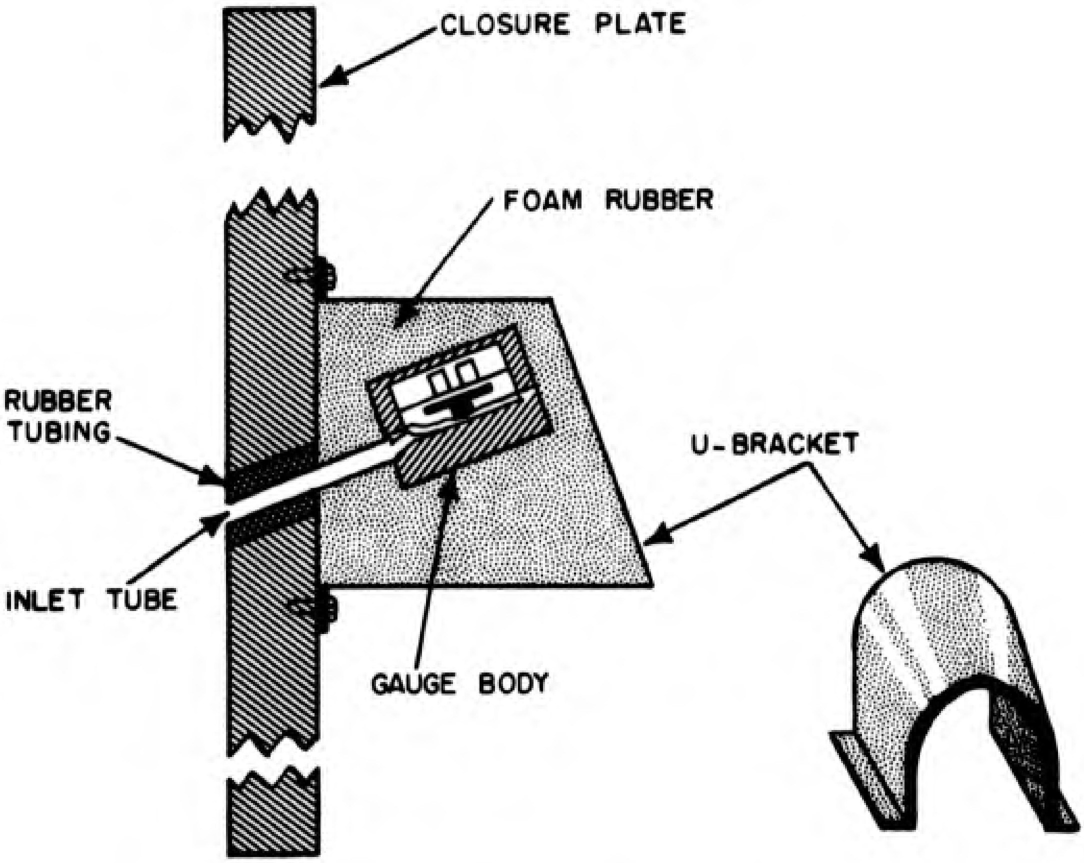

Fig. 2.7 Gauge Mounting at a Vertical Station

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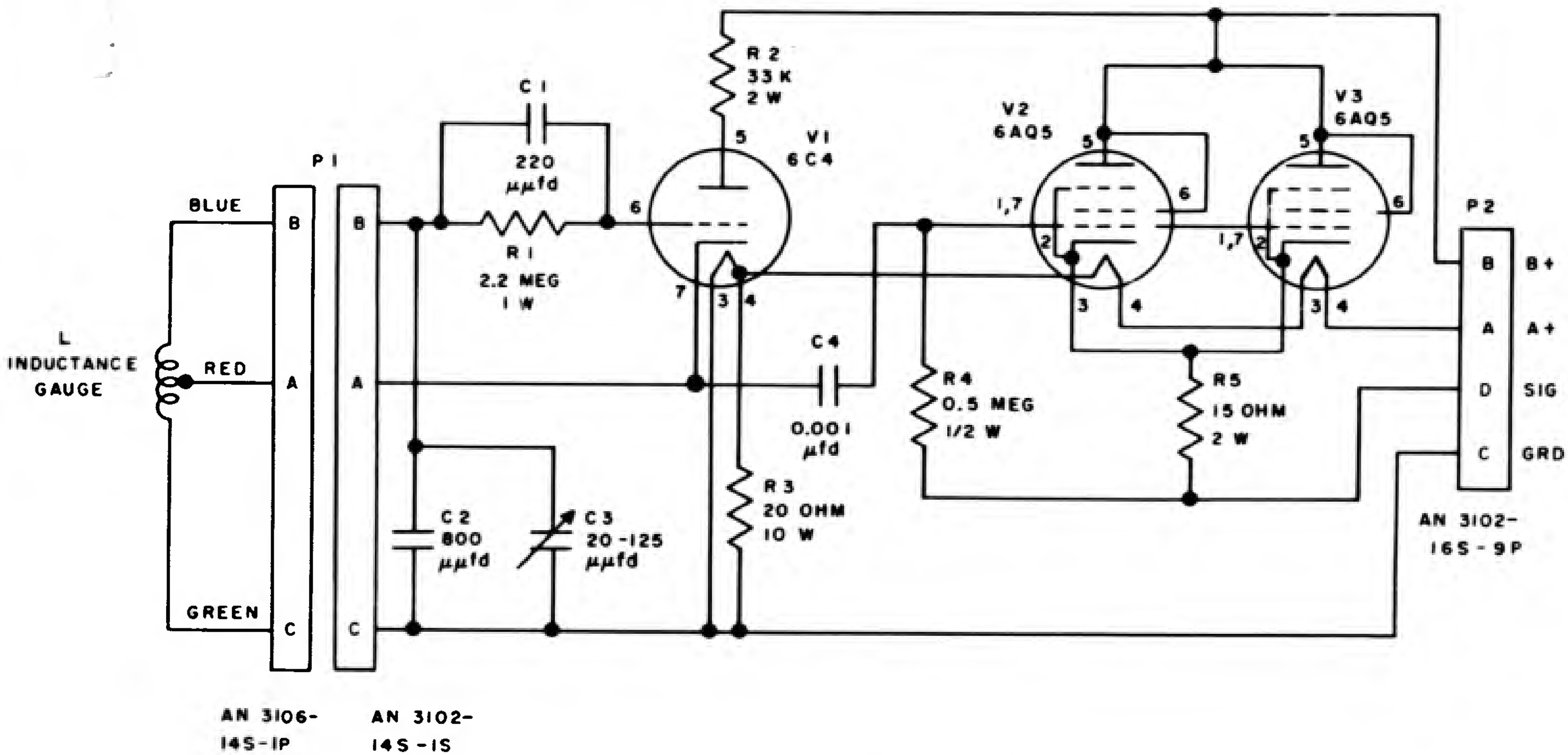

Fig. 2.8 Circuit Diagram of Gauge Oscillator

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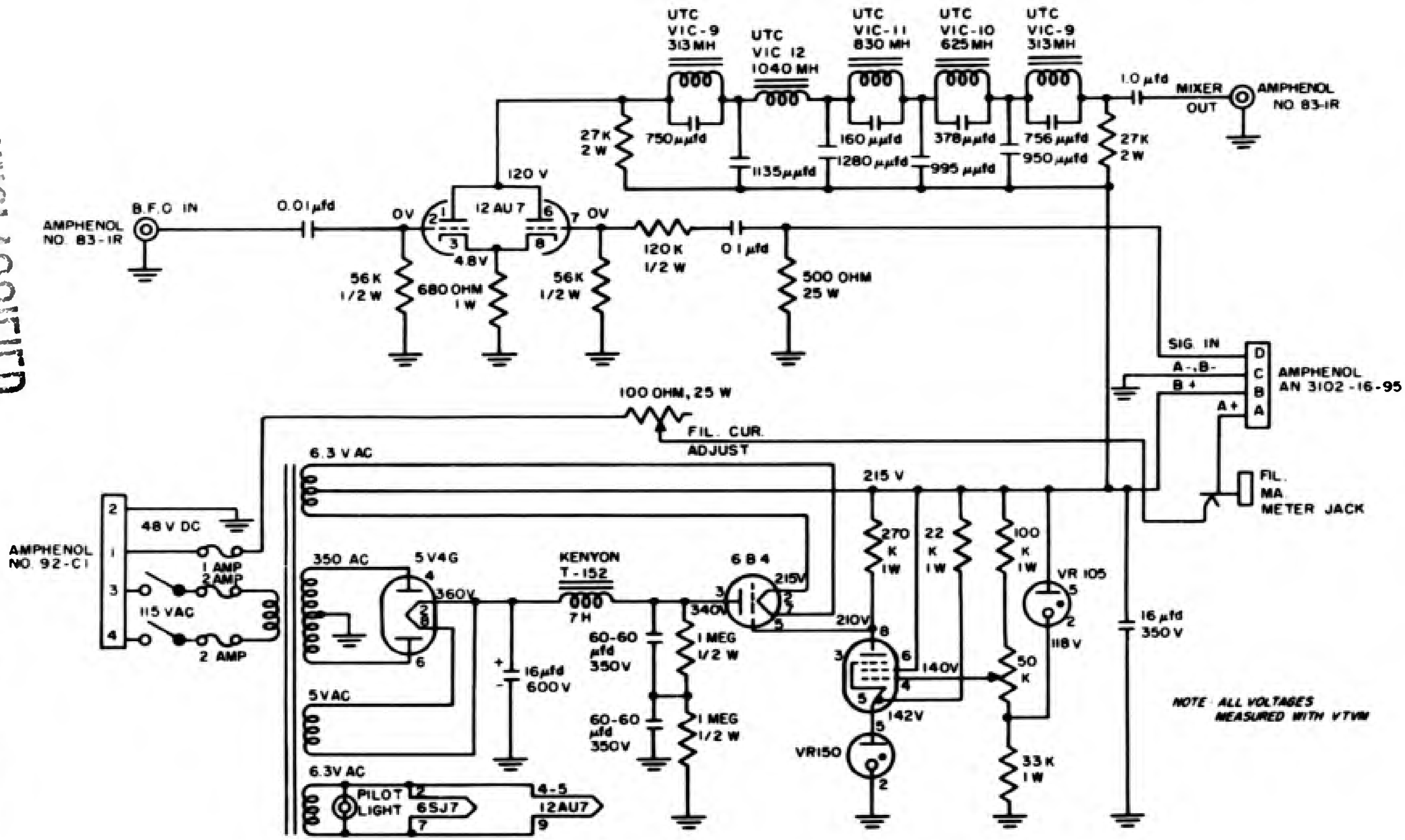


Fig. 2.9 Circuit Diagram of Prestorage Mixer and Gauge-oscillator Power Supply

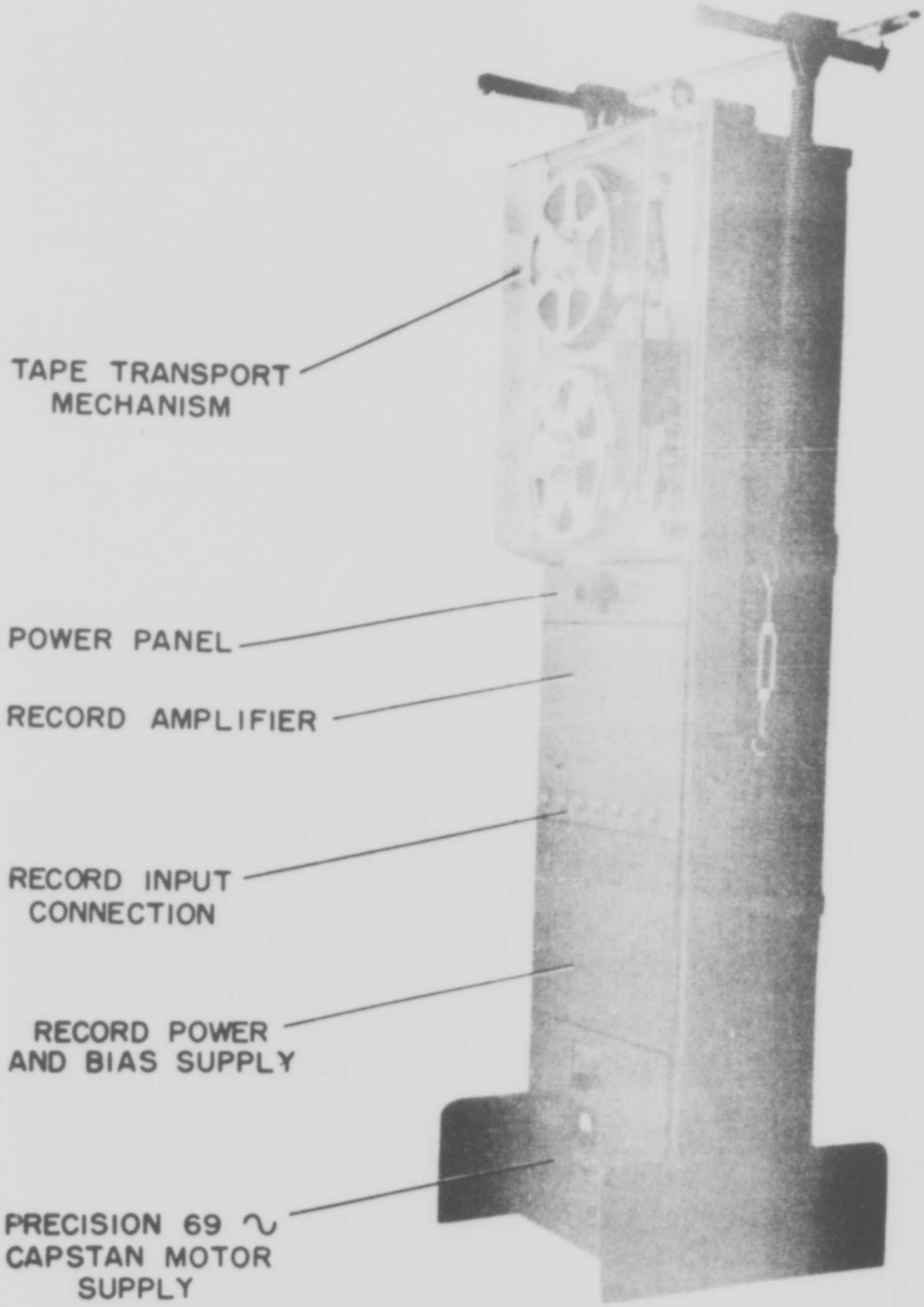


Fig. 2.10 Magnetic-tape Recorder

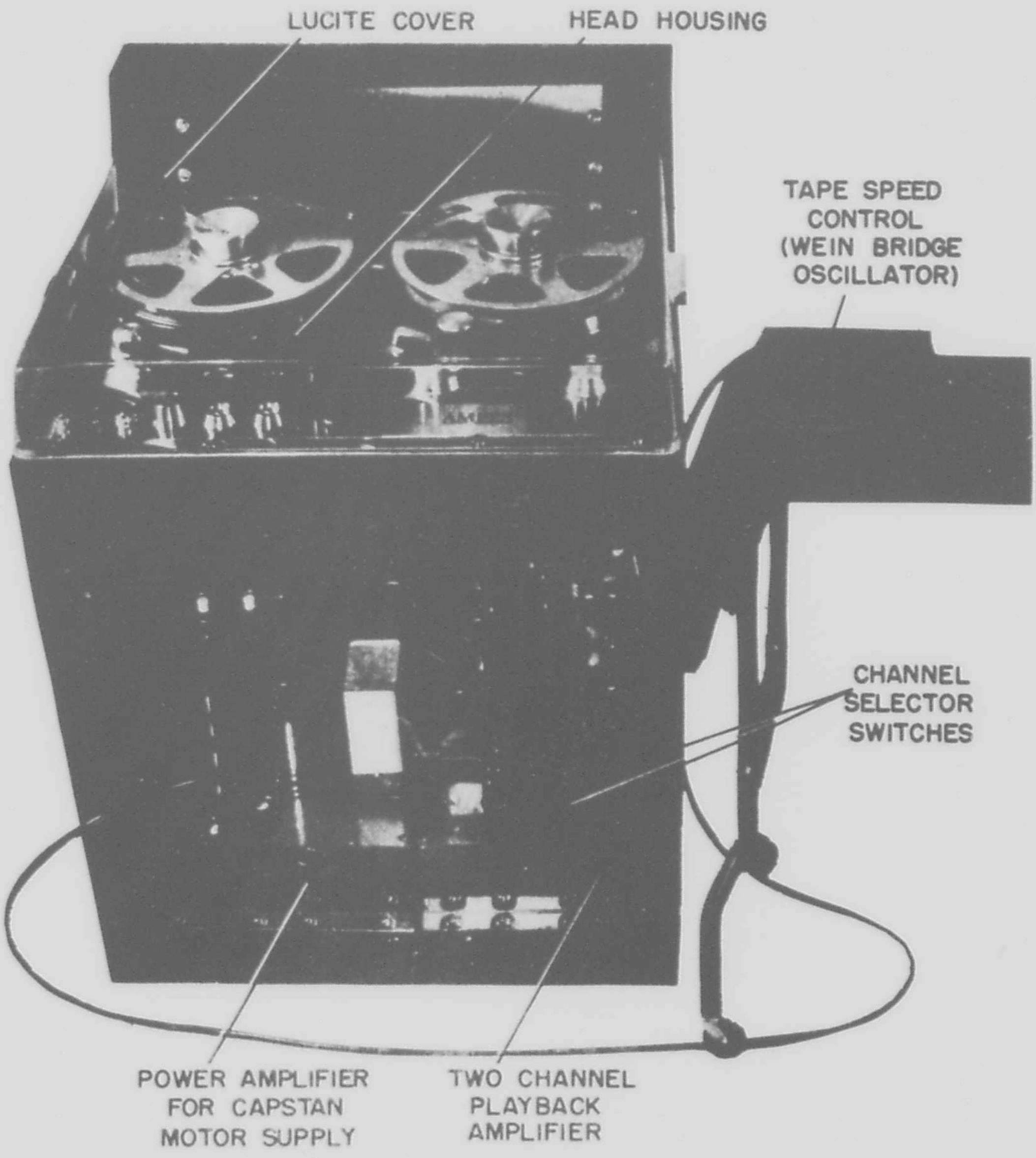
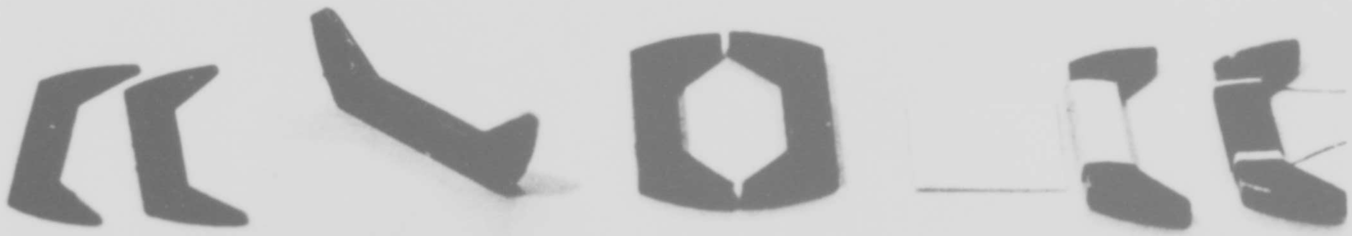


Fig. 2.11 Magnetic-tape Reproducer



1. INDIVIDUAL LAMINATIONS IDENTICAL TO THOSE USED ON STANDARD AMPEX RECORDERS.
2. SAME AS 1.
3. SOLID UNIT, 0.050 IN. WIDE, CONSISTING OF SEVEN LAMINATIONS BONDED TOGETHER.
4. CORE OF RECORDING HEAD MADE OF TWO BONDED UNITS.
5. INSULATING STRIP.
6. INSULATING STRIP WRAPPED AROUND CORE.
7. CORE AND INSULATING STRIP WRAPPED WITH 75 TURNS OF WIRE.

Fig. 2.12 Construction of Recording Head

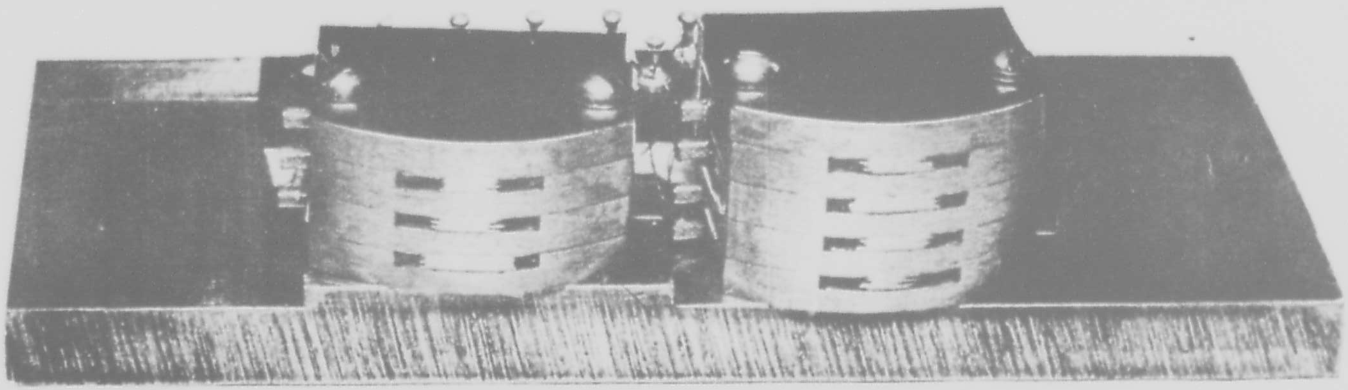


Fig. 2.13 Assembled Recording Head

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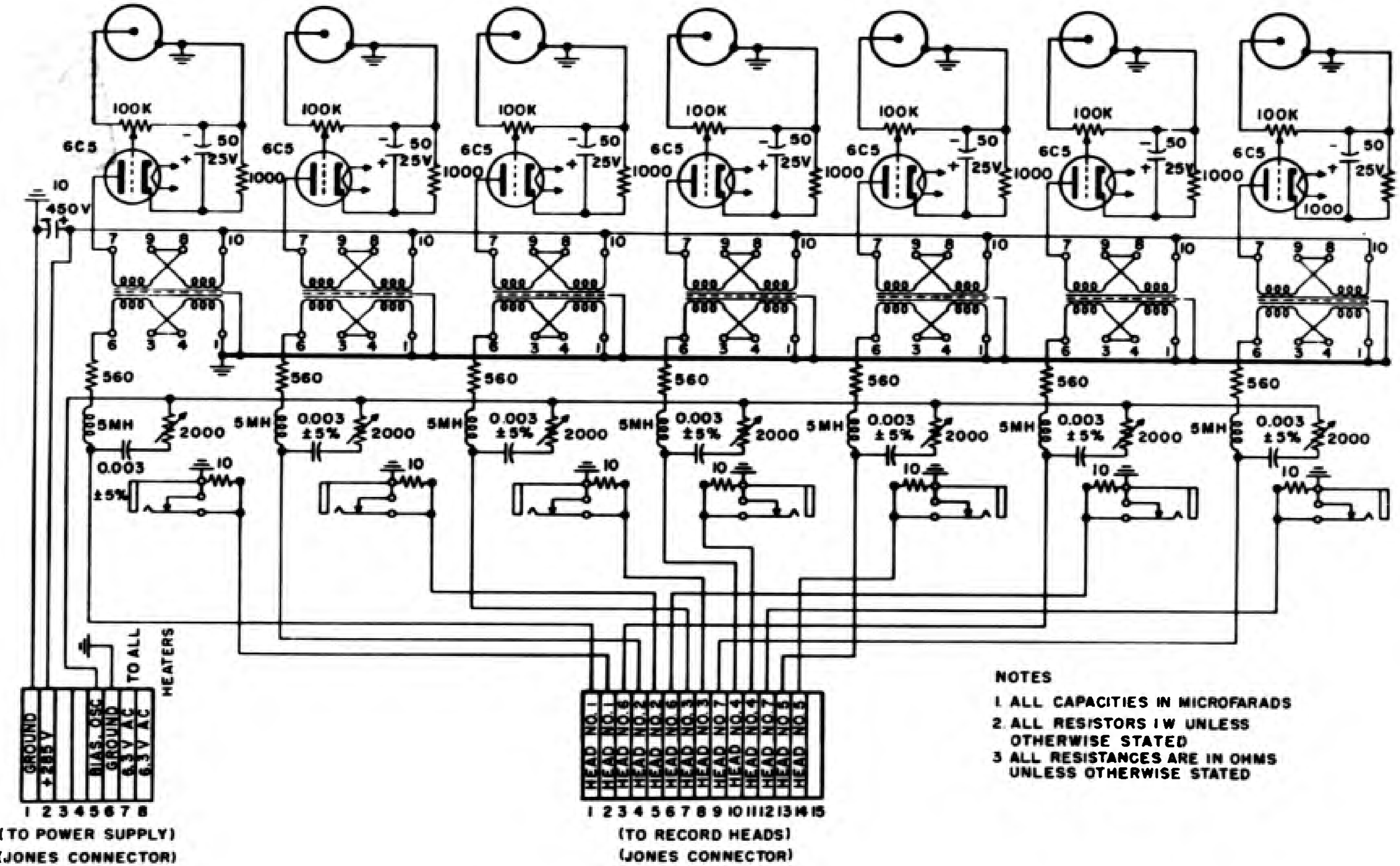


Fig. 2.14 Circuit Diagram of Seven-channel Record Amplifier

[redacted]

[redacted]

[redacted]

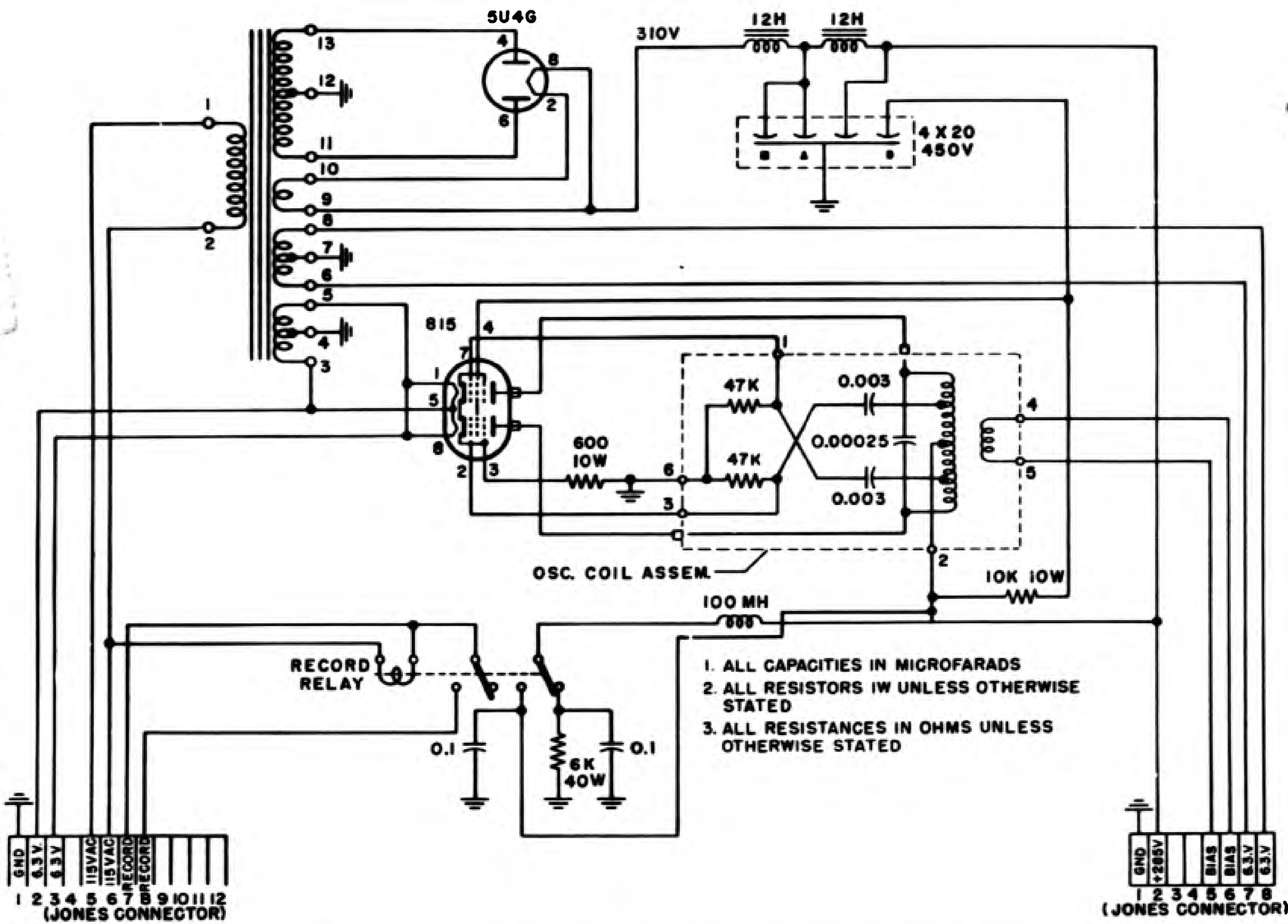


Fig. 2.15 Circuit Diagram of Record-amplifier Power Supply and Bias Oscillator

[redacted]

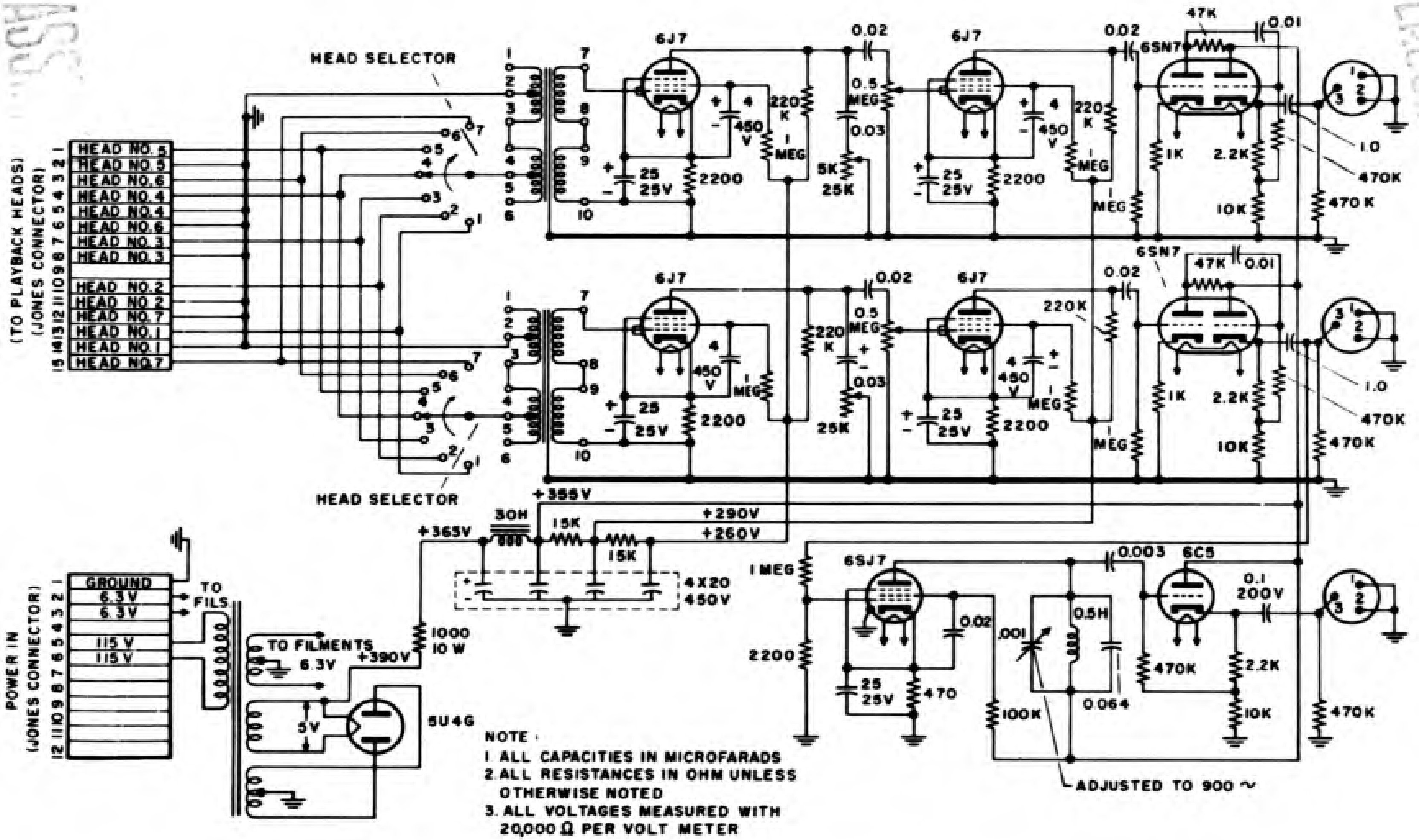
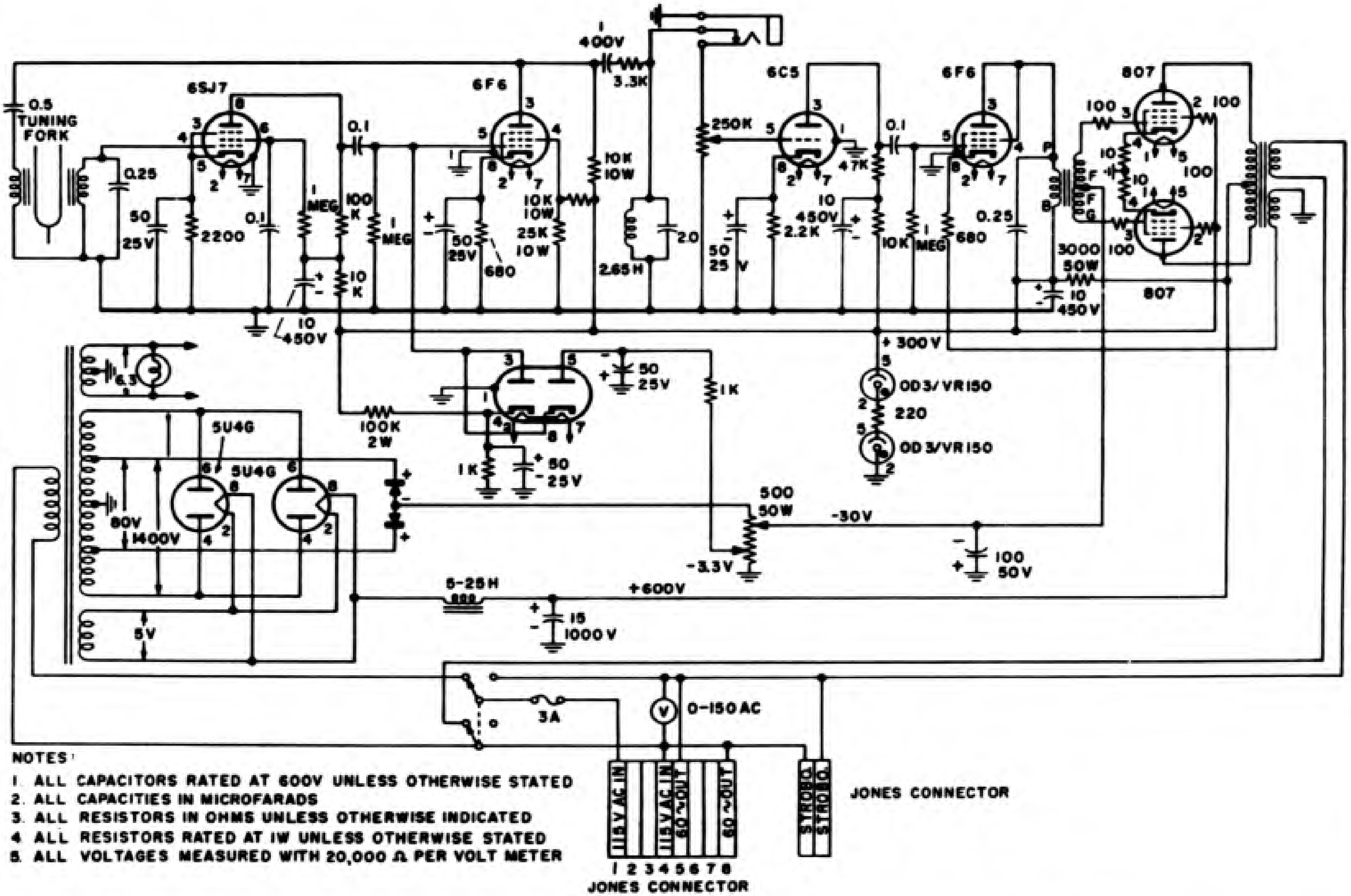


Fig. 2.16 Circuit Diagram of Two-channel Playback Amplifier



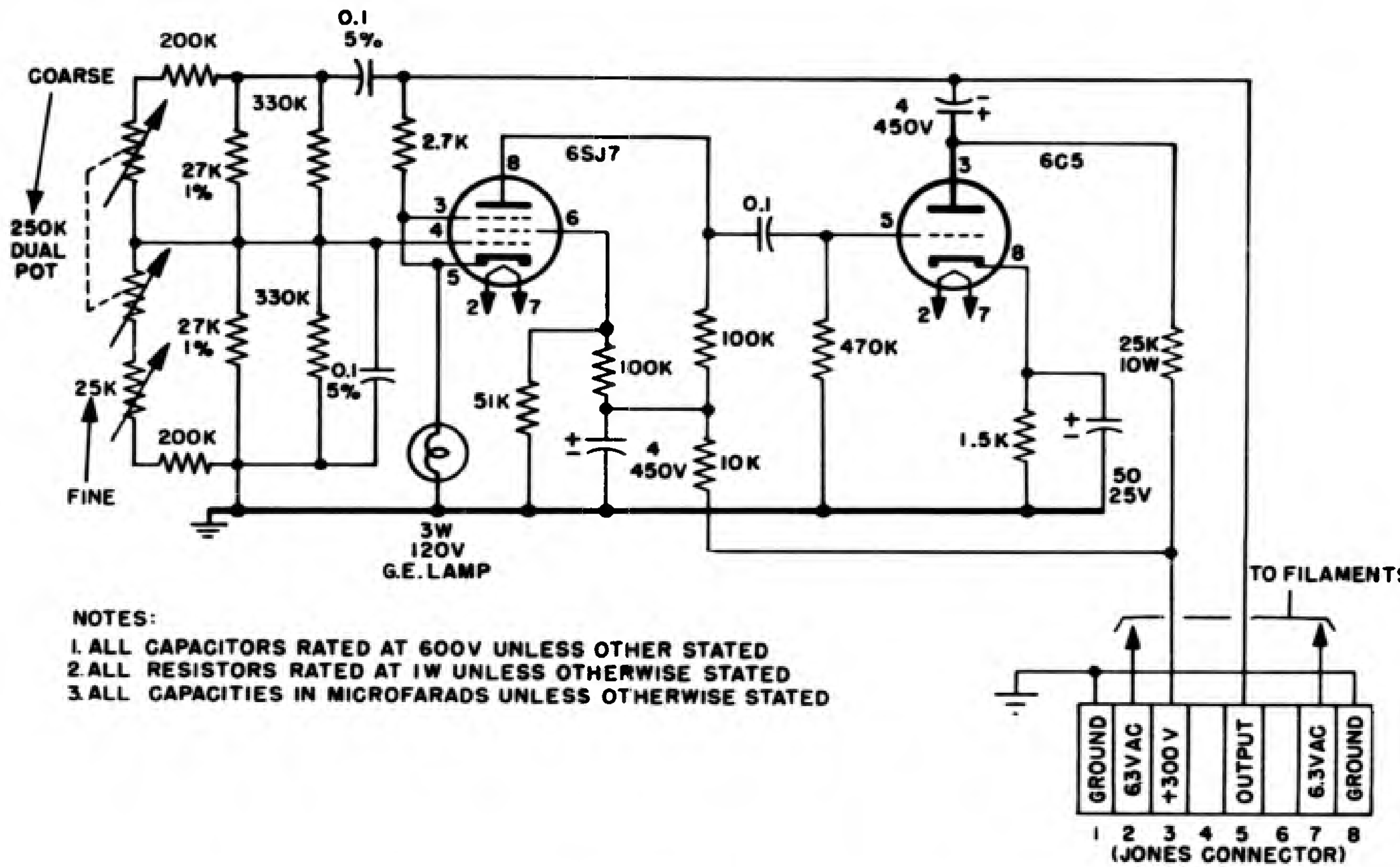
NOTES:

1. ALL CAPACITORS RATED AT 600V UNLESS OTHERWISE STATED
2. ALL CAPACITIES IN MICROFARADS
3. ALL RESISTORS IN OHMS UNLESS OTHERWISE INDICATED
4. ALL RESISTORS RATED AT 1W UNLESS OTHERWISE STATED
5. ALL VOLTAGES MEASURED WITH 20,000 Ω PER VOLT METER

Fig. 2.17 Circuit Diagram of Precision 69-cycle Amplifier for Record Capstan Drive Motor

[redacted]

[redacted]



NOTES:
1. ALL CAPACITORS RATED AT 600V UNLESS OTHER STATED
2. ALL RESISTORS RATED AT 1W UNLESS OTHERWISE STATED
3. ALL CAPACITIES IN MICROFARADS UNLESS OTHERWISE STATED

Fig. 2.18 Circuit Diagram of Wien Bridge Oscillator for Capstan Motor Supply

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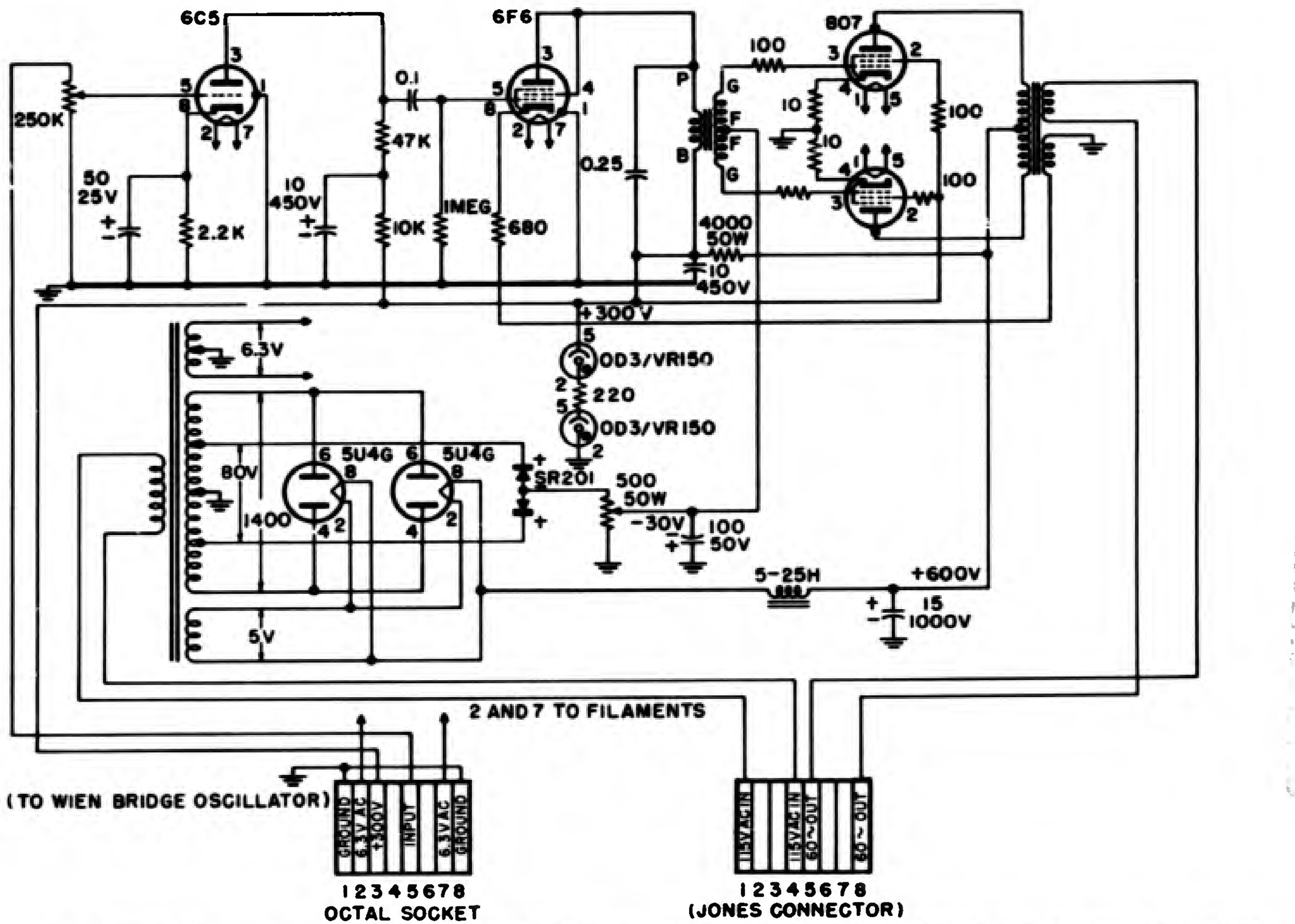

1. ALL CAPACITORS RATED AT 600V UNLESS OTHERWISE STATED
2. ALL CAPACITIES IN MICROFARADS
3. ALL RESISTORS RATED AT 1W UNLESS OTHERWISE STATED
4. ALL VOLTAGES MEASURED WITH 20,000 VOLT METER
5. ALL RESISTANCES IN OHMS UNLESS OTHERWISE STATED

Fig. 2.19 Circuit Diagram of Power Amplifier for Playback Capstan Motor Supply

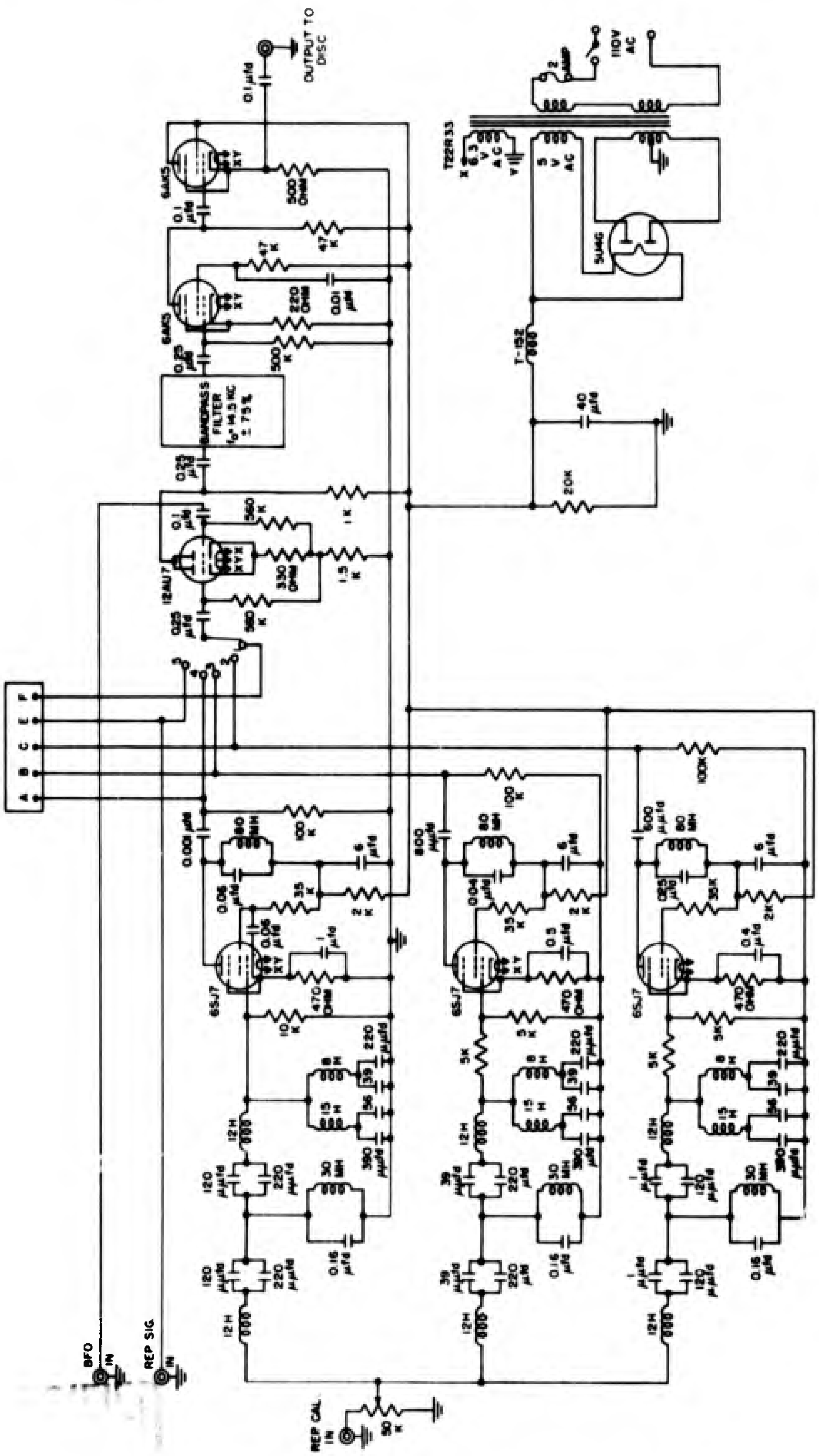

Fig. 2.20 Circuit Diagram of Poststorage Mixer

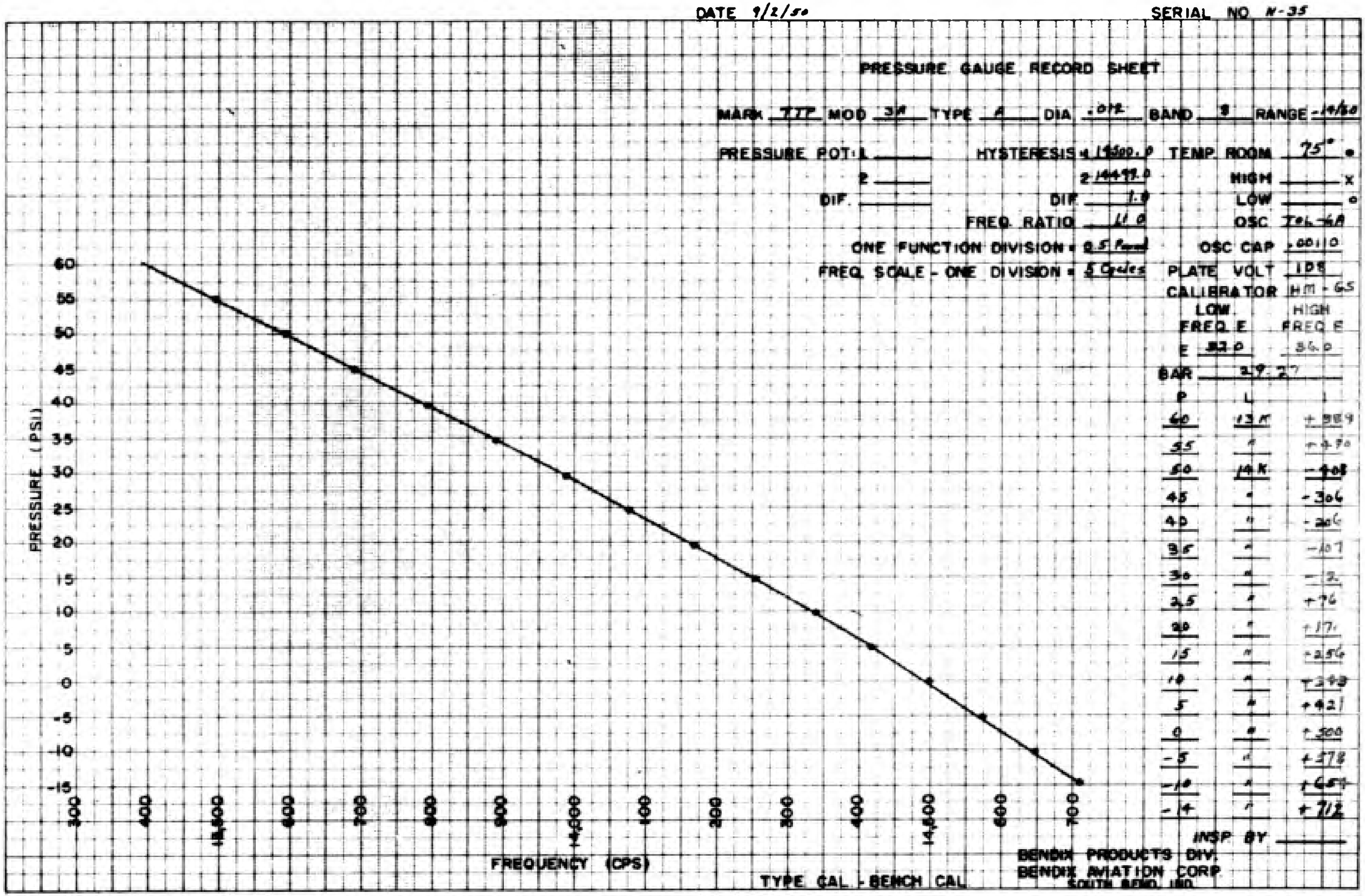

Fig. 2.21 Manufacturer's Calibration Curve for 60-psi Gauge

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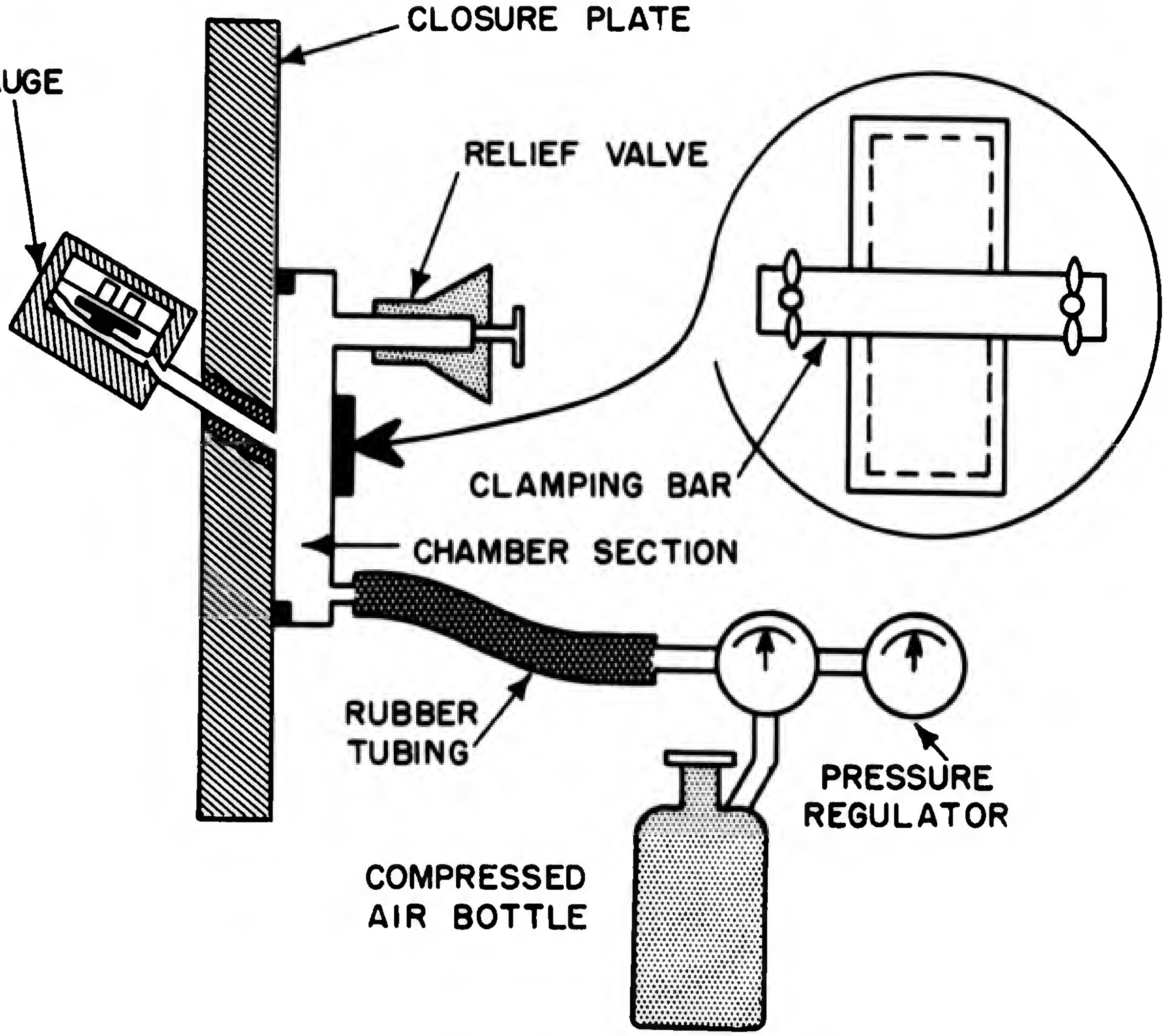

Fig. 2.22 Sketch of Pressure Calibration Assembly

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[redacted]

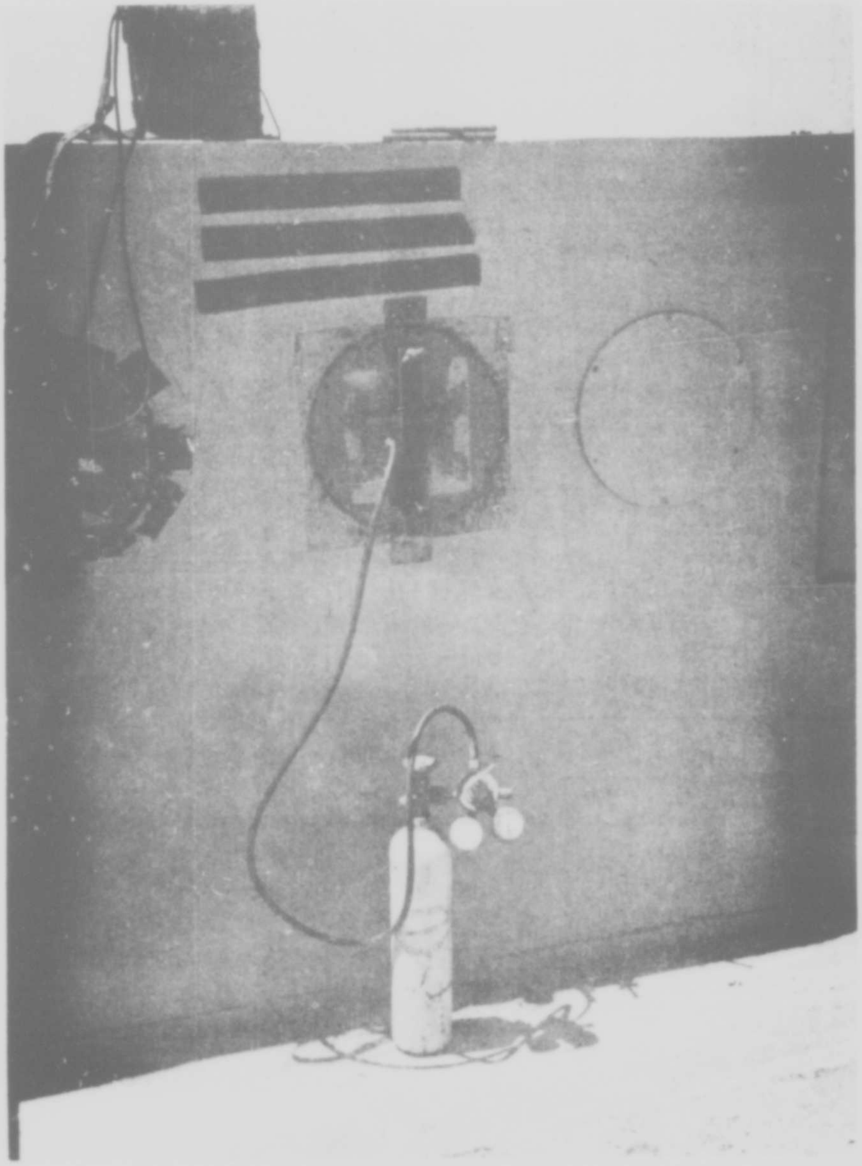

Fig. 2.23 Field Pressure Calibrator Mounted on Wall Closure Plate

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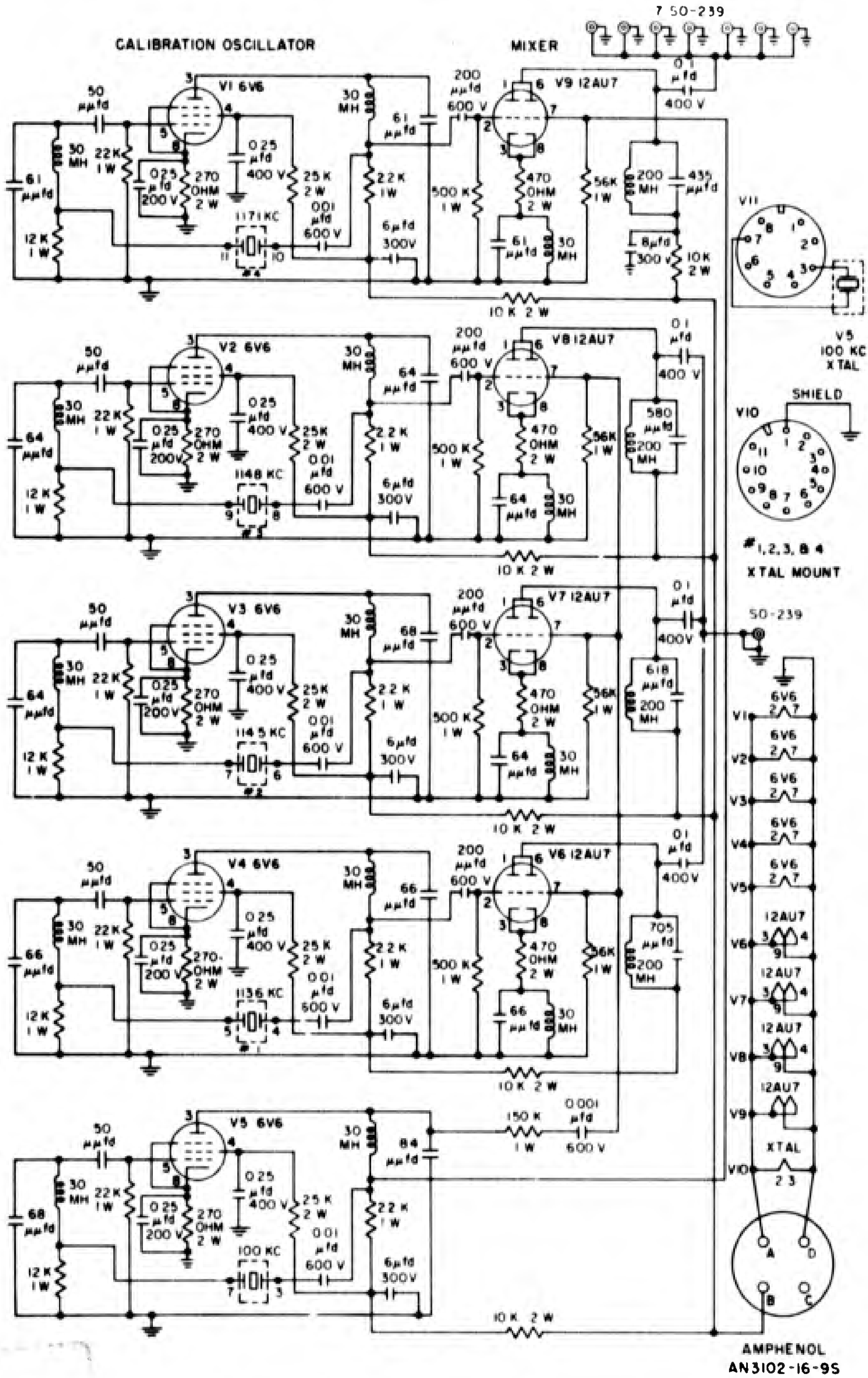

Fig. 2.24 Circuit Diagram of Recording Calibration Beat-frequency Oscillator Unit

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HA[redacted]
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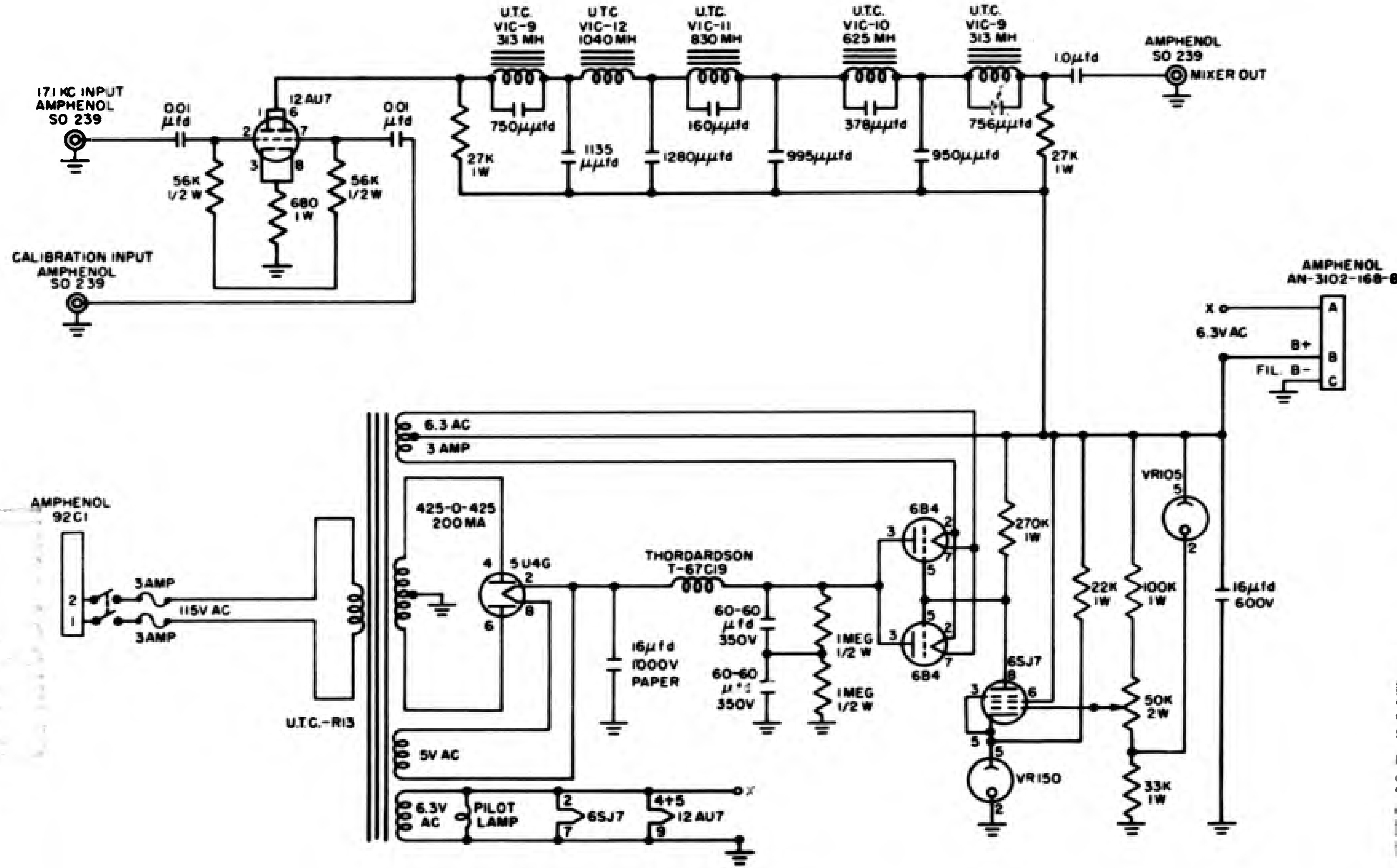


Fig. 2.25 Circuit Diagram of Prestorage Mixer for Calibration Channel

[redacted]

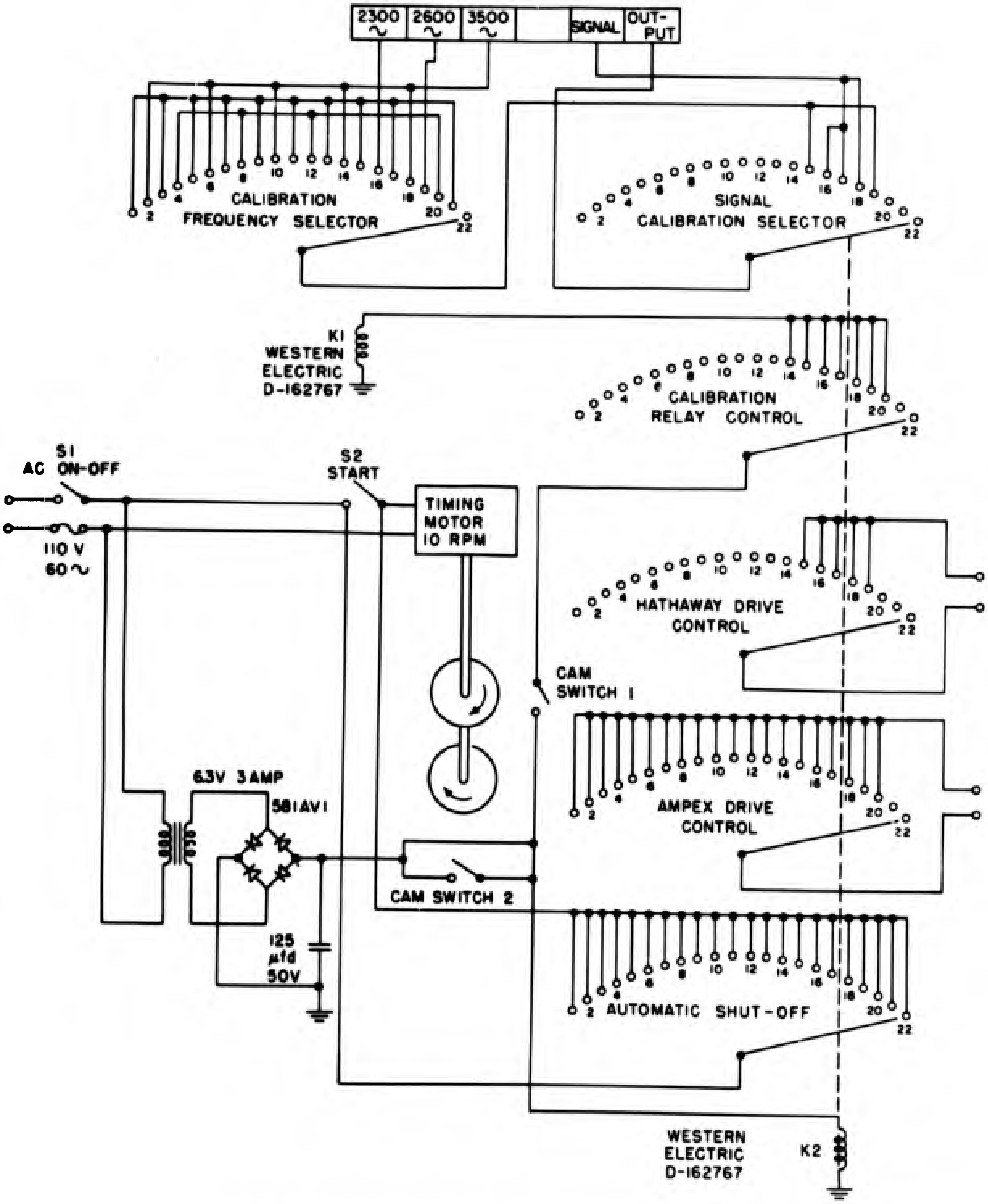
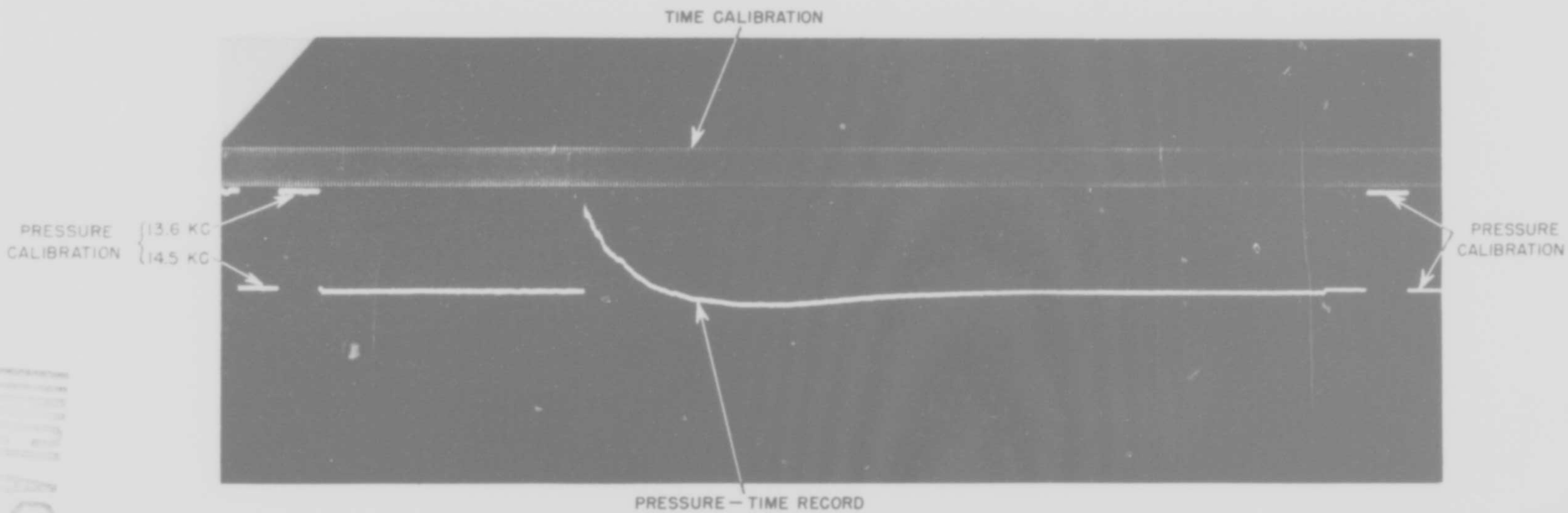


Fig. 2.26 Schematic Diagram of Sequence Switching Circuit

[redacted]

[redacted]



THE FREQUENCY-SHIFT PRESSURE CALIBRATION FOR NEGATIVE PRESSURE, 14.8 KC, WAS NOT USED ON THIS RECORD.

Fig. 2.27 Typical Pressure-Time Record Showing Calibration and Data Information

[redacted]

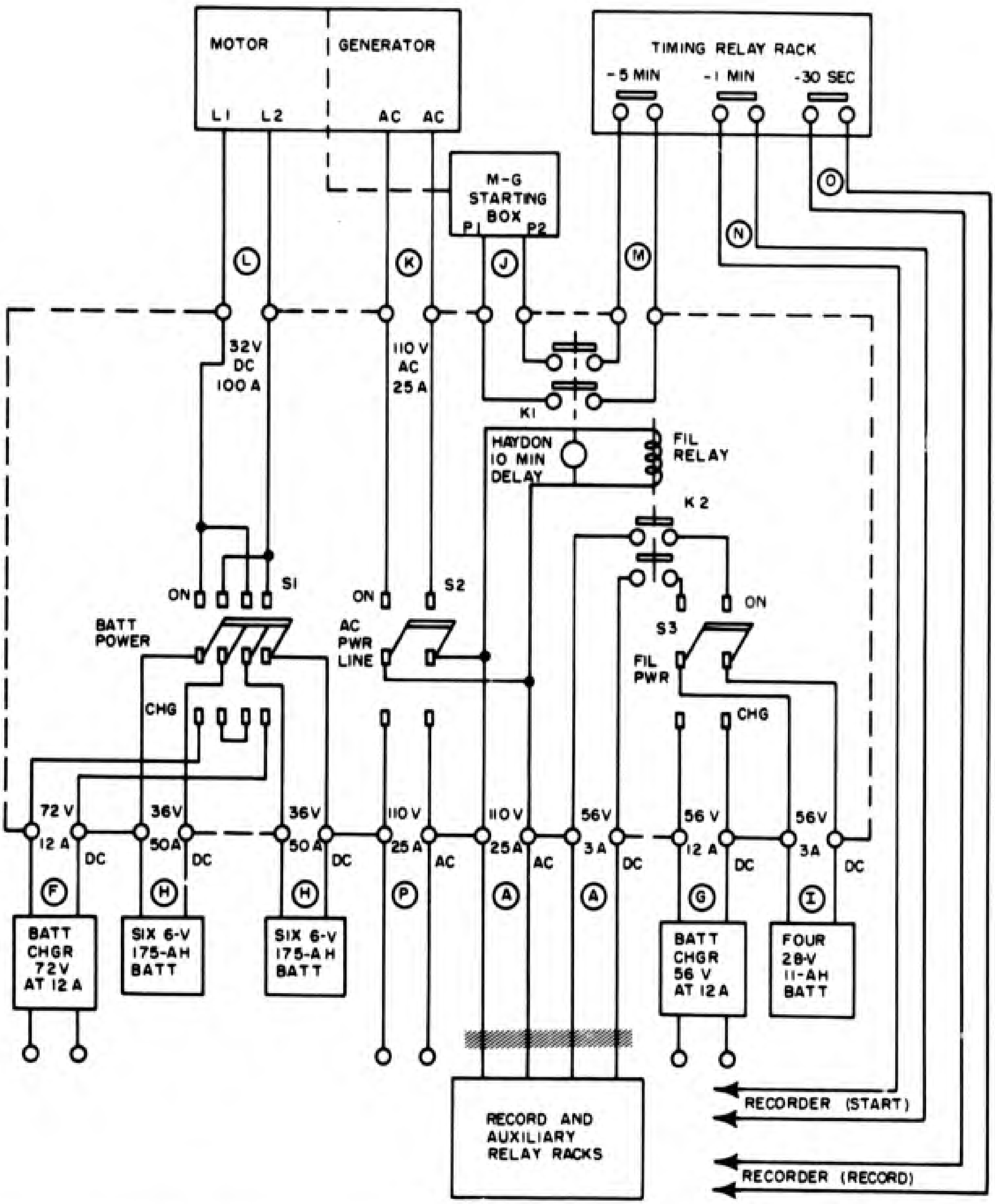


Fig. 2.28 Schematic Diagram of Power Distribution and Control for Single Recorder Installation in Hut

[redacted]

[redacted]

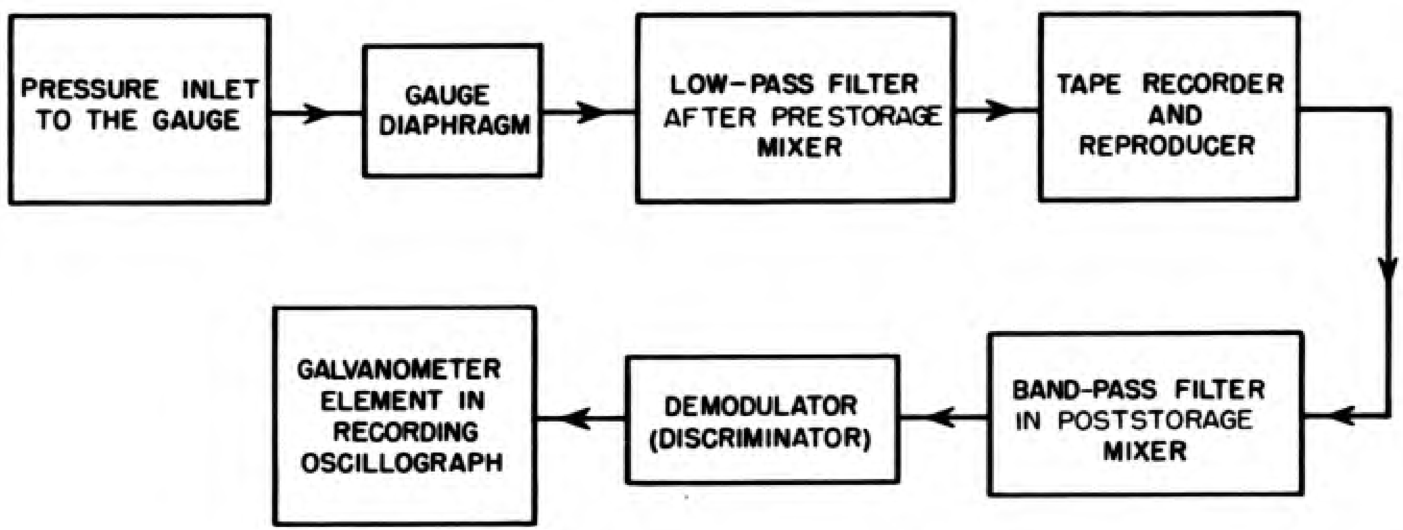


Fig. 2.29 Functional Diagram of Response Determining Elements of the Over-all System

[redacted]

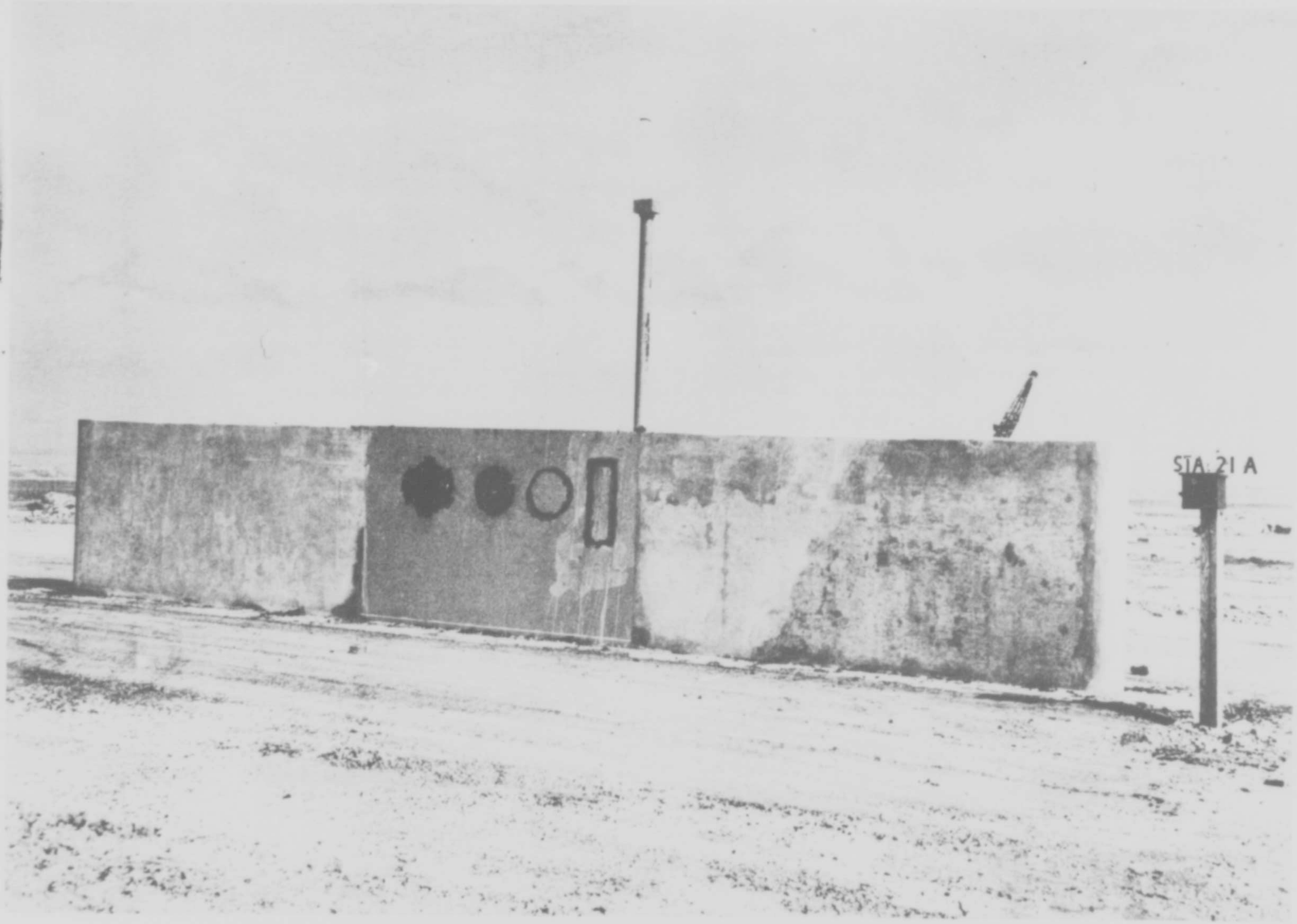


Fig. 3.1 Test Easy, Station 21a; Side View of Wall

[redacted]

[redacted]

Fig. 3.2 Test Easy, Station 21a; End View of Wall toward Zero

[redacted] DATA

[redacted]

[redacted]

Fig. 3.3 Test Dog, Station 20a; Metal Center Section of Inductance-gauge Wall Mount in Center Circular Access

[redacted]

Fig. 3.4 Test Easy, Station 37e; Ground Station

[redacted]

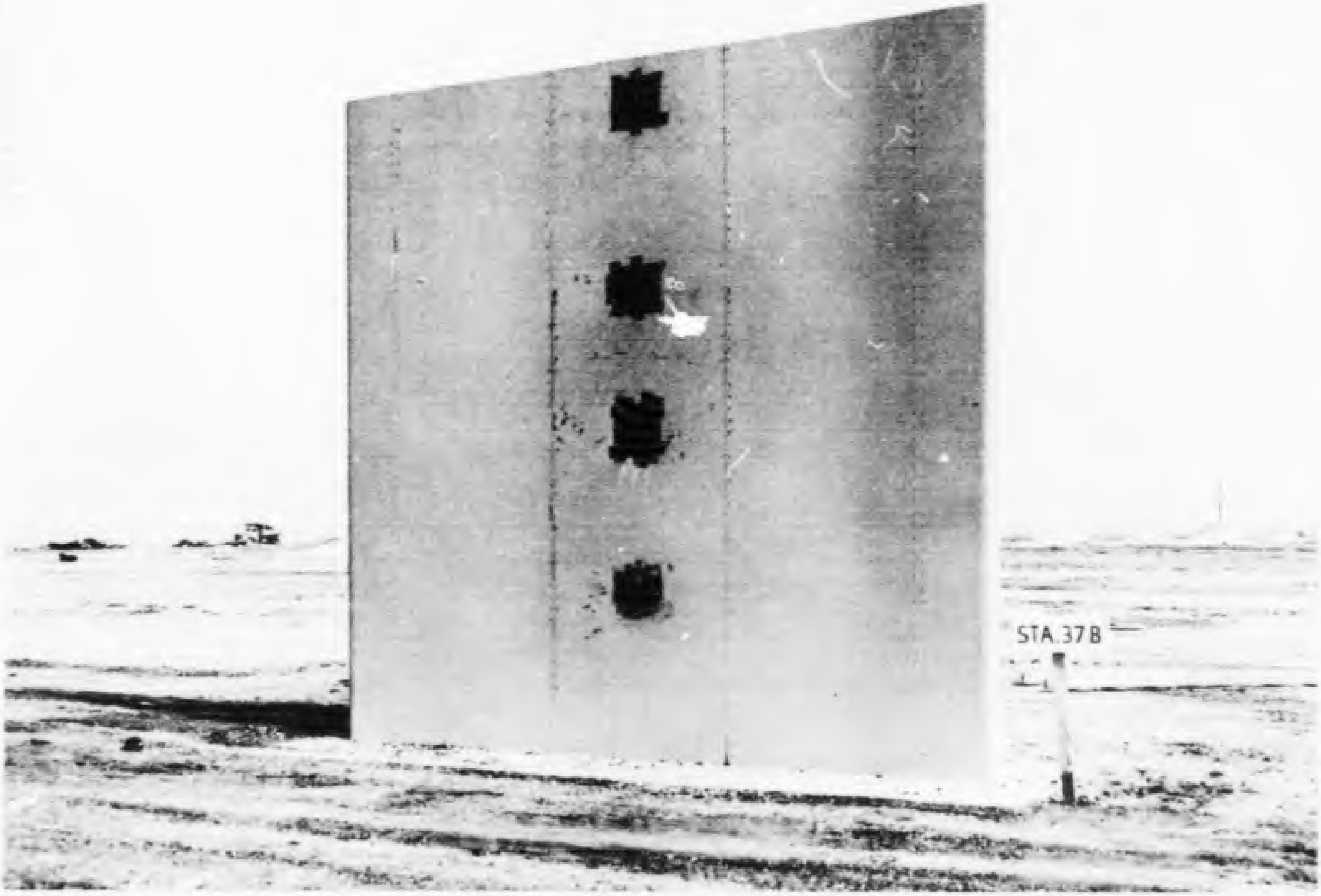


Fig. 3.5 Test Easy, Station 37b; Side View of Pylon

[redacted]

Fig. 3.6 Test Easy, Station 37b; End View of Pylon toward Zero

[redacted]

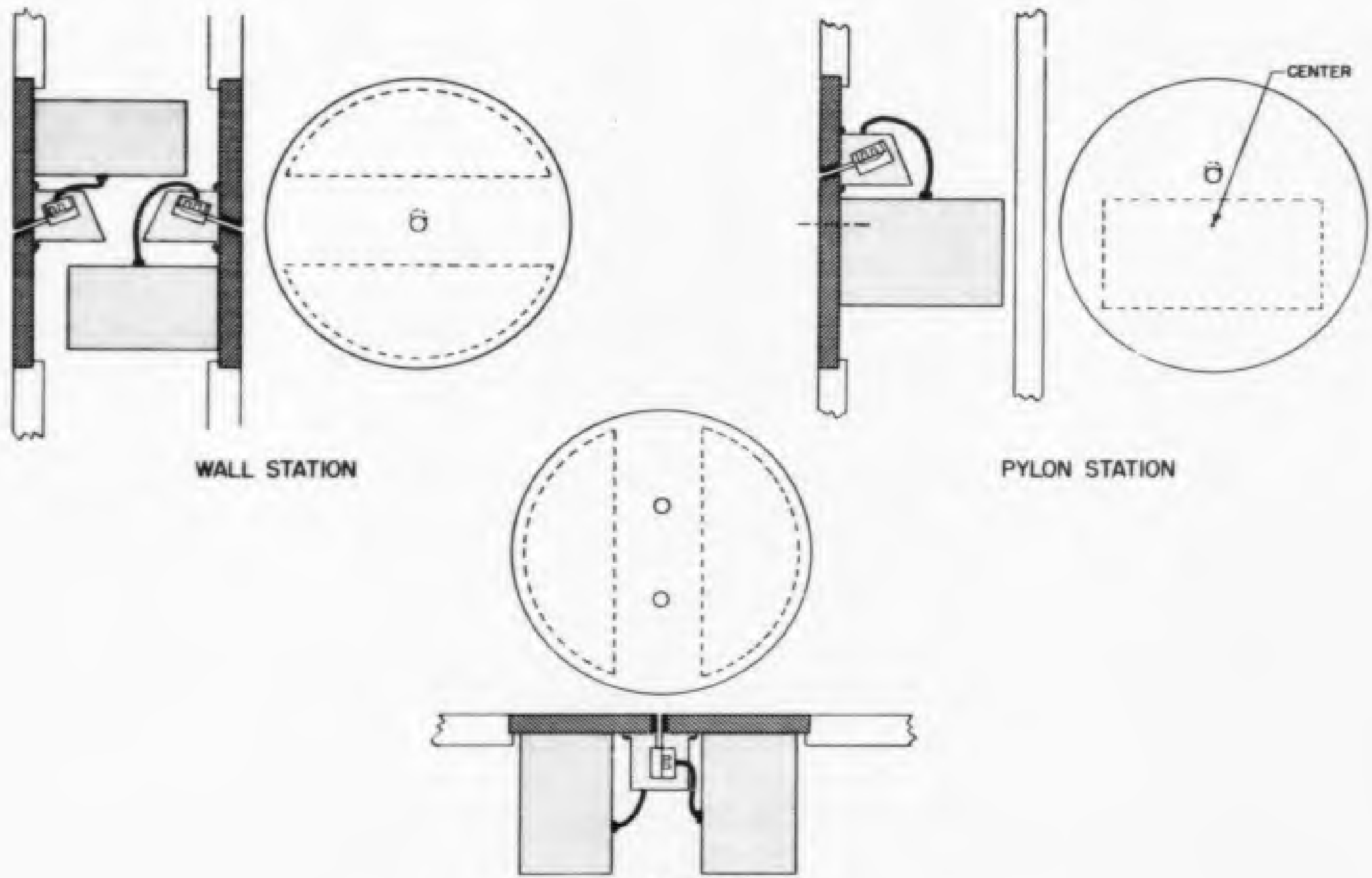


Fig. 3.7 Sketch of Gauge Assembly Types

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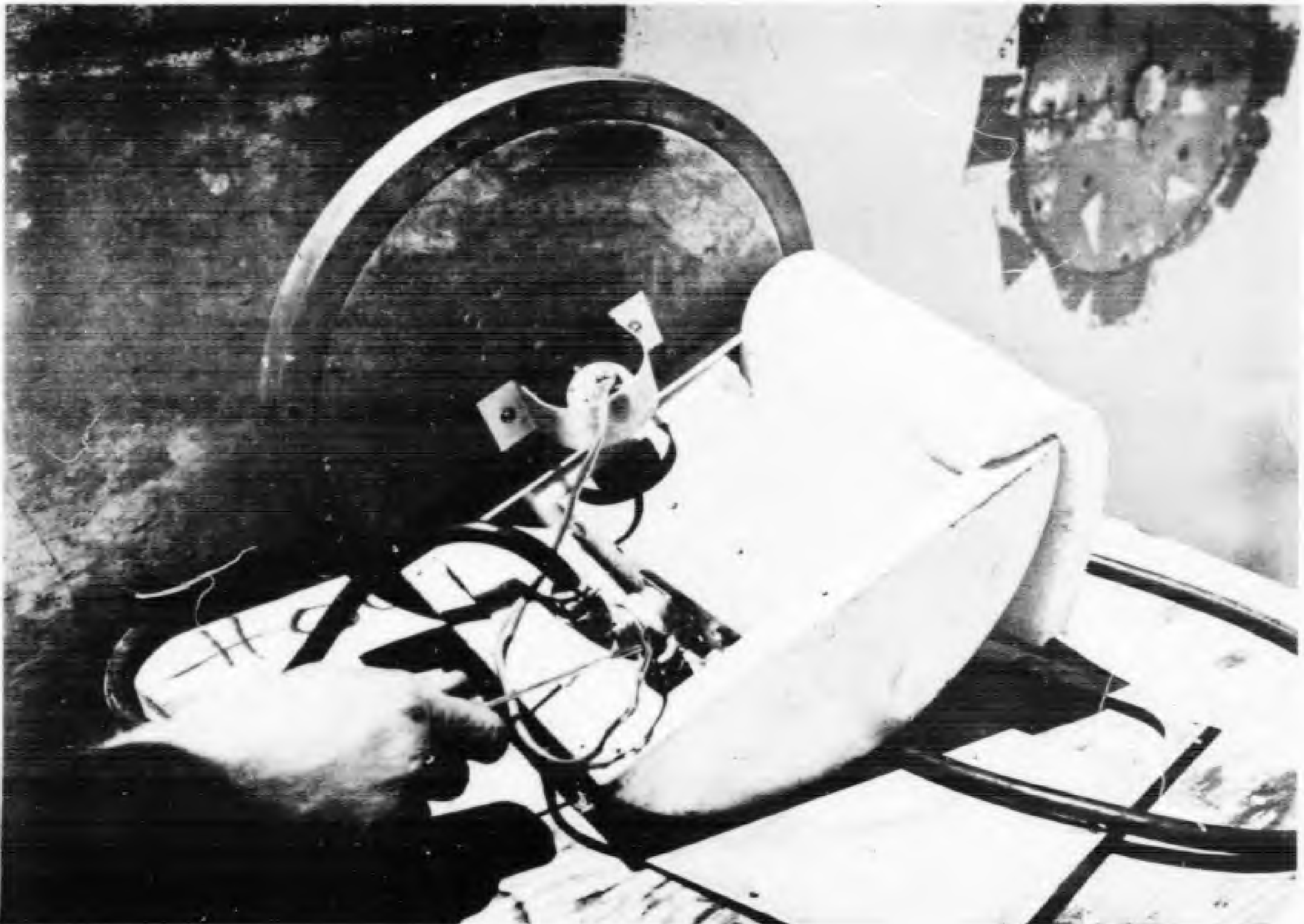

Fig. 3.8 Wall Oscillator and Gauge Assembly

[redacted]

Fig. 3.9 Wall and Pylon Assemblies; Bottom View

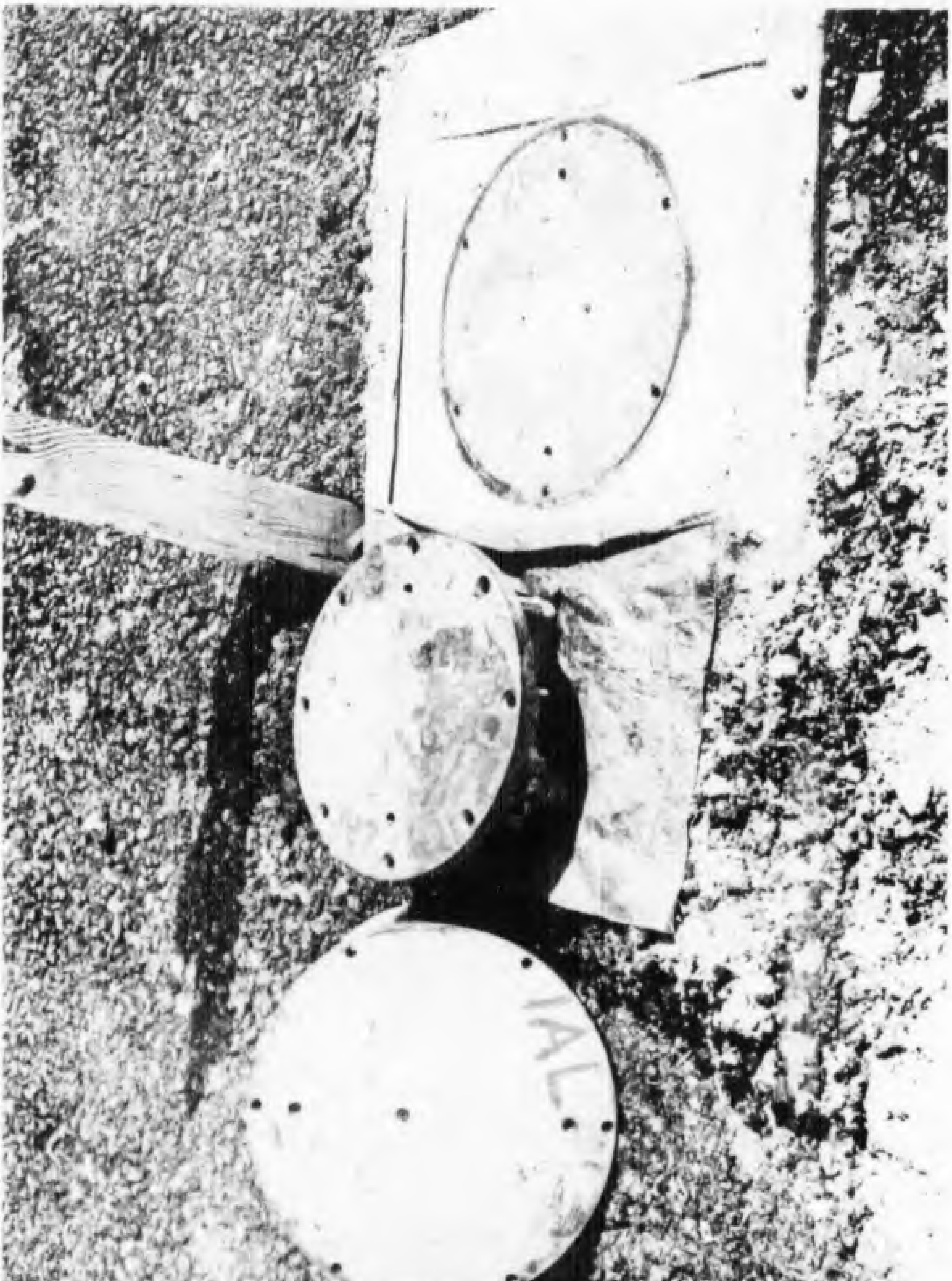

Fig. 3.10 Wall, Pylon, and Ground Assemblies; Top View

[redacted]

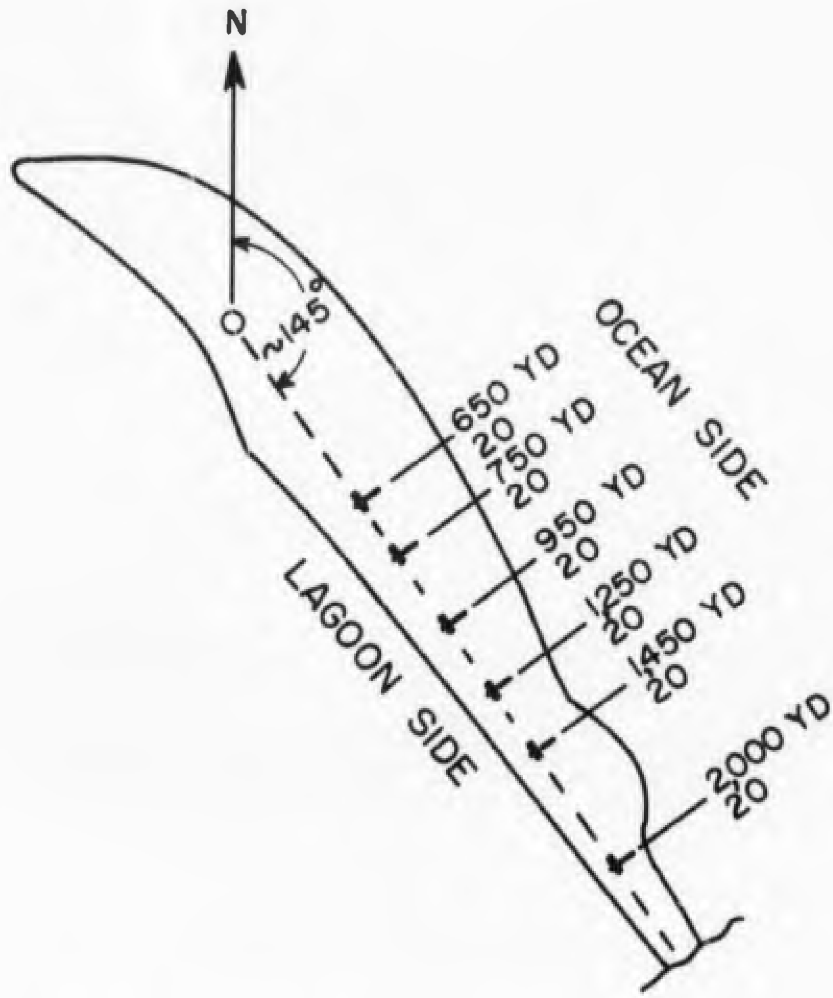

Fig. 4.1 Orientation of Blast Line on Runit for Test Dog

[redacted]

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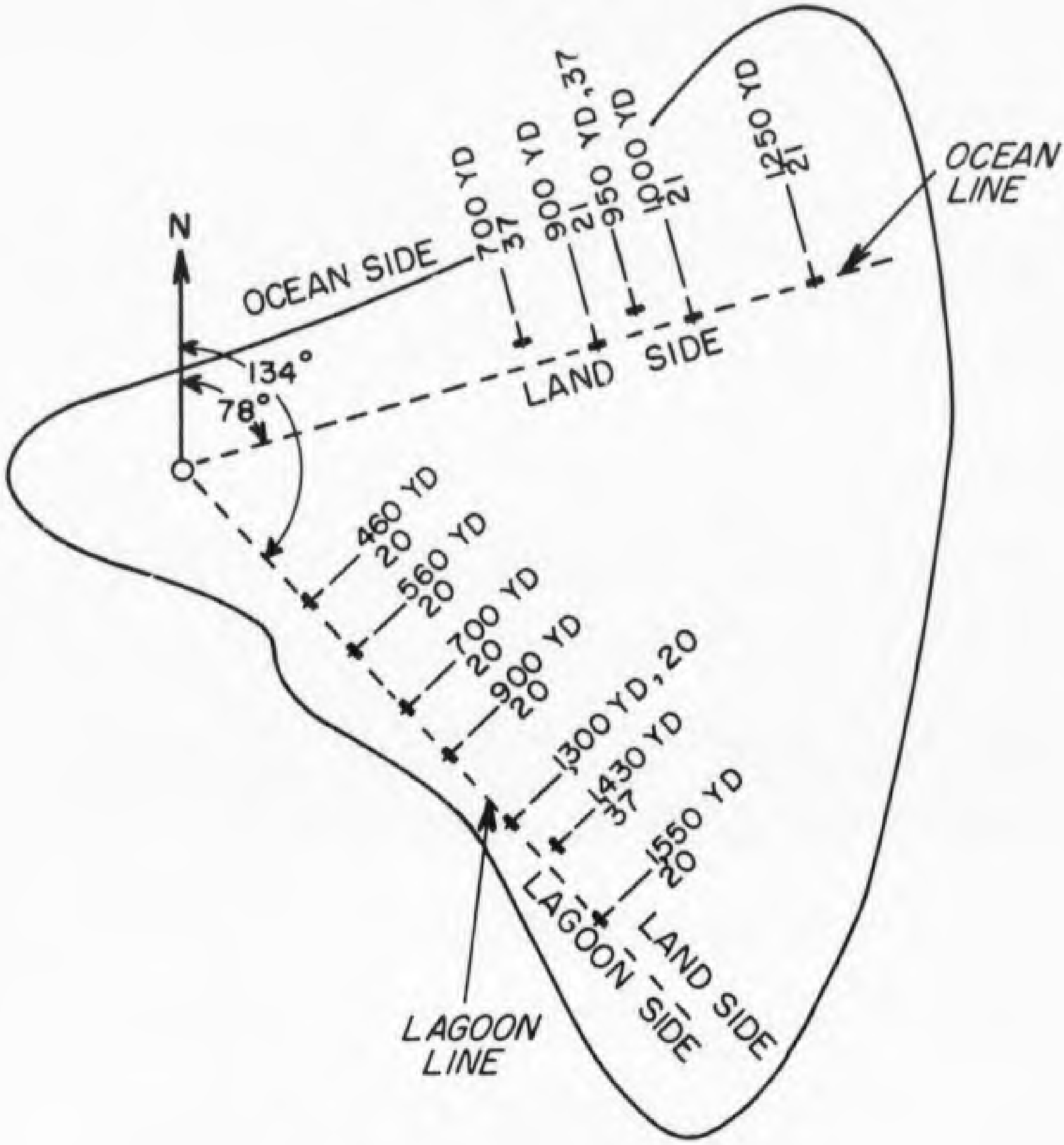
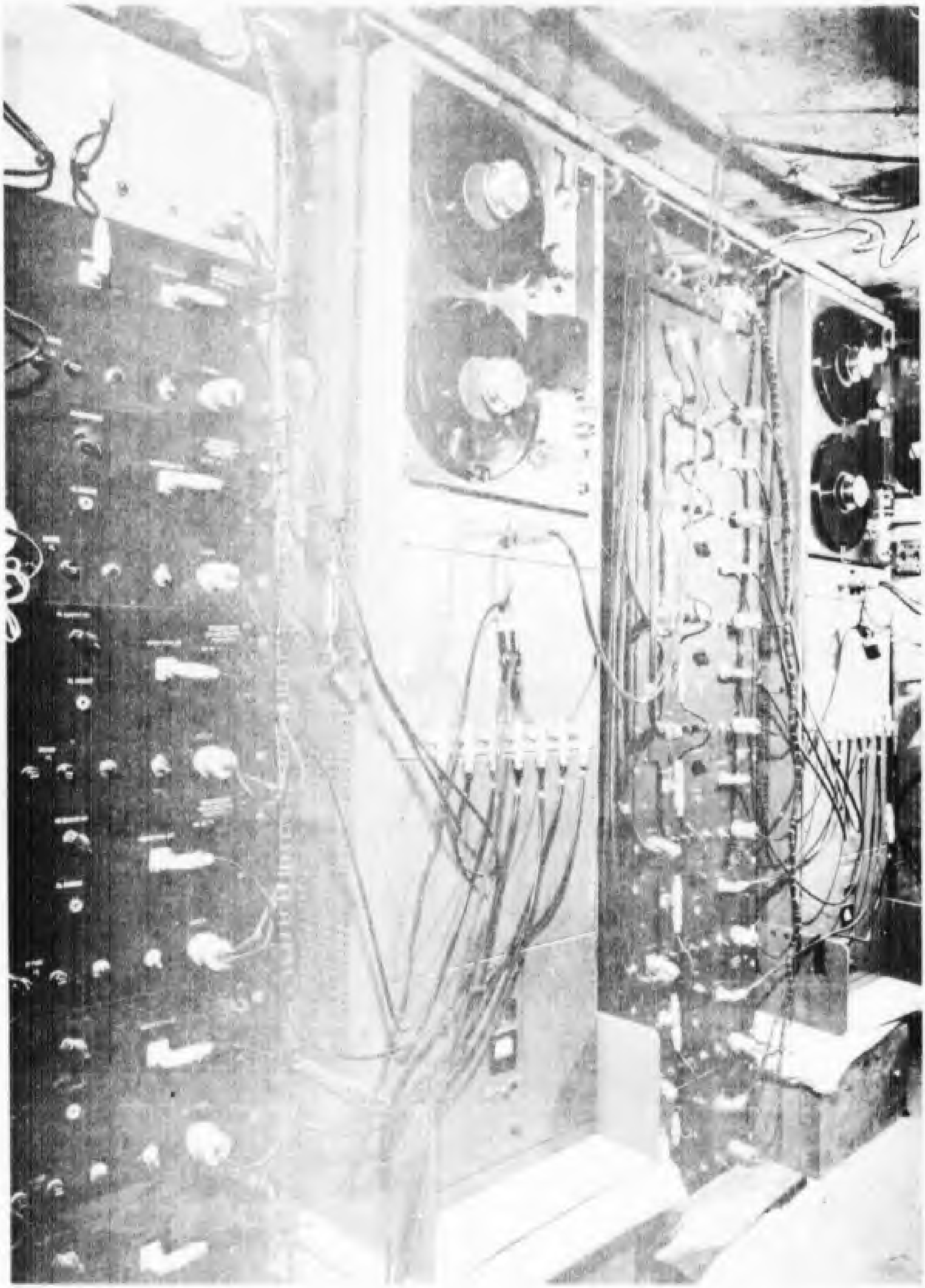


Fig. 4.2 Orientation of Blast Lines on Engebi for Test Easy

Fig. 4.3 Exterior Rear View of Runit Blast Hut



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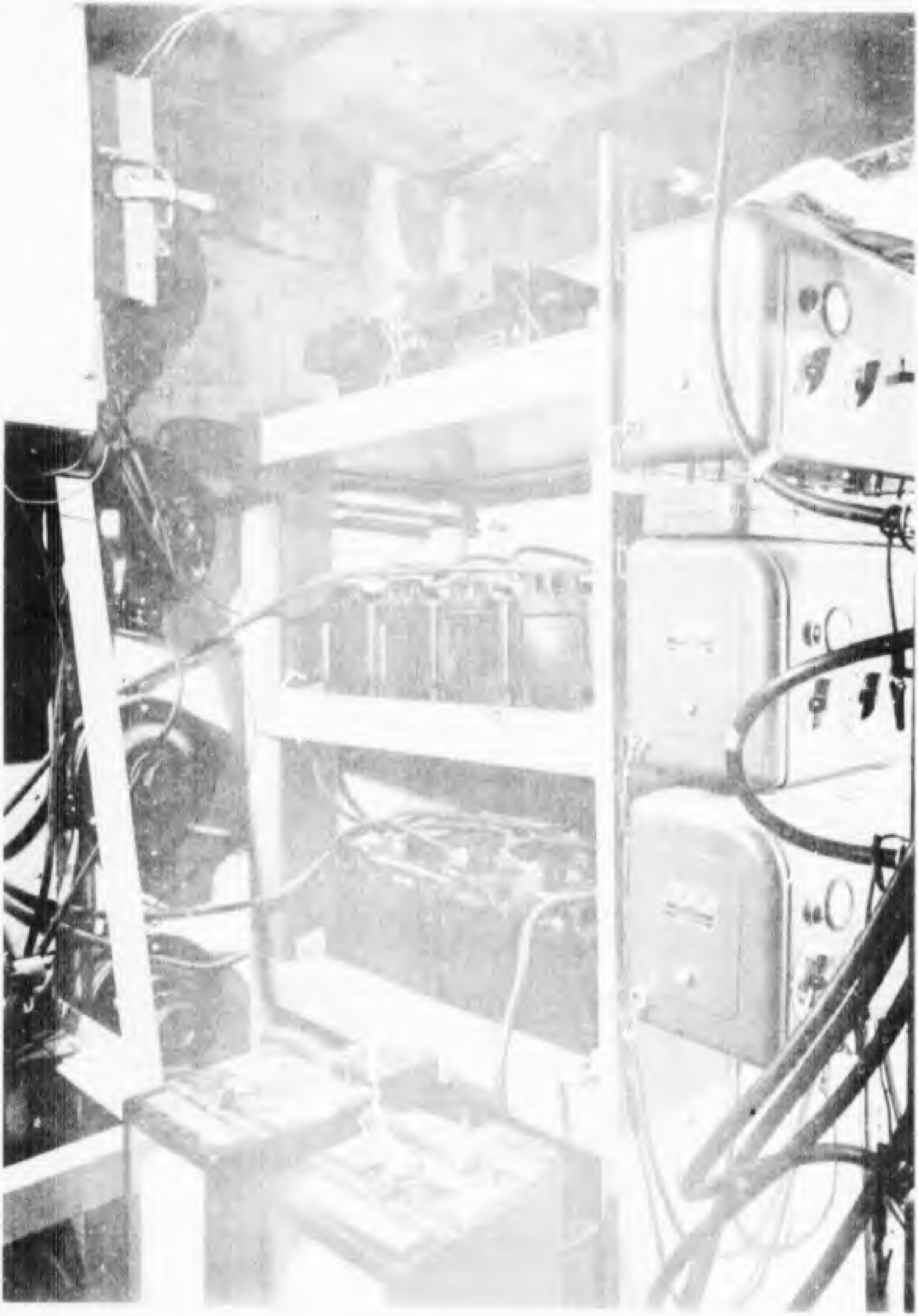

Fig. [illegible]

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[illegible] Batteries & [illegible] Blast Hut Converters

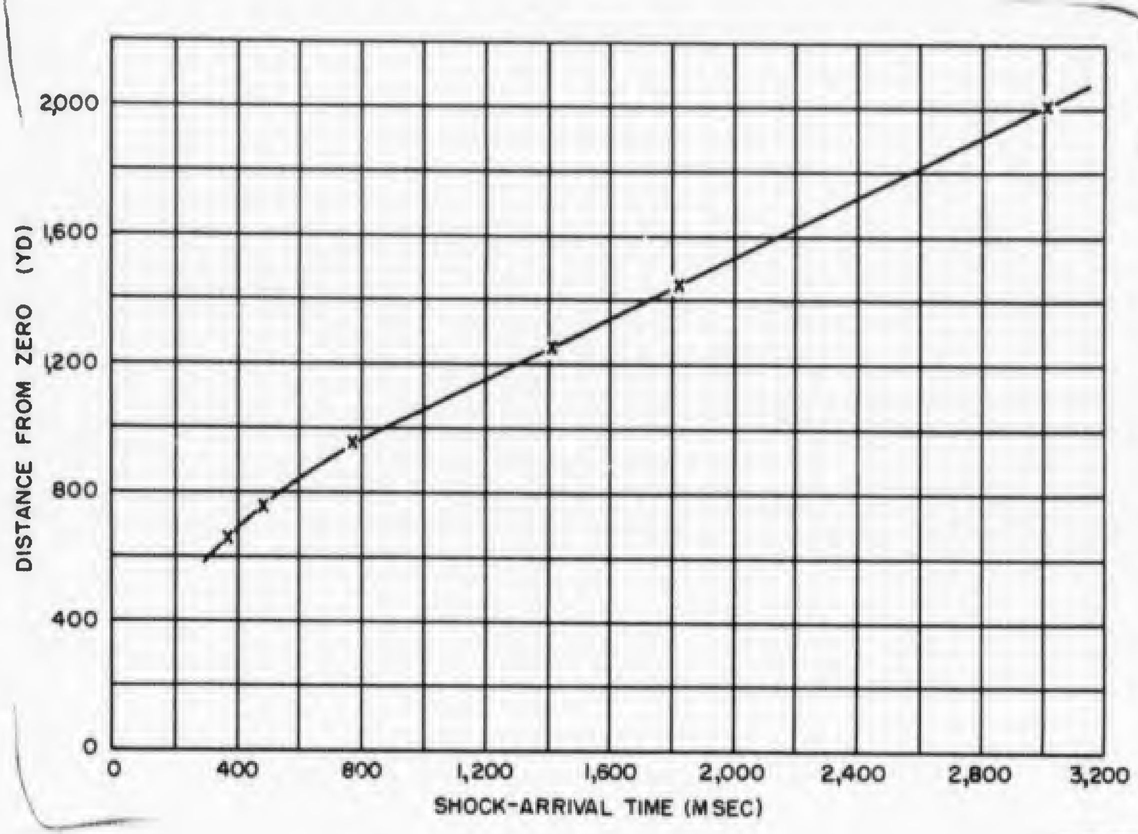

Fig. 4.7 Shock-arrival Time, Test Dog

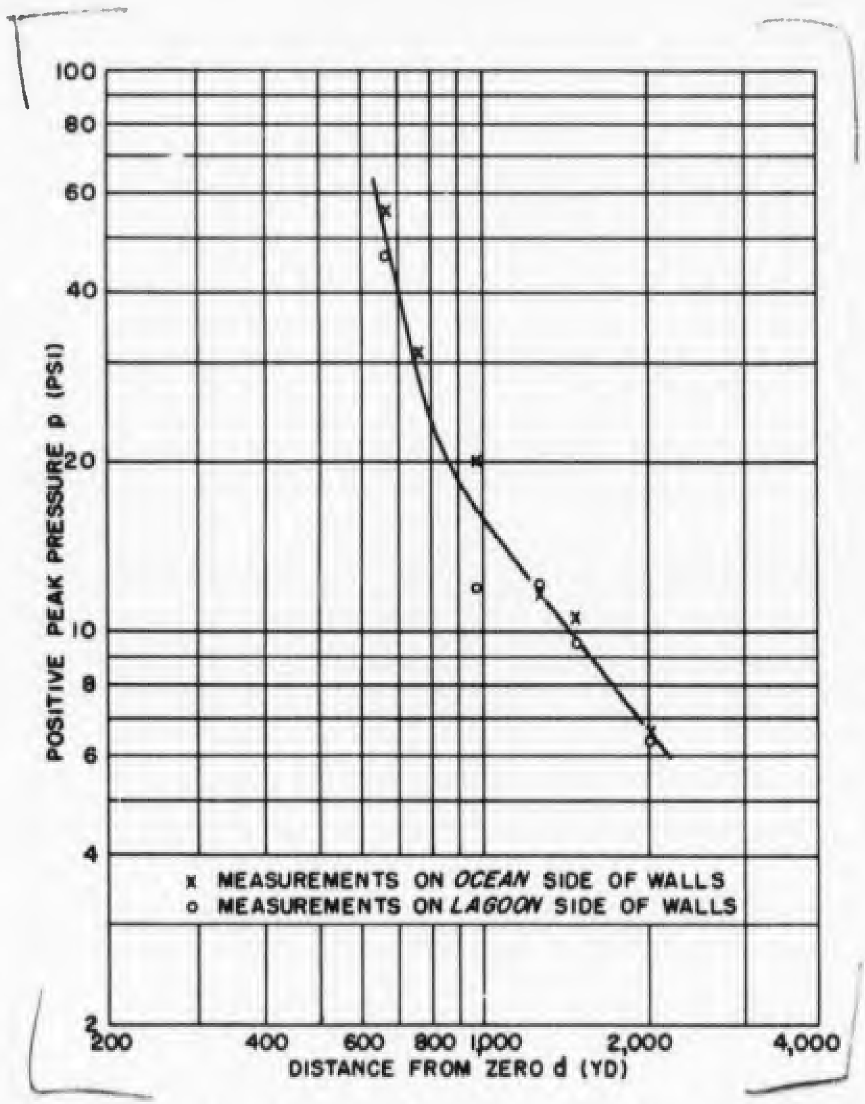

Fig. 4.8 Positive Peak Pressure, Test Dog

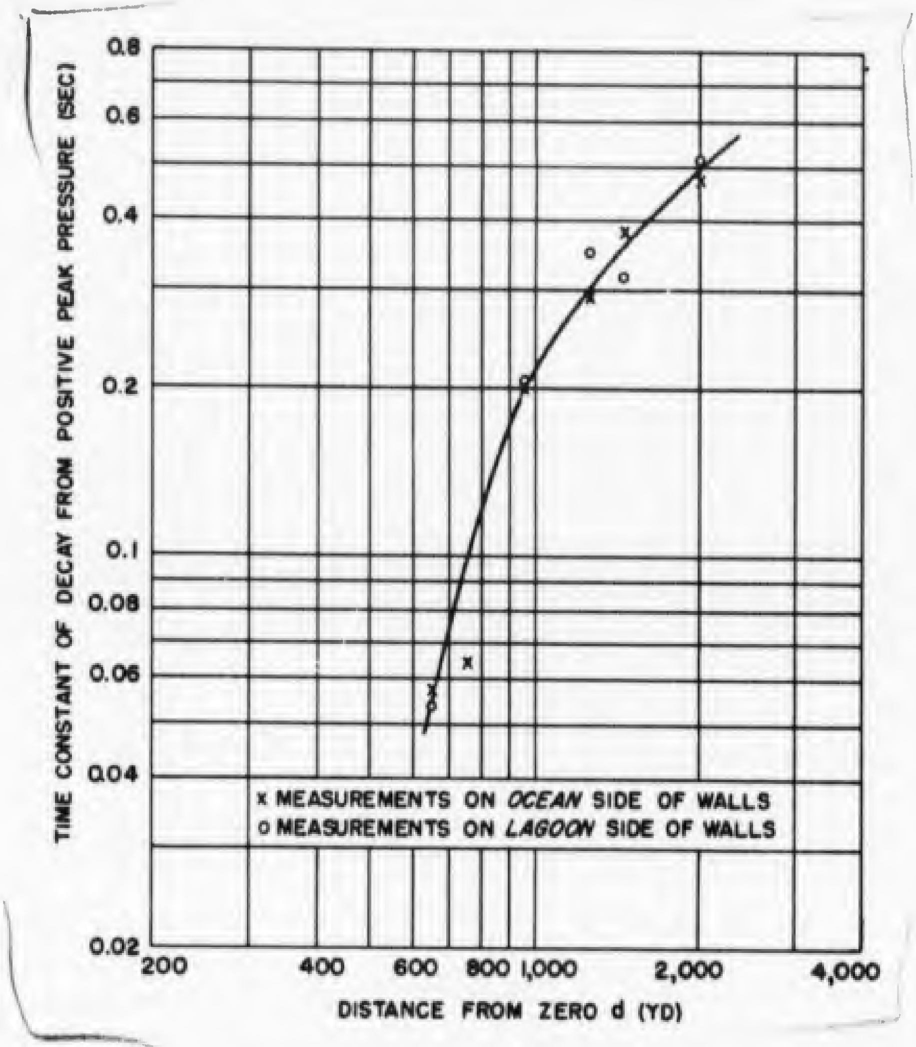

Fig. 4.9 Time Constant of Decay from Positive Peak Pressure, Test Dog

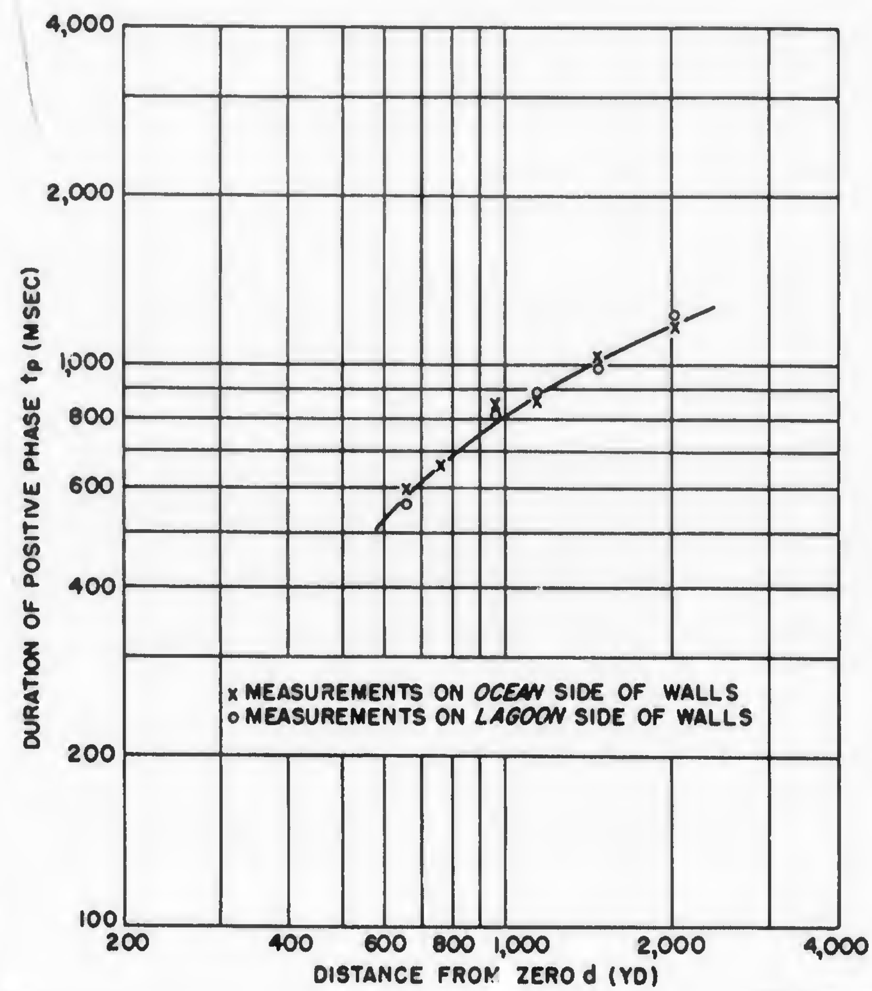

Fig. 4.10 Duration of Positive Phase, Test Dog

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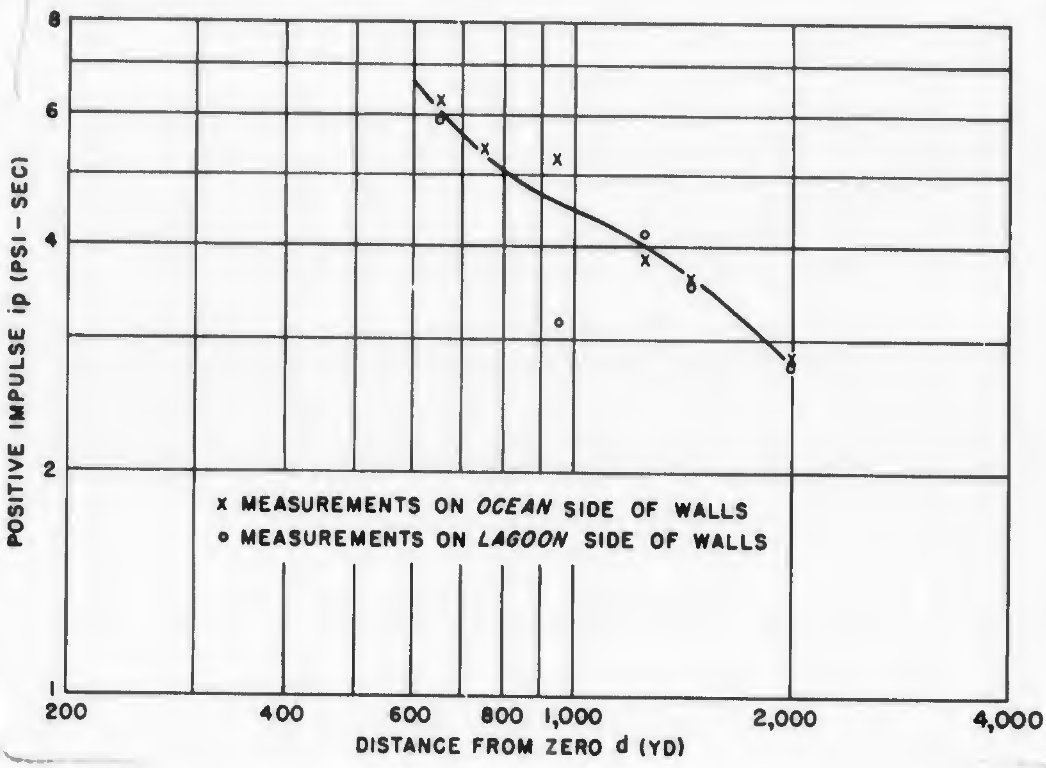

Fig. 4.11 Positive Impulse, Test Dog

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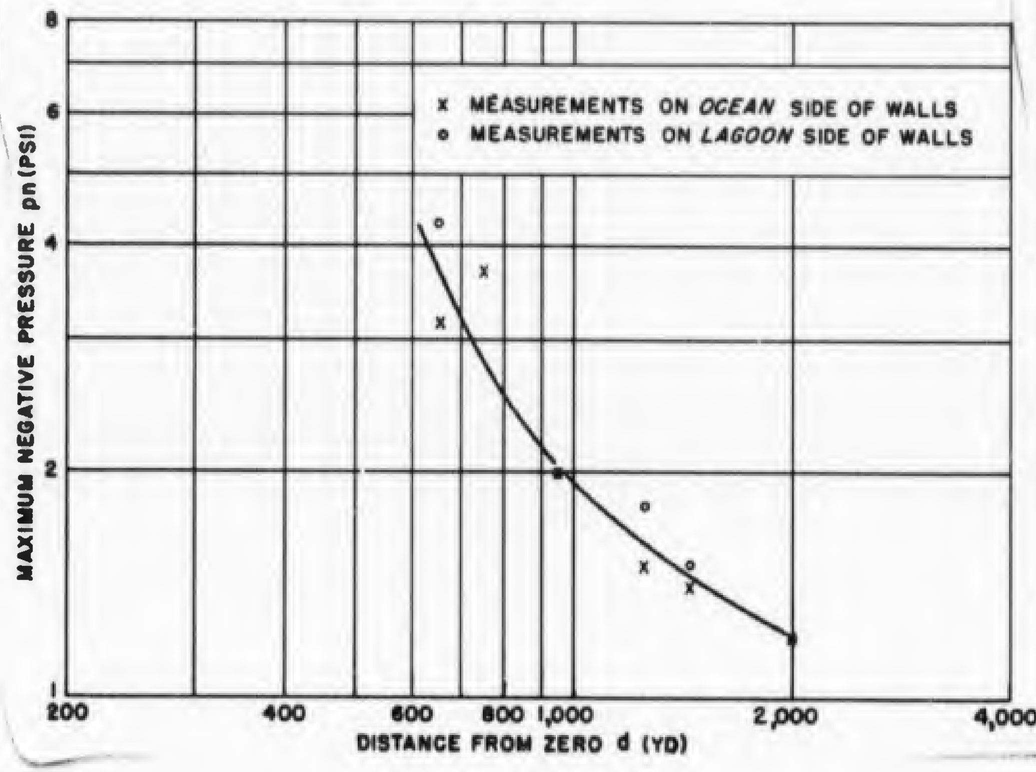

Fig. 4.12 Maximum Negative Pressure, Test Dog

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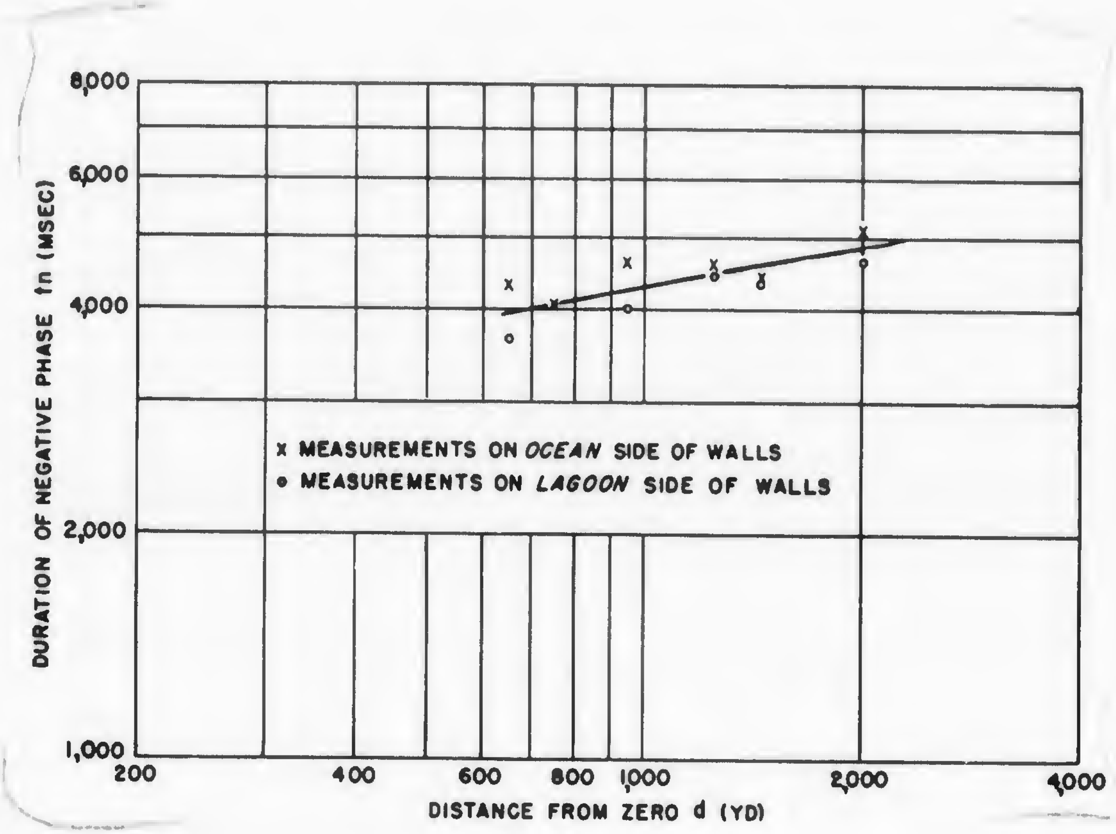

Fig. 4.13 Duration of Negative Phase, Test Dog

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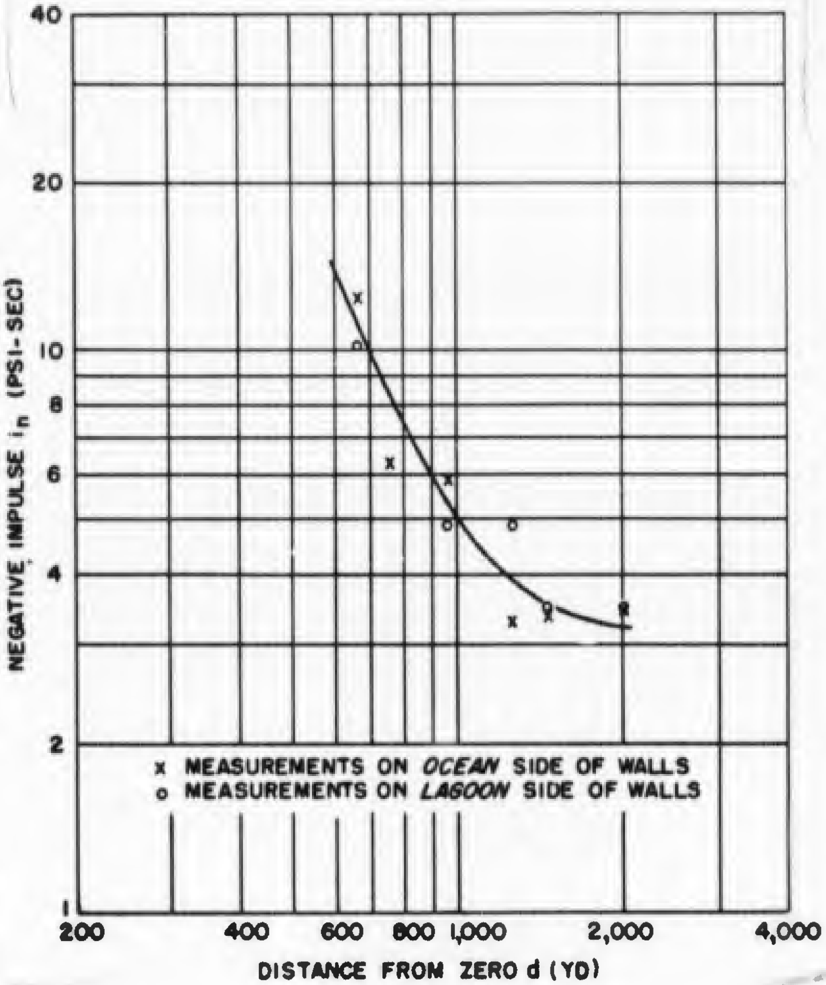

Fig. 4.14 Negative Impulse, Test Dog

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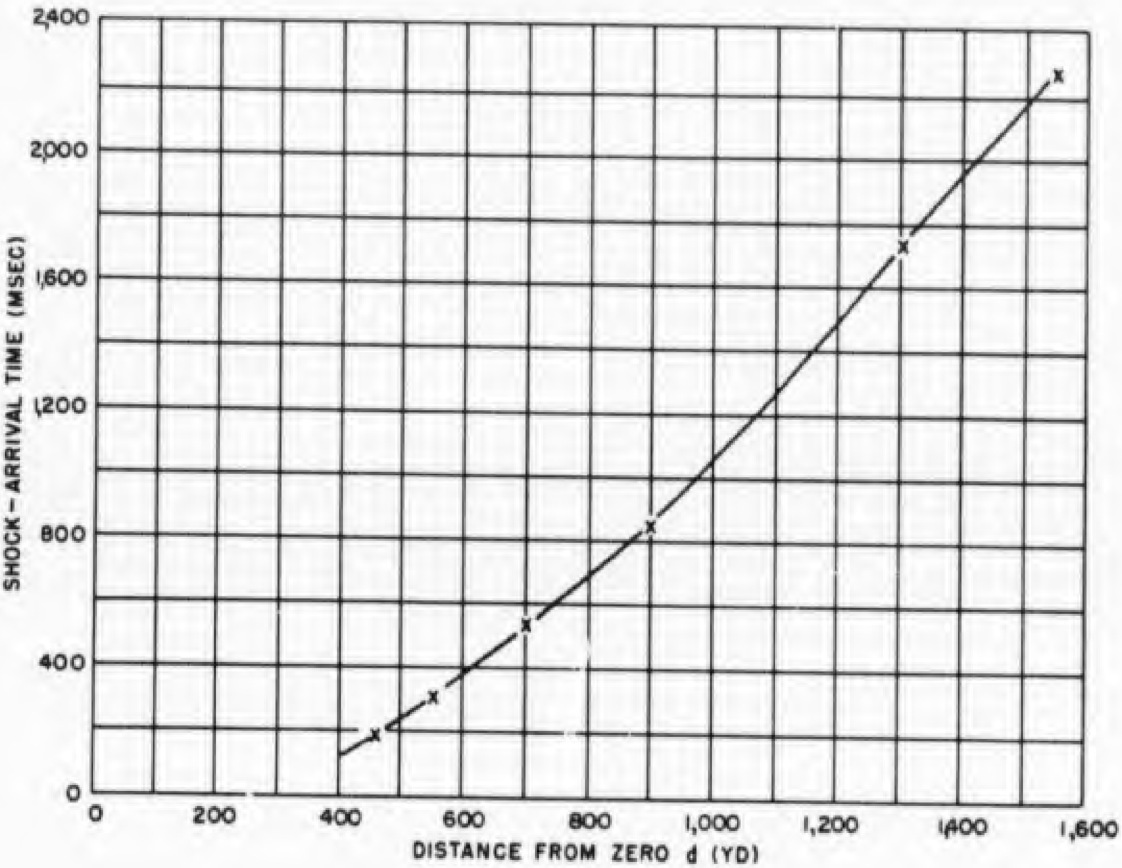

Fig. 4.15 Shock-arrival Time, Test Easy, Lagoon Line

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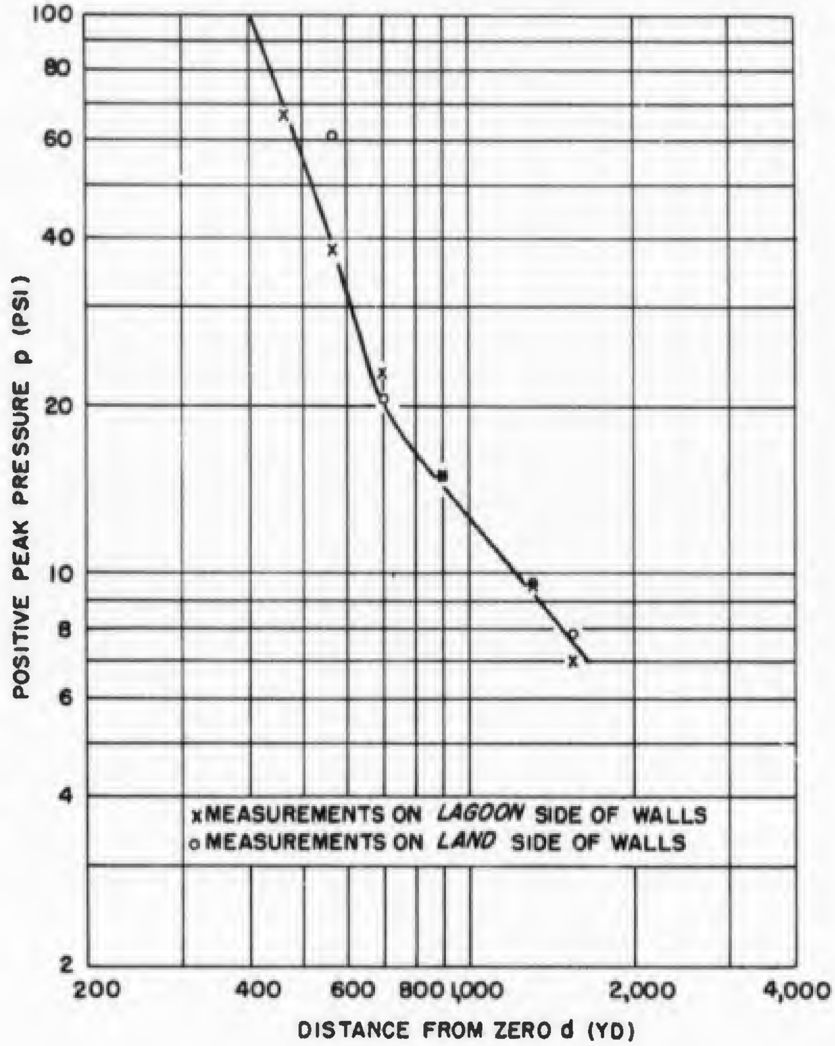

Fig. 4.16 Positive Peak Pressure, Test Easy, Lagoon Line

[redacted]

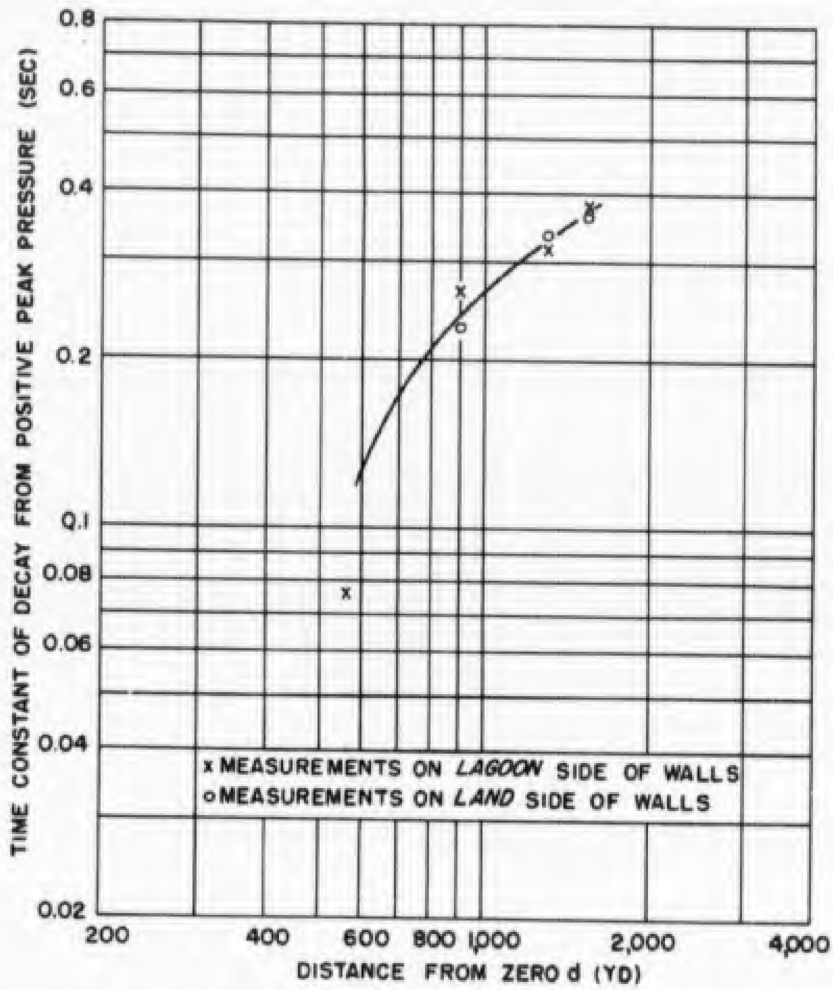

Fig. 4.17 Time Constant of Decay from Positive Peak Pressure, Test Easy, Lagoon Line

[redacted]

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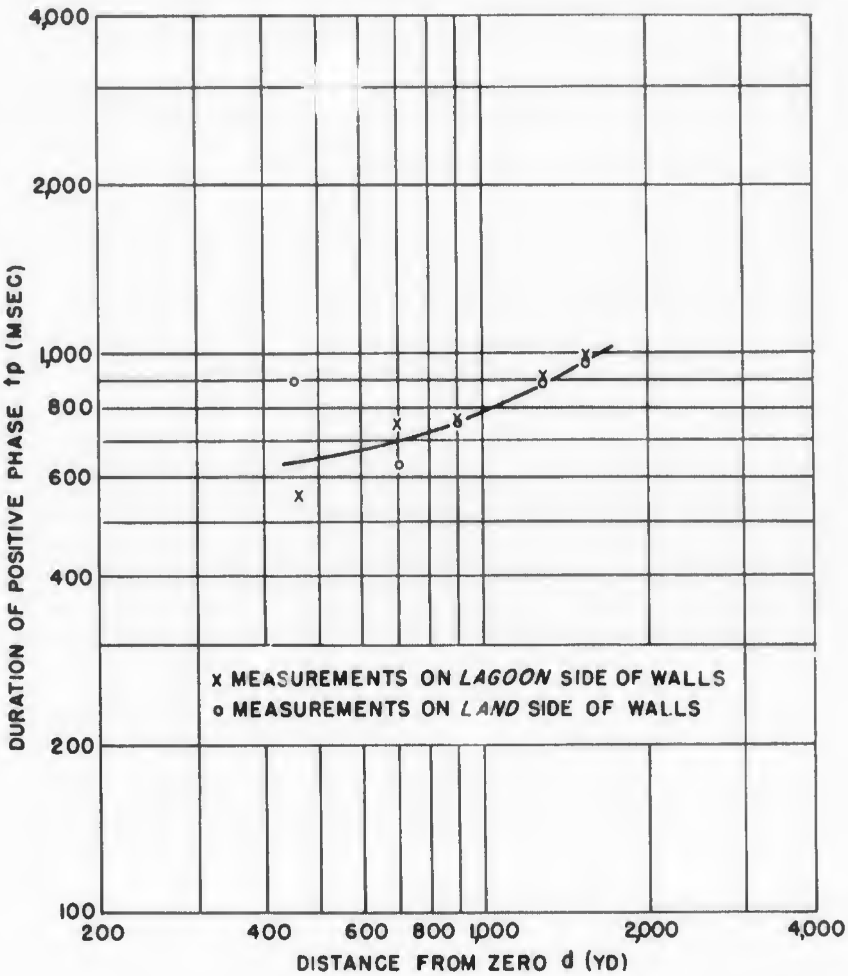

Fig. 4.18 Duration of Positive Phase, Test Easy, Lagoon Line

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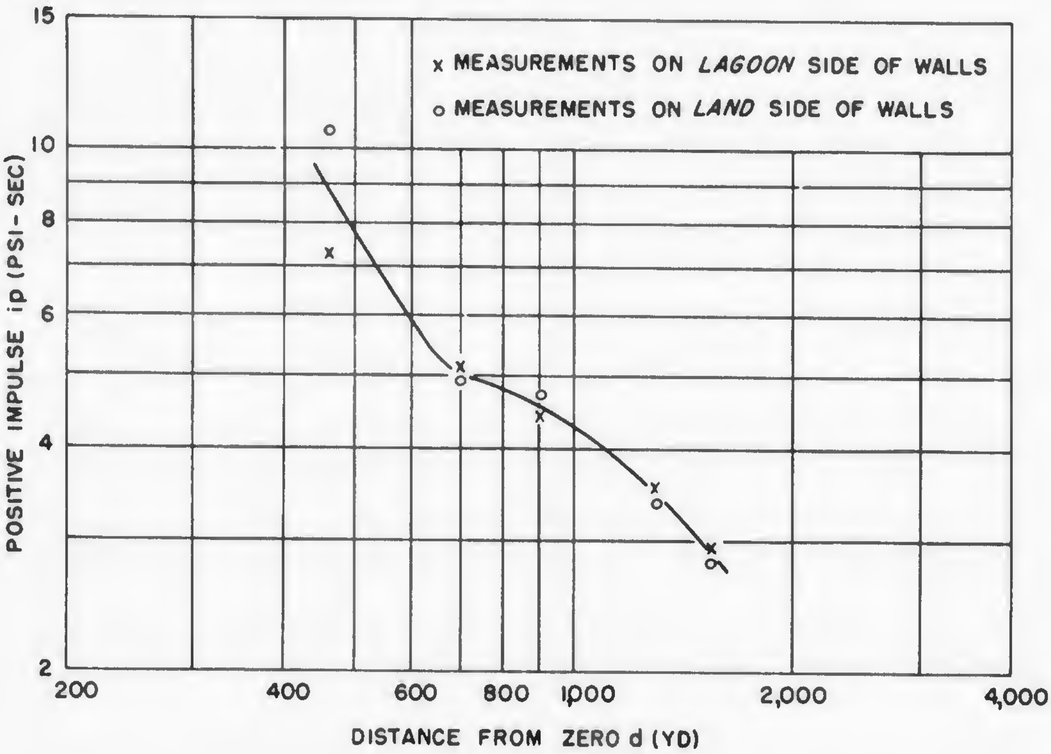

Fig. 4.19 Positive Impulse, Test Easy, Lagoon Line

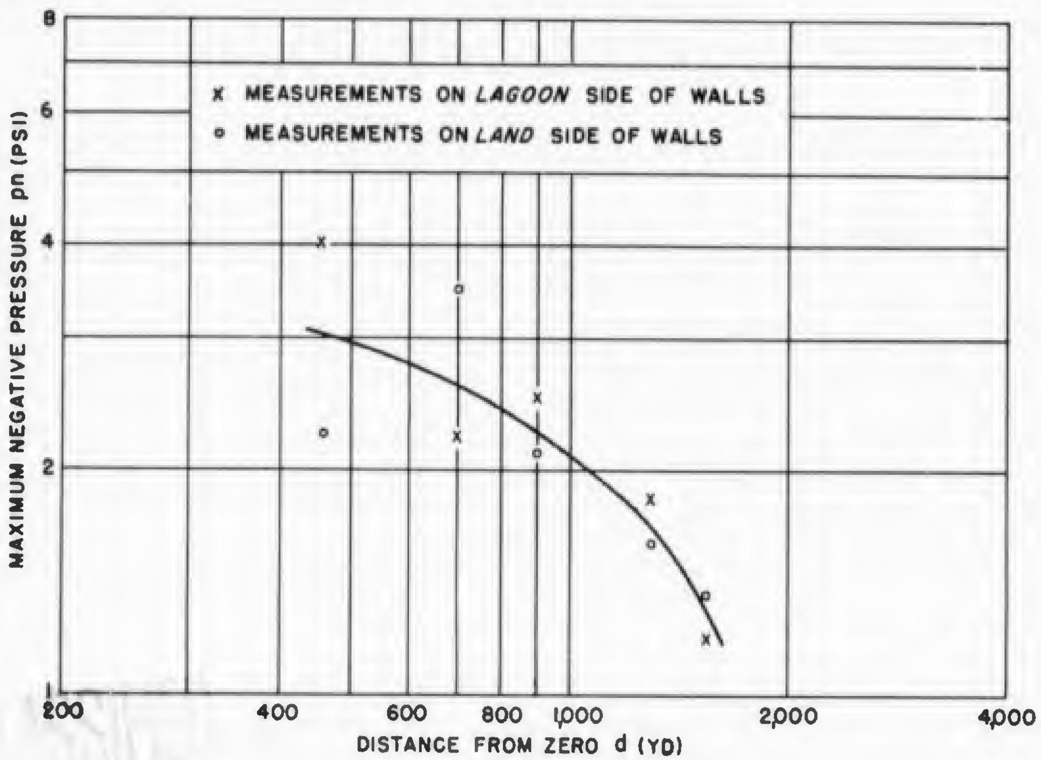

Fig. 4.20 Maximum Negative Pressure, Test Easy, Lagoon Line

[redacted]

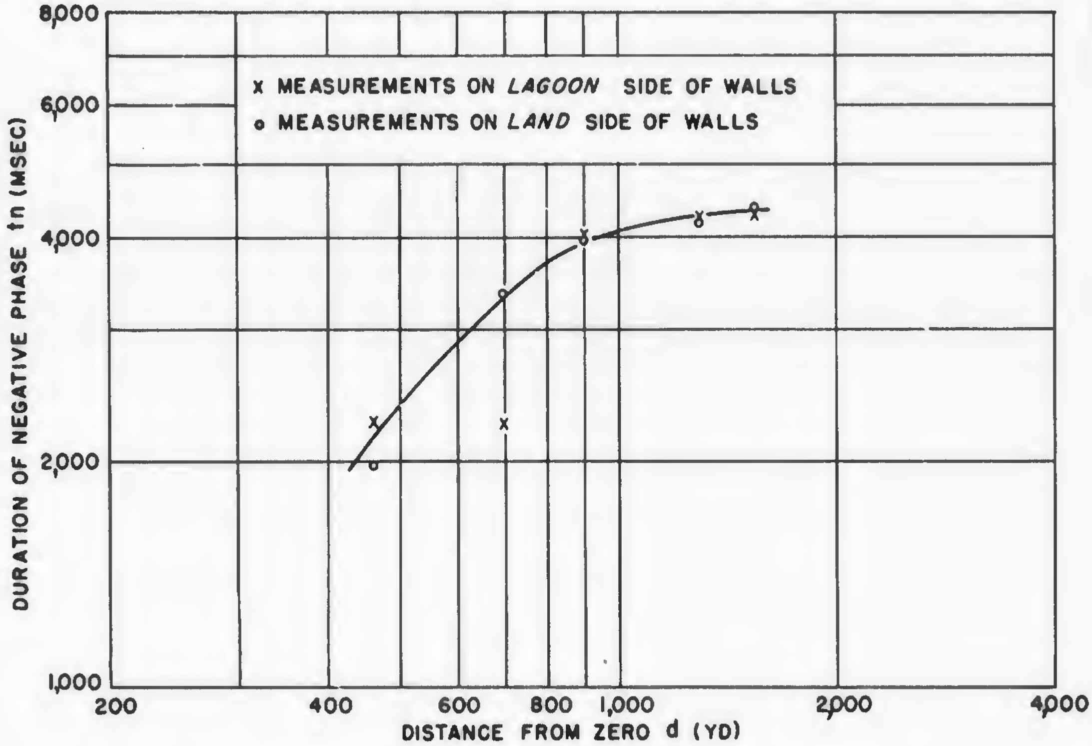

Fig. 4.21 Duration of Negative Phase, Test Easy, Lagoon Line

[redacted]

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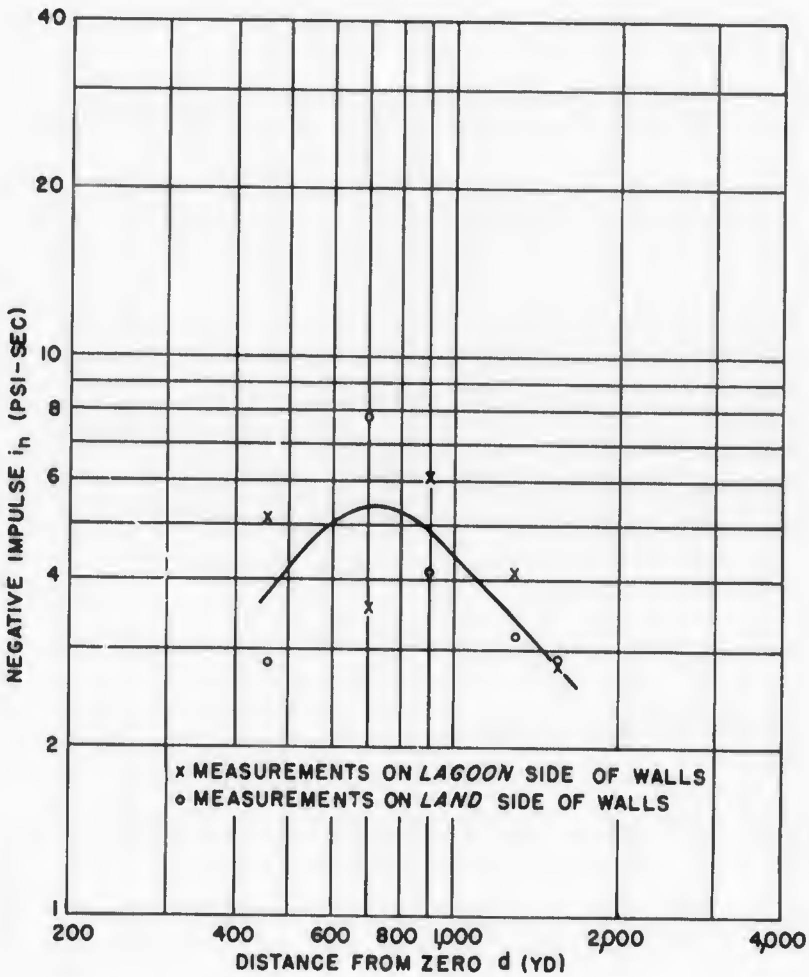

Fig. 4.22 Negative Impulse, Test Easy, Lagoon Line

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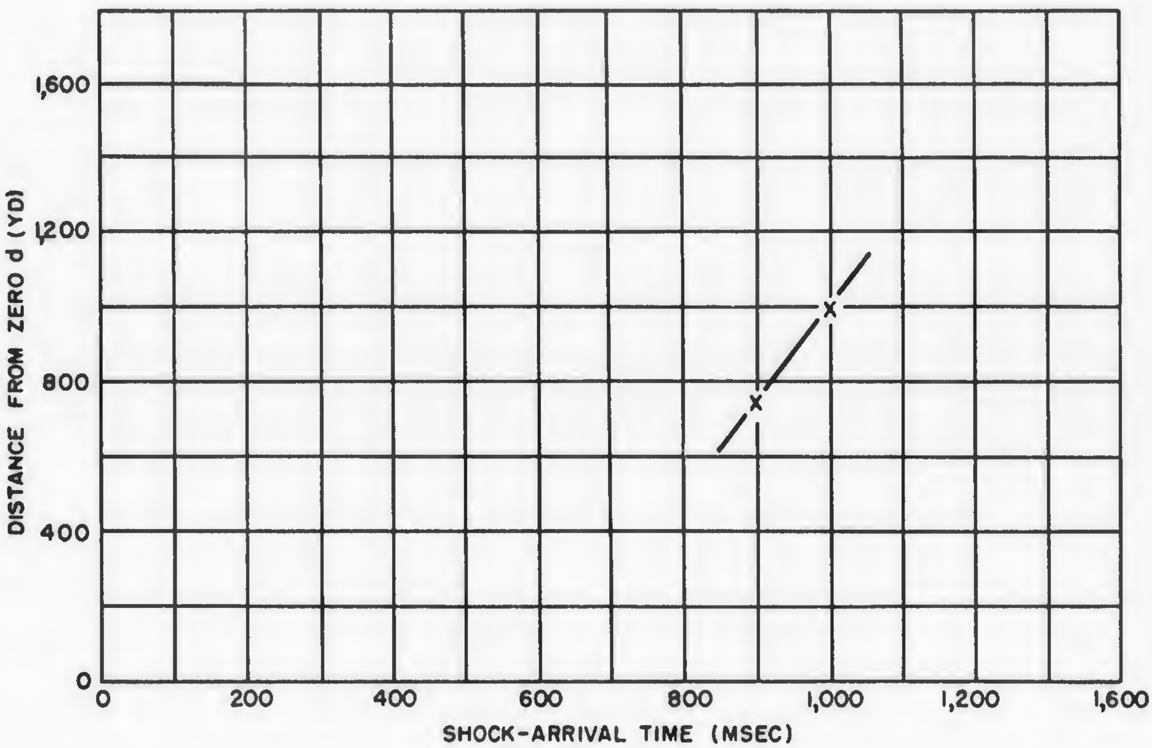

Fig. 4.23 Shock-arrival Time, Test Easy, Ocean Line

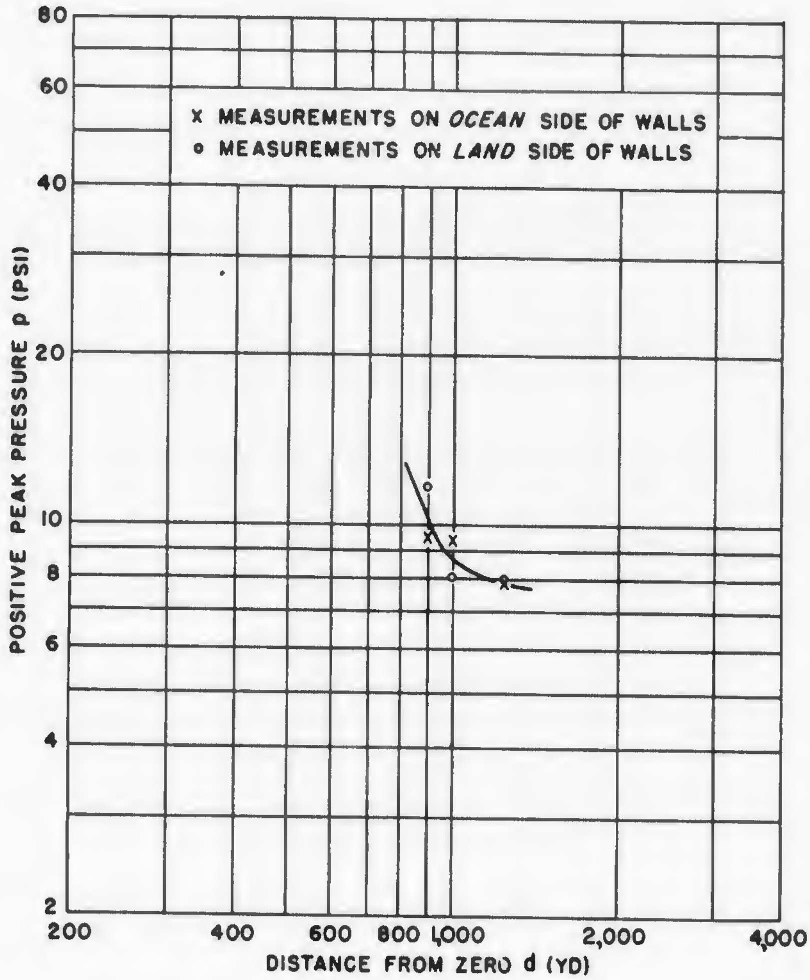

Fig. 4.24 Positive Peak Pressure, Test Easy, Ocean Line

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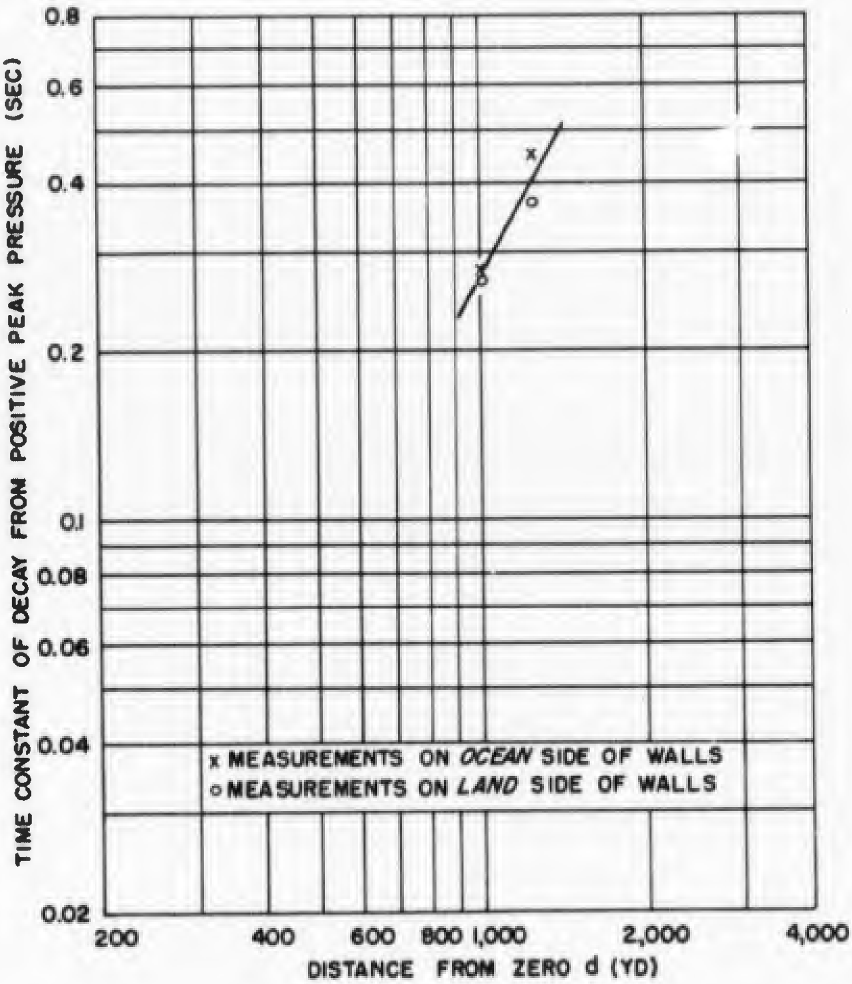

Fig. 4.25 Time Constant of Decay from Positive Peak Pressure, Test Easy, Ocean Line

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SECTION 144b, ATOMIC ENERGY ACT 1954

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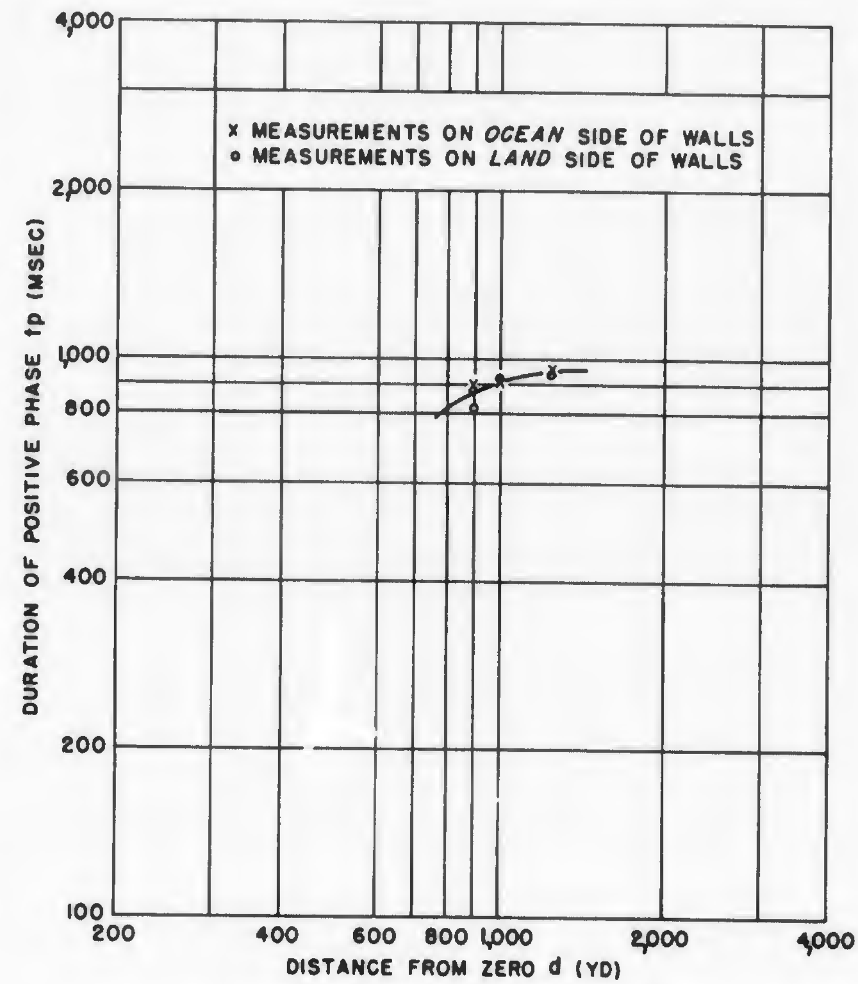

Fig. 4.26 Duration of Positive Phase, Test Easy, Ocean Line

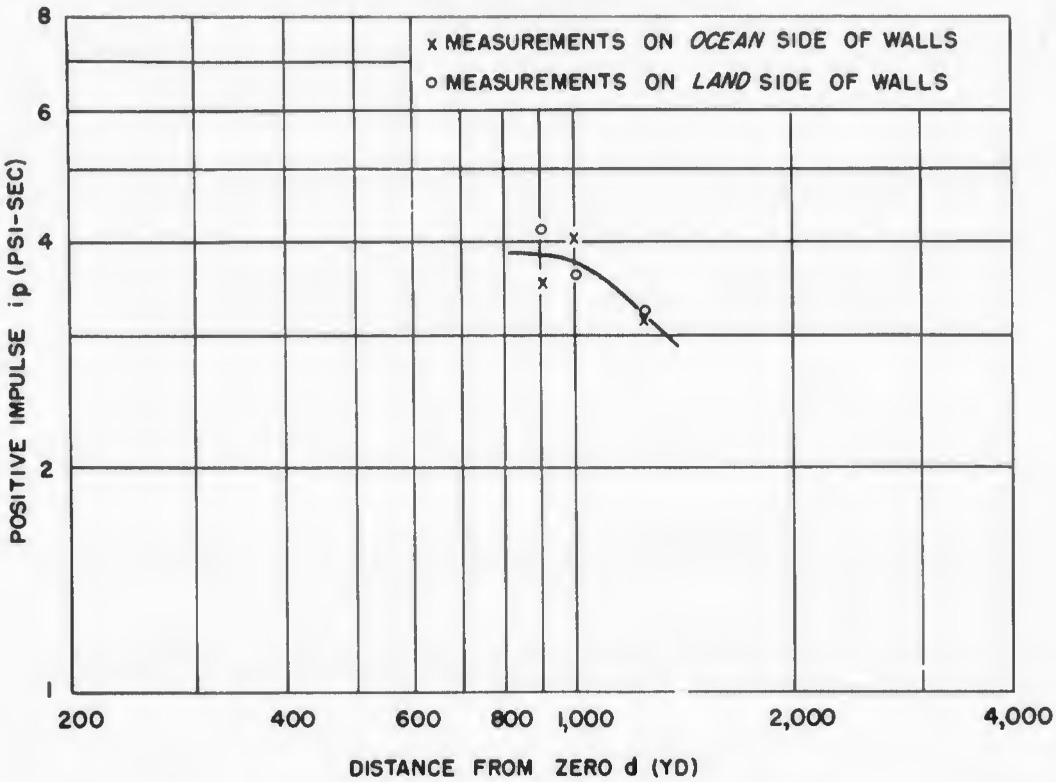

Fig. 4.27 Positive Impulse, Test Easy, Ocean Line

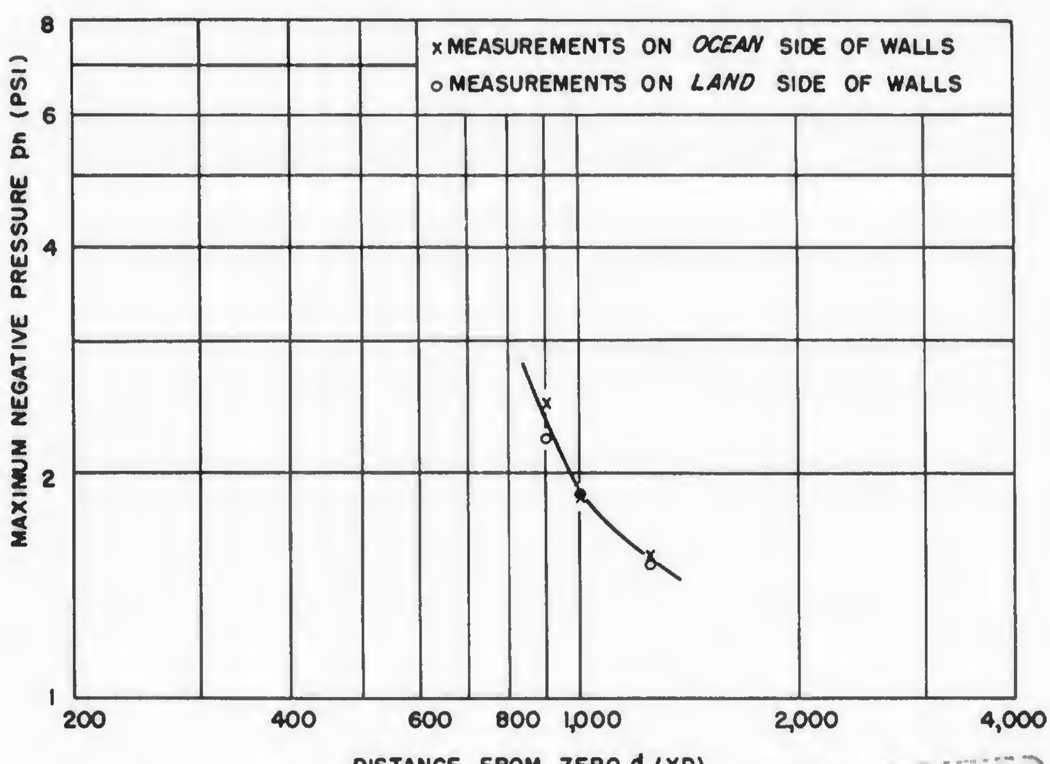

Fig. 4.28 Maximum Negative Pressure, Test Easy, Ocean Line

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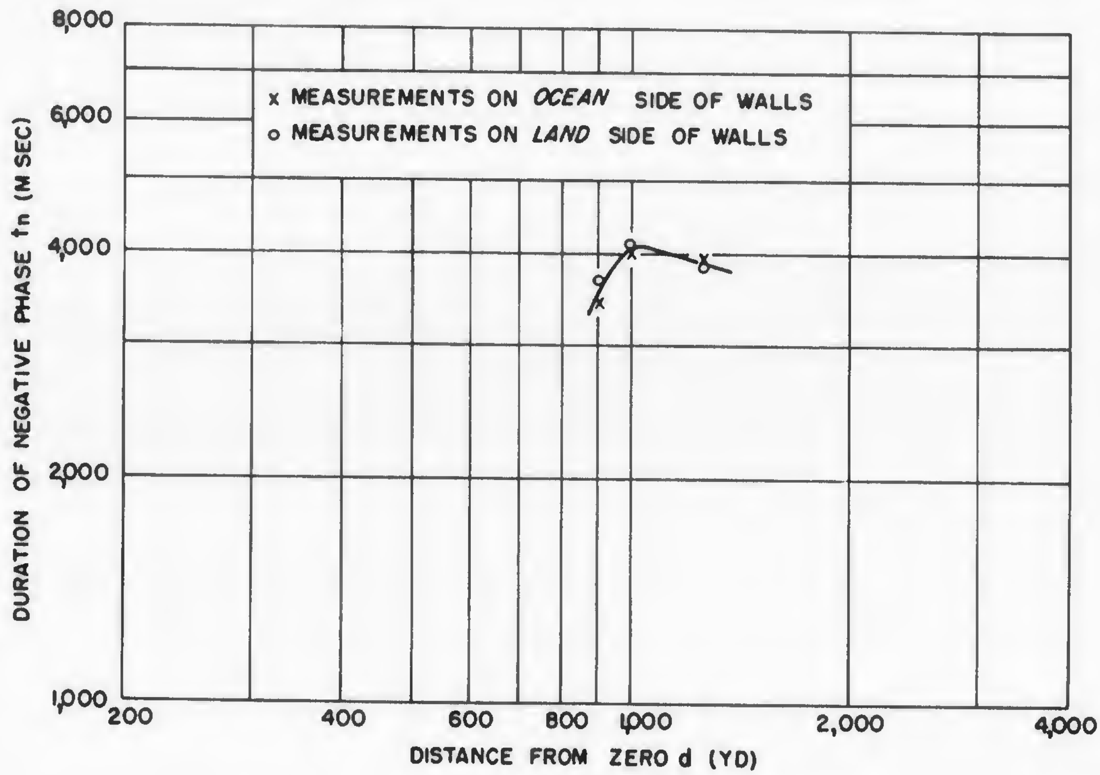

Fig. 4.29 Duration of Negative Phase, Test Easy, Ocean Line

[redacted]

[redacted]

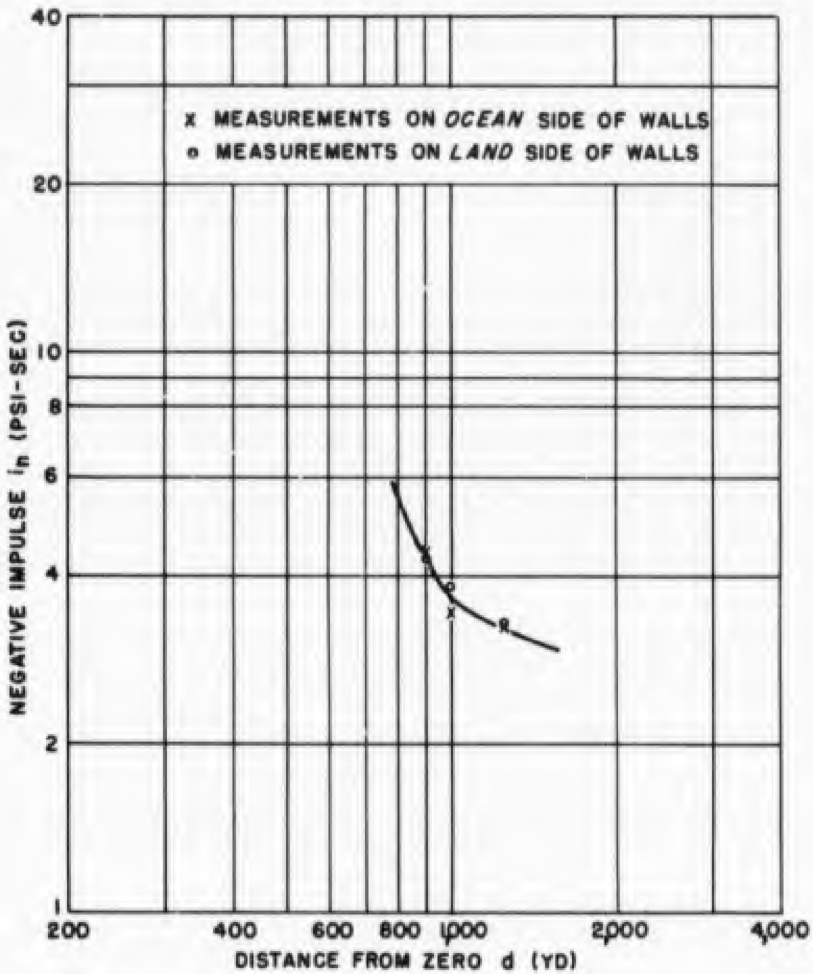

Fig. 4.30 Negative Impulse, Test Easy, Ocean Line

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Fig. 4.31 Test Dog, Station 20a; View of Wall toward Ocean

Fig. 4.32 Test Dog, Station 20b; View of Wall toward Lagoon

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Fig. 4.33 Test Dog, Station 20b; View of Wall toward Zero

Fig. 4.34 Test Dog, Station 20c; View of Wall away from Zero

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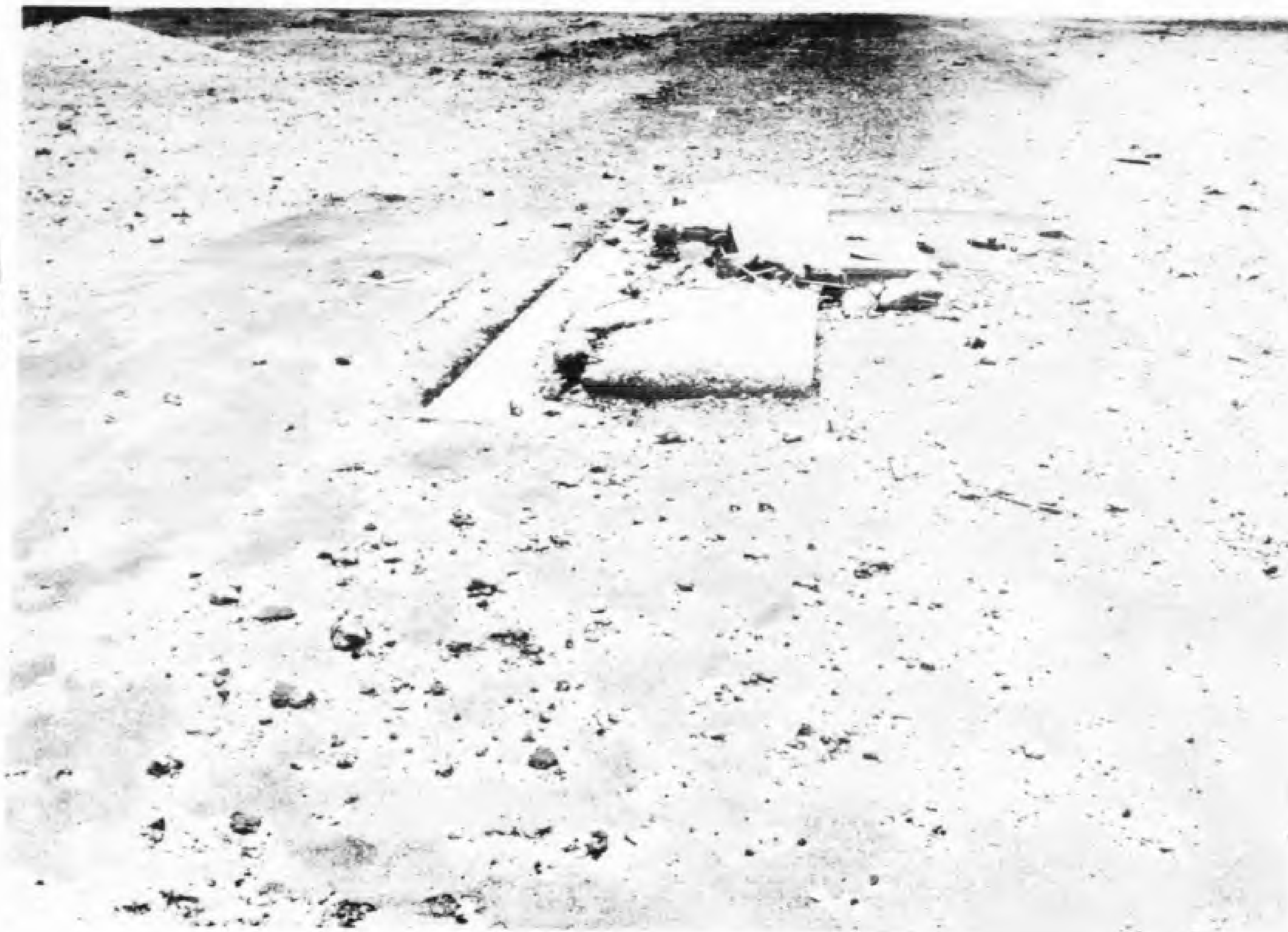

Fig. 4.35 Test Easy, Station 20b; View of Wall away from Zero

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Fig. 4.36 Test Easy, Section of Pylon 37a (not at Station 37a); View toward Zero

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Fig. 4.37 Test Easy, Station 37b; View of Pylon toward Ocean

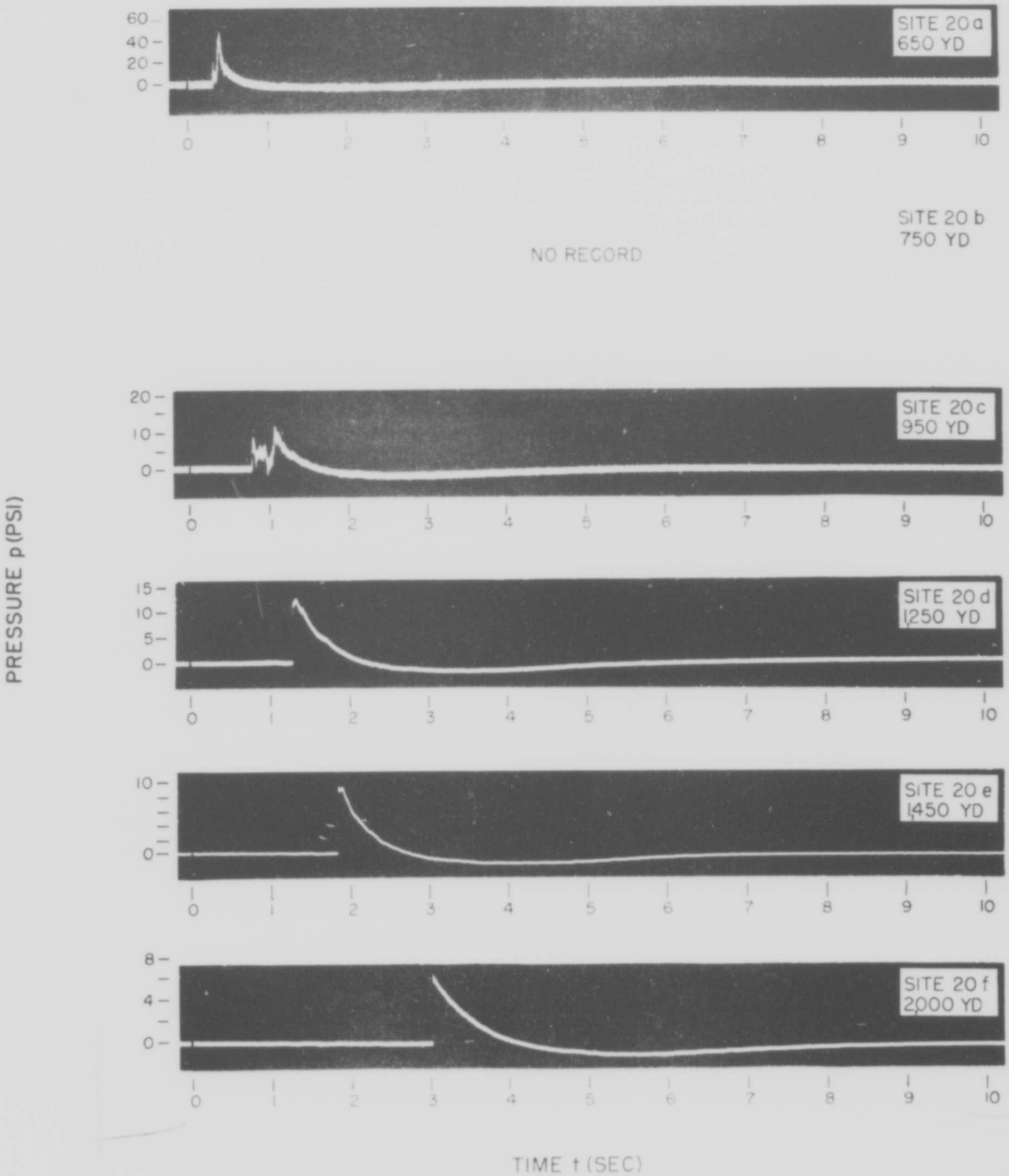

Fig. 4.38 Test Dog, Lagoon Side; Pressure-Time Curves

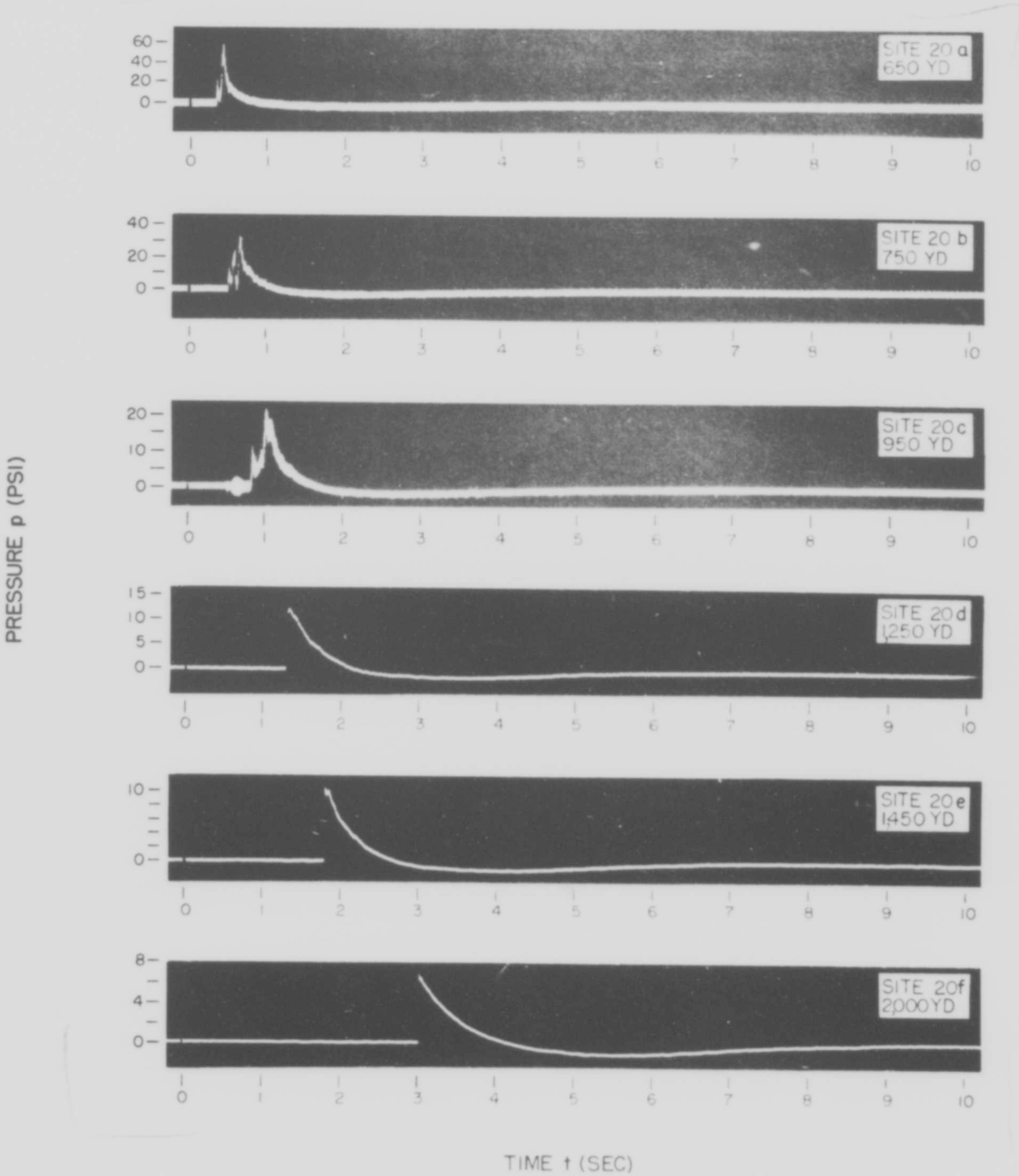

Fig. 4.39 Test Dog, Ocean Side; Pressure-Time Curves

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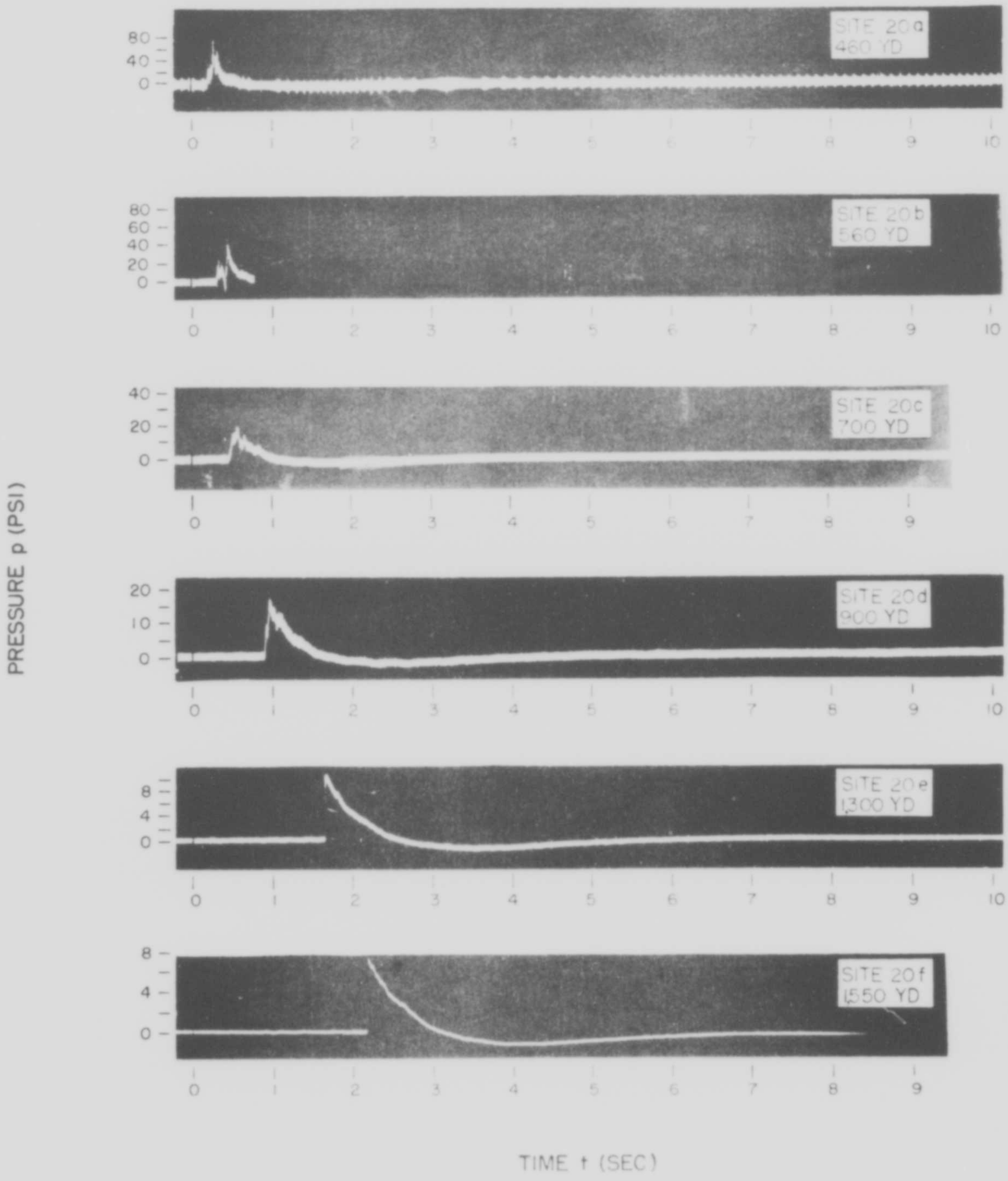

Fig. 4.40 Test Easy, Lagoon Line, Lagoon Side; Pressure-Time Curves

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SECTION 144b, ATOMIC ENERGY ACT 1954

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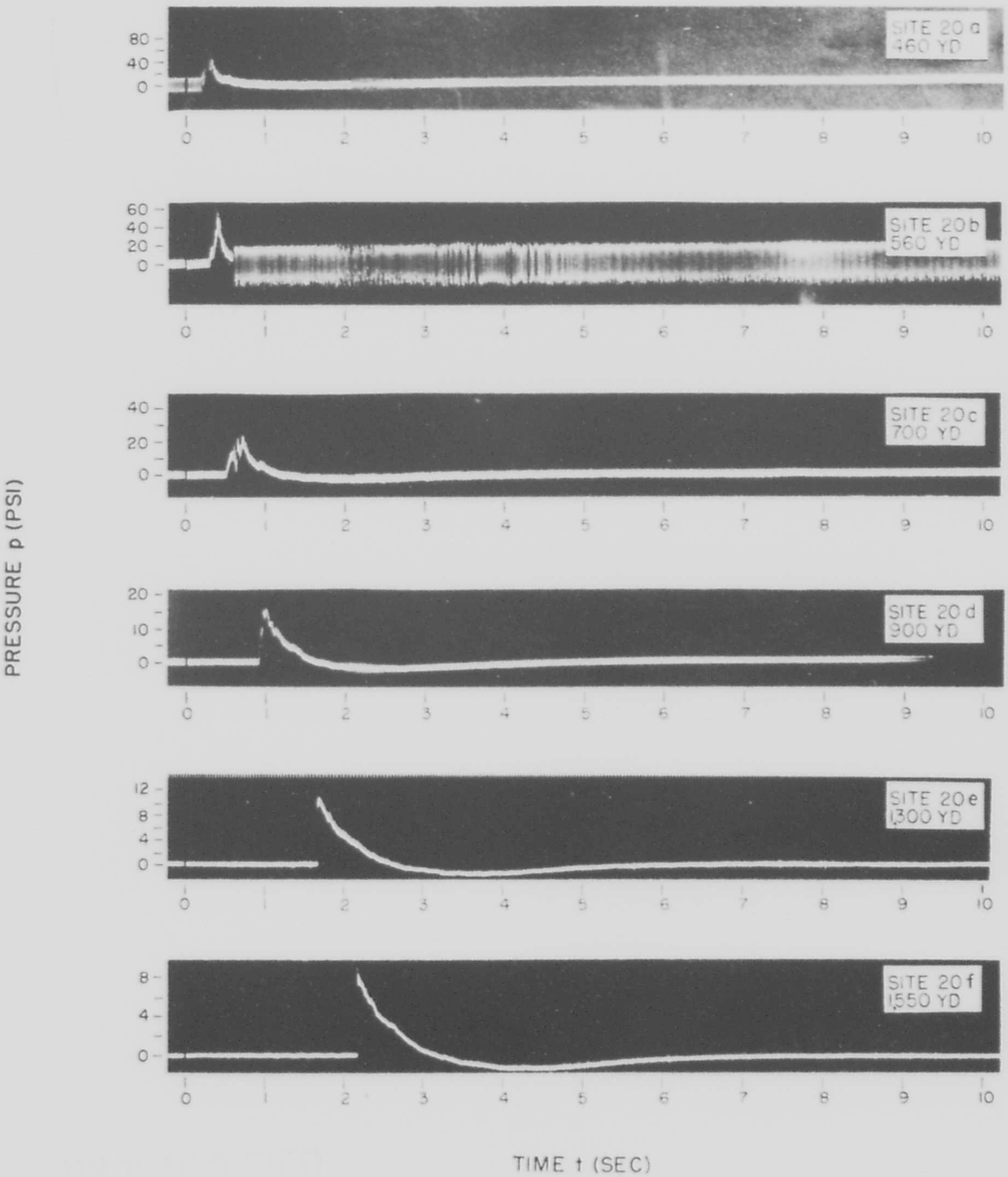

Fig. 4.41 Test Easy, Lagoon Line, Land Side; Pressure-Time Curves

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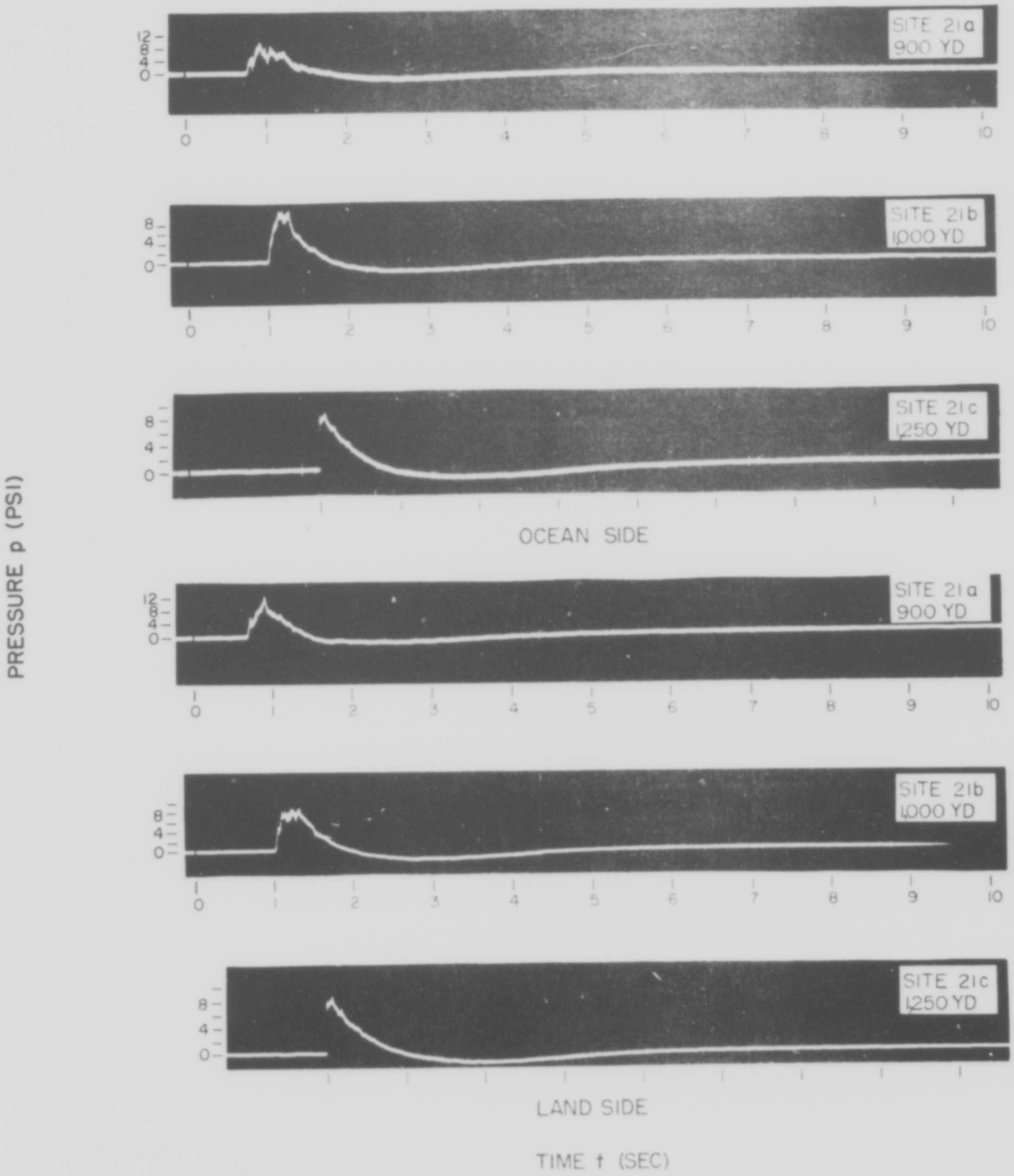

Fig. 4.42 Test Easy, Ocean Line; Pressure-Time Curves

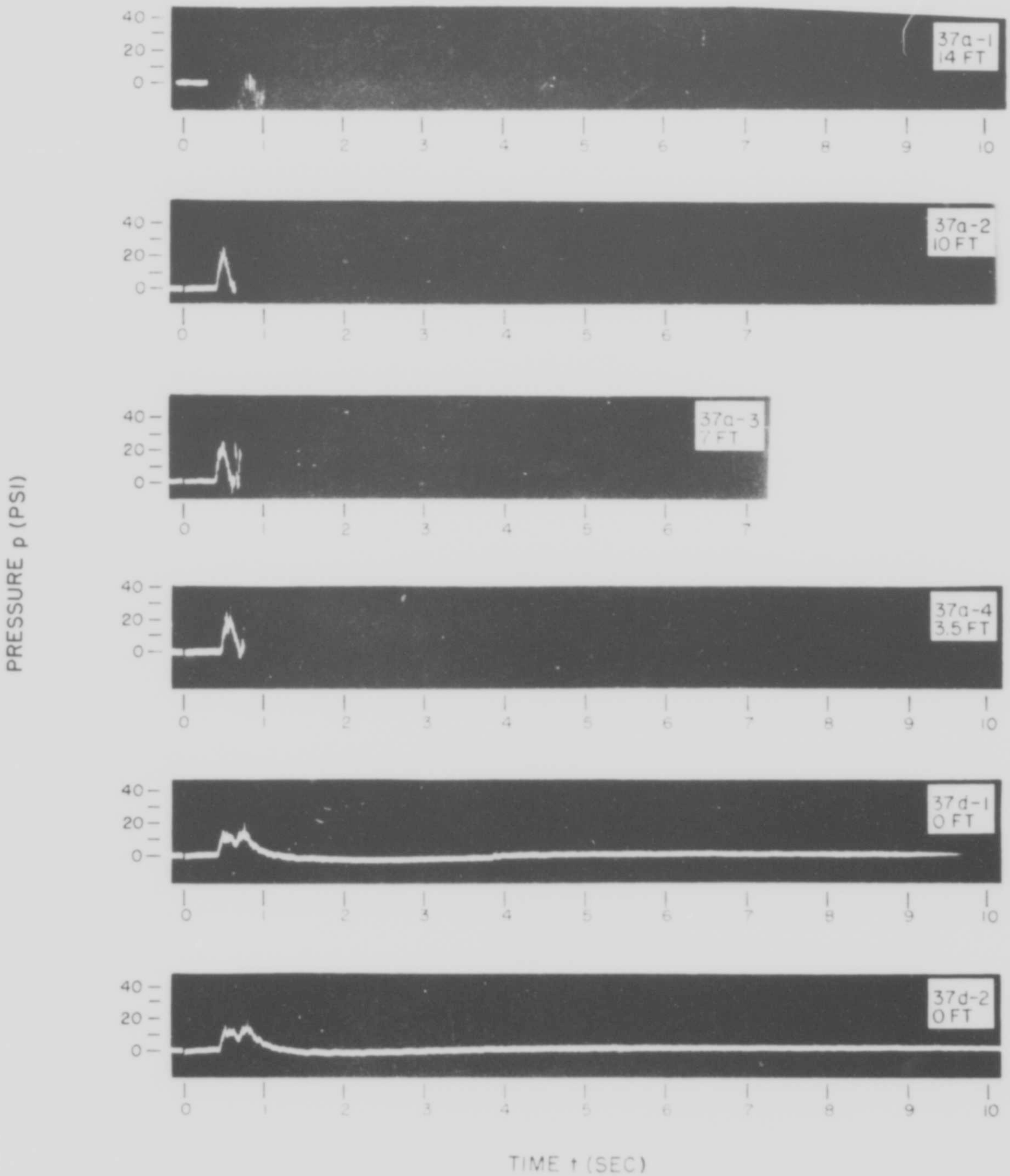

Fig. 4.43 Test Easy, Pylon 37a; Pressure-Time Curves

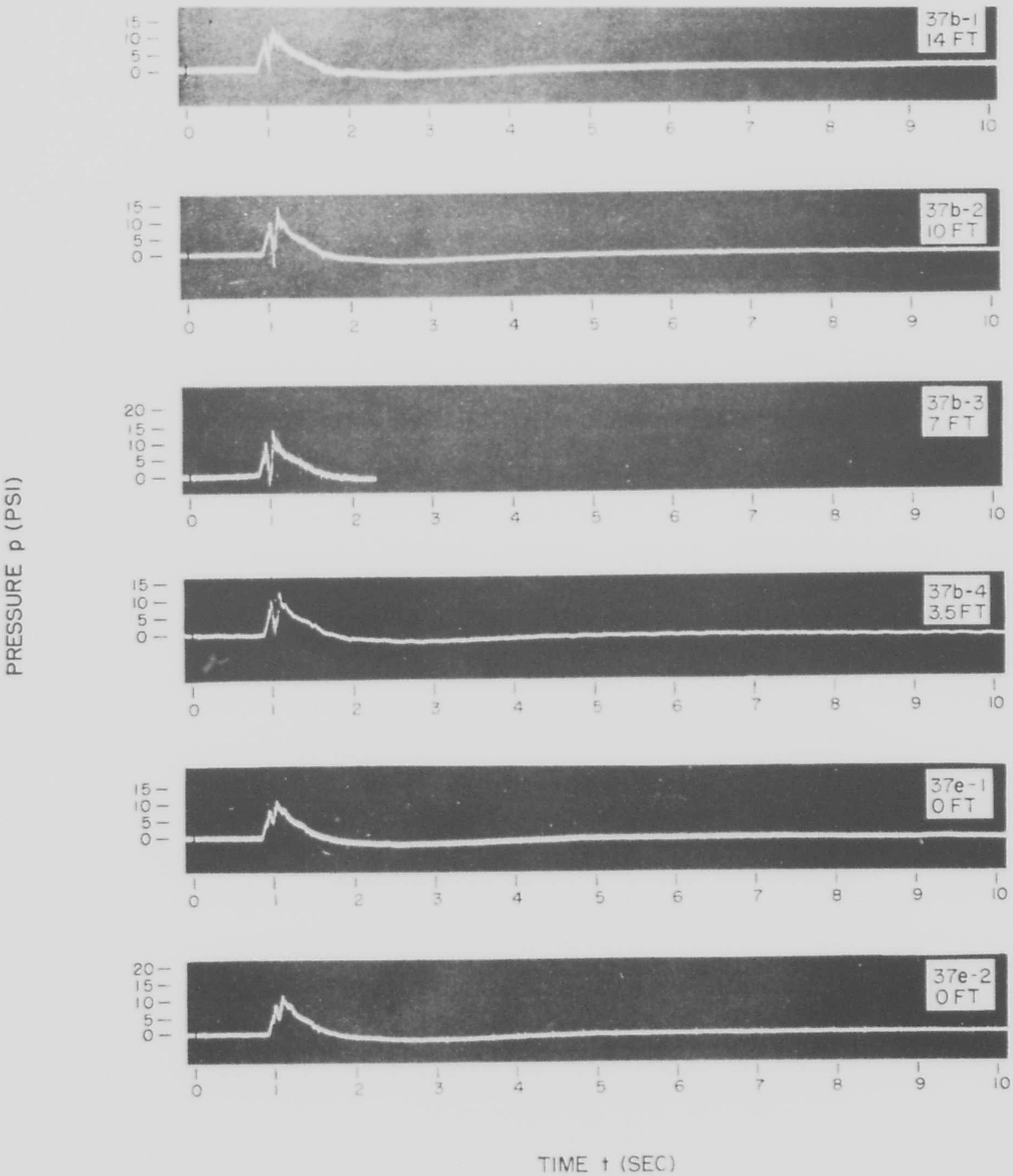

Fig. 4.44 Test Easy, Pylon 37b and Ground Station 37e; Pressure-Time Curves

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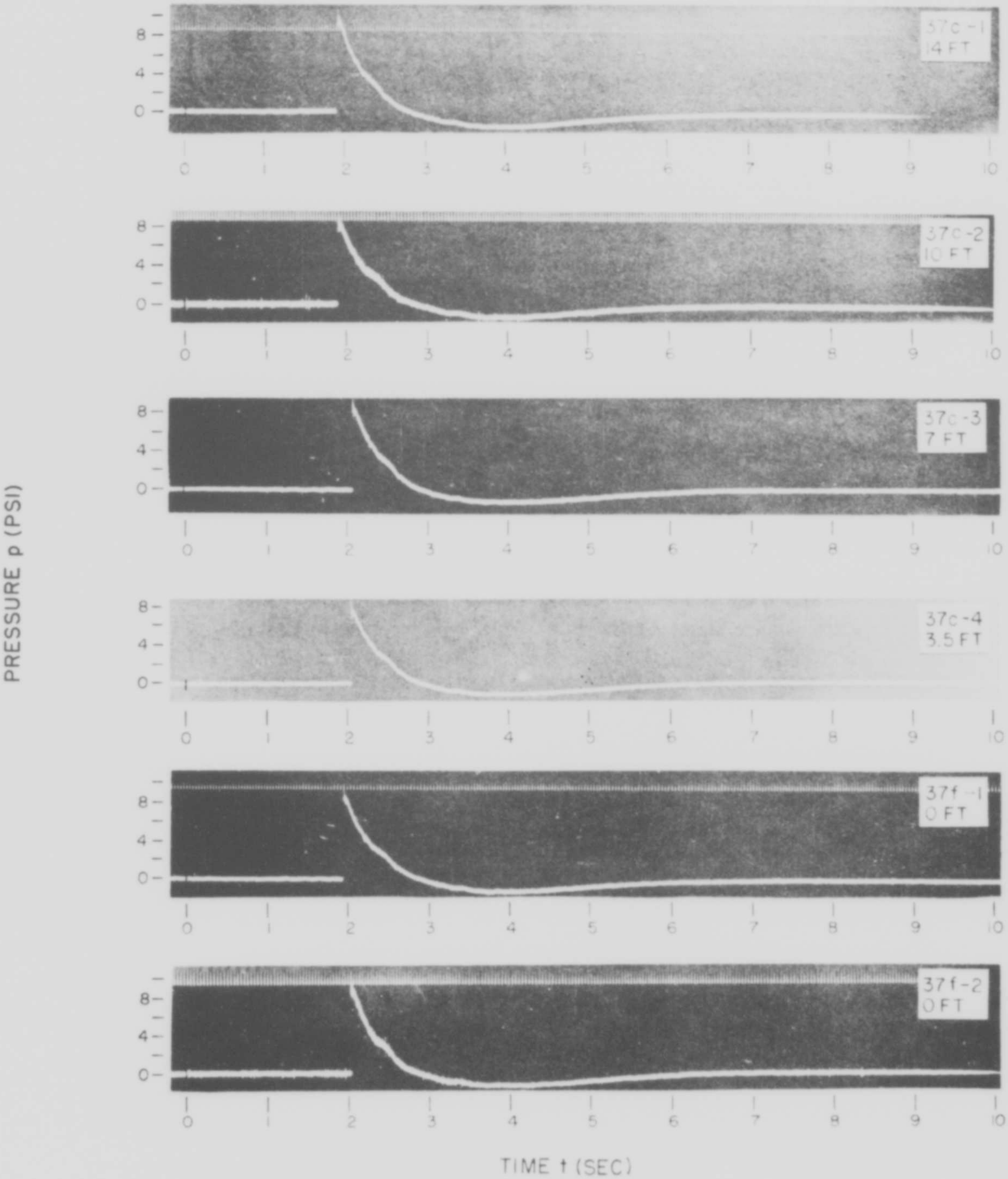

Fig. 4.45 Test Easy, Pylon 37c and Ground Station 37f; Pressure-Time Curves

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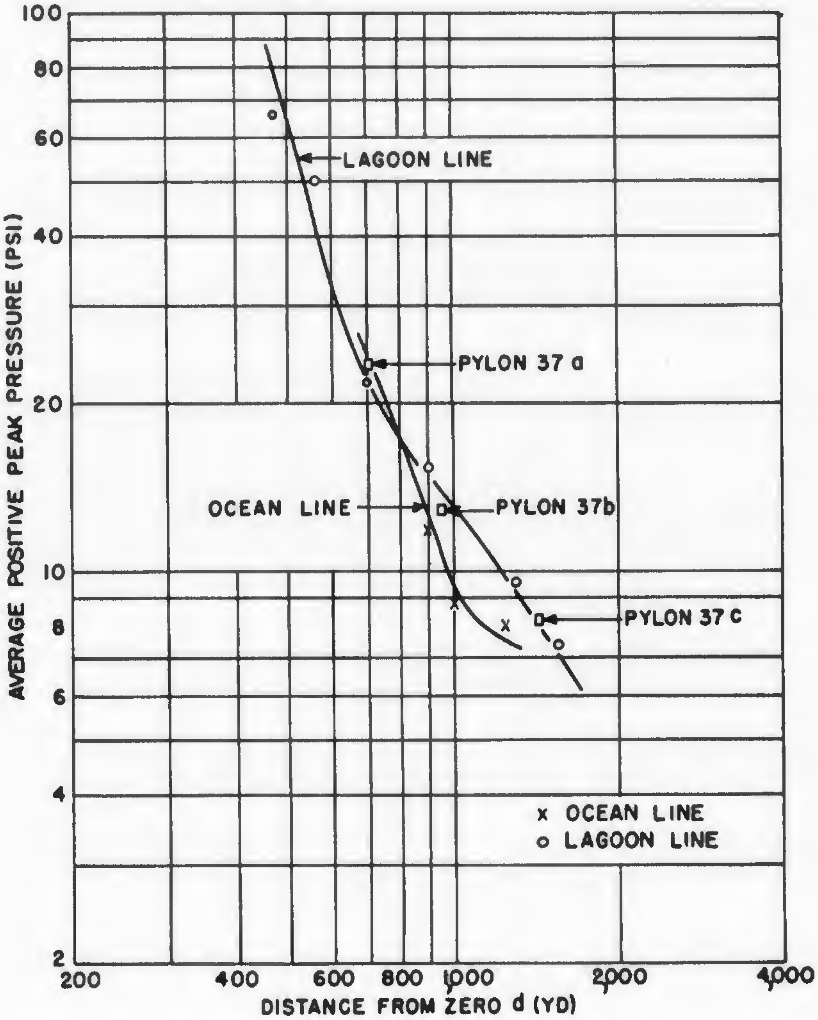

Fig. 4.46 Comparison of Peak Pressures along Ocean and Lagoon Lines (includes average peaks from pylons)

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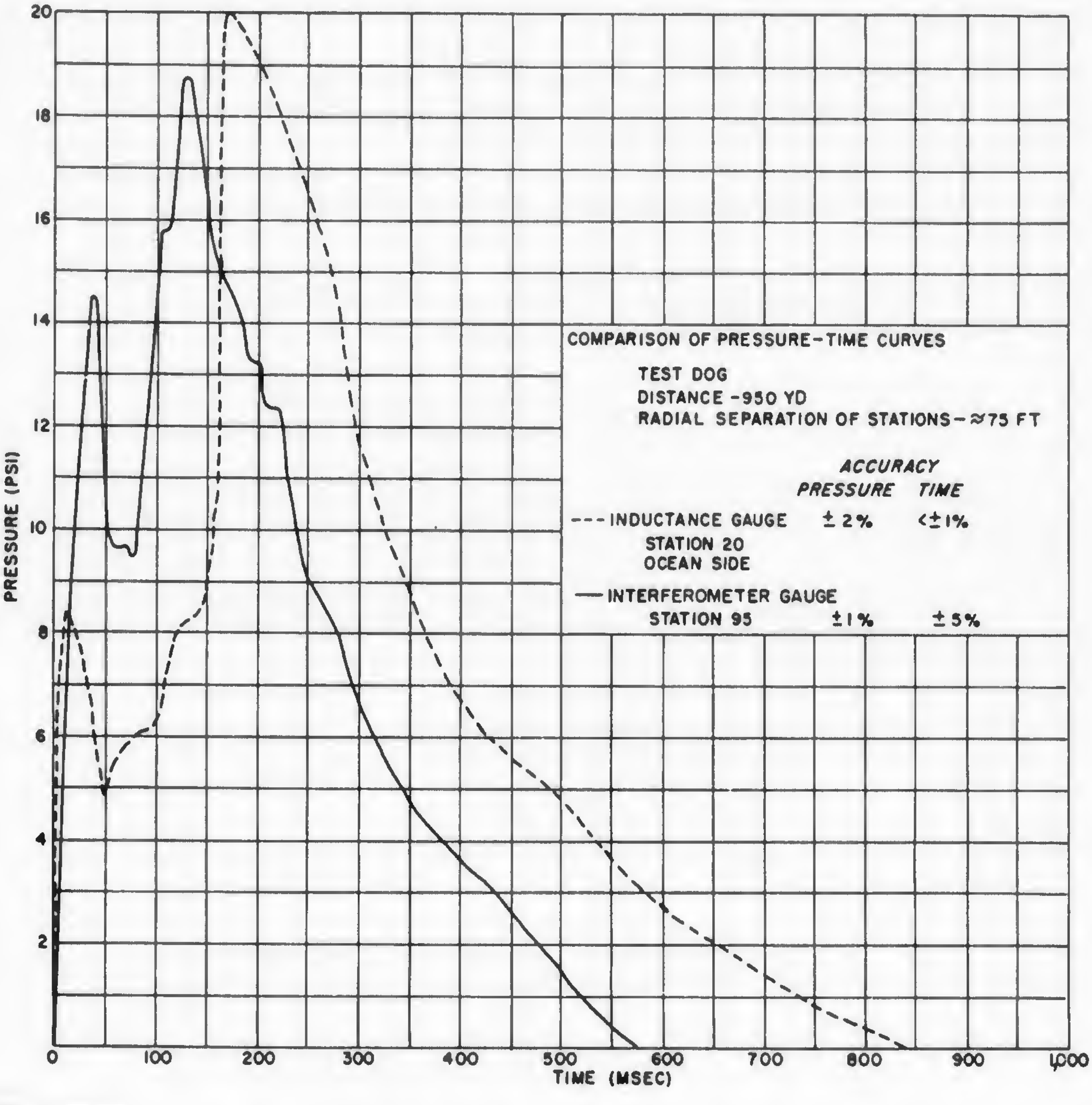

Fig. 5.1 Inductance Gauge; Interferometer Gauge; Test Dog, 950 yd

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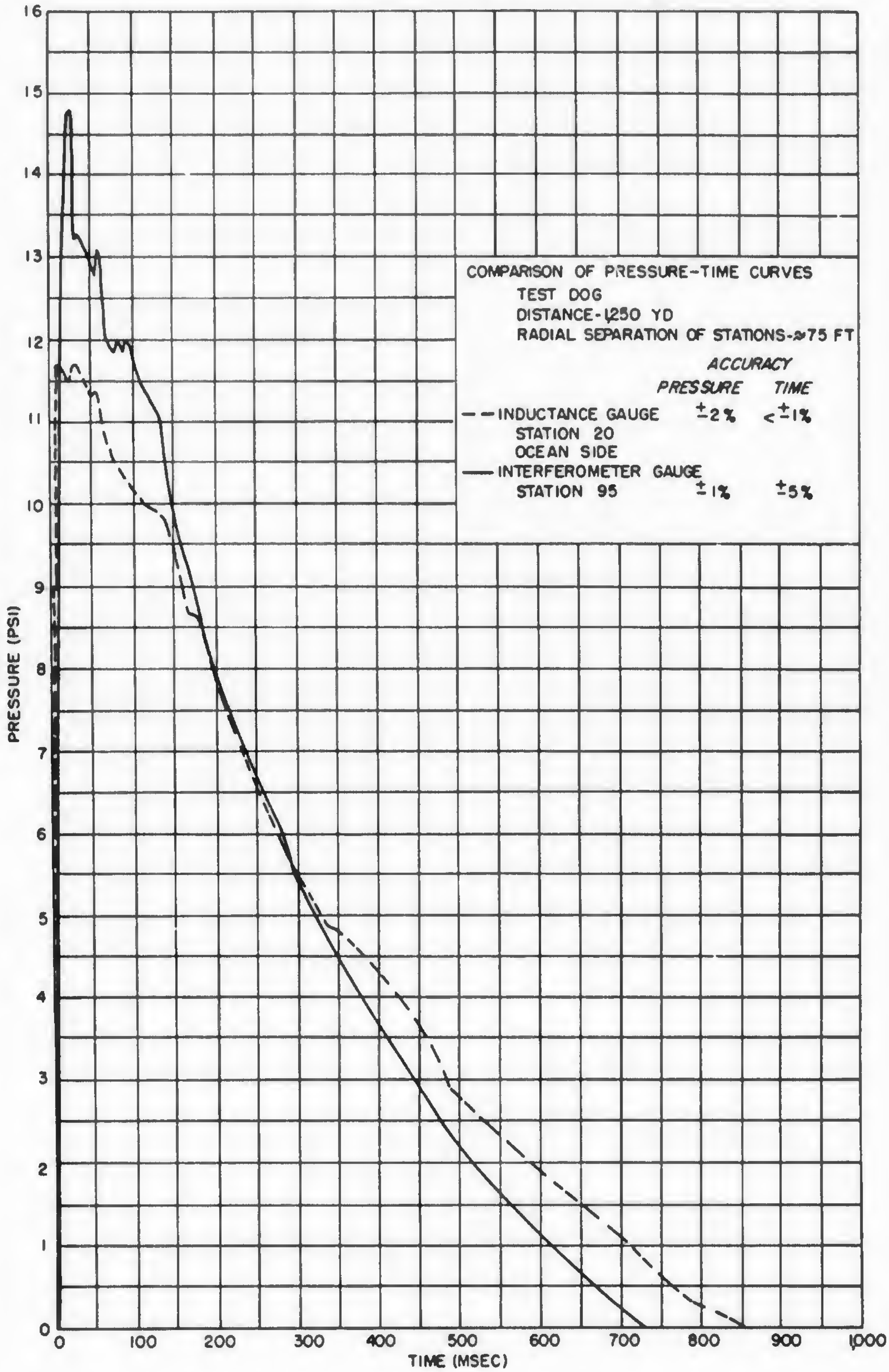

Fig. 5.2 Inductance Gauge; Interferometer Gauge; Test Dog, 1,250 yd

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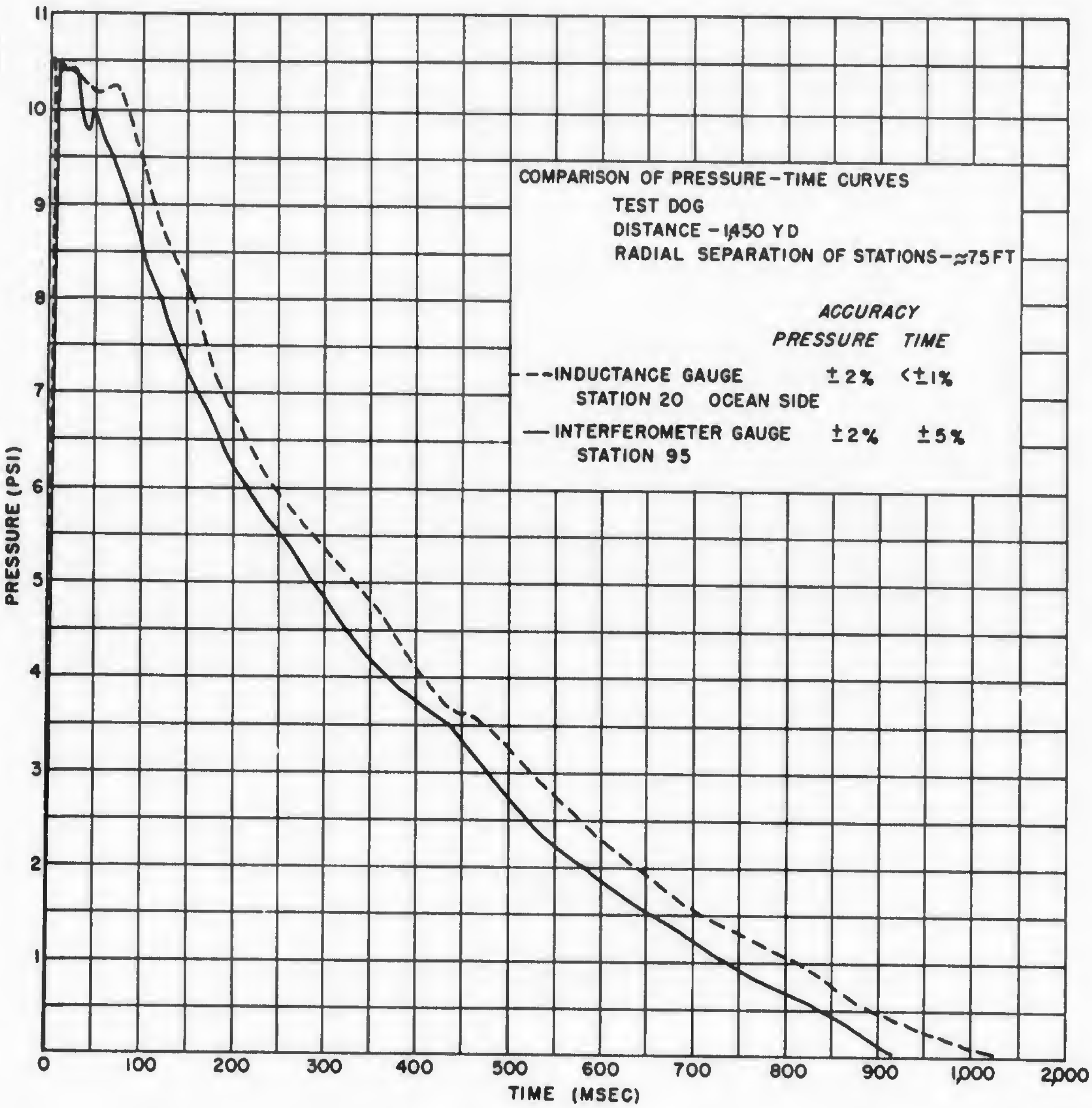

Fig. 5.3 Inductance Gauge; Interferometer Gauge; Test Dog, 1,450 yd

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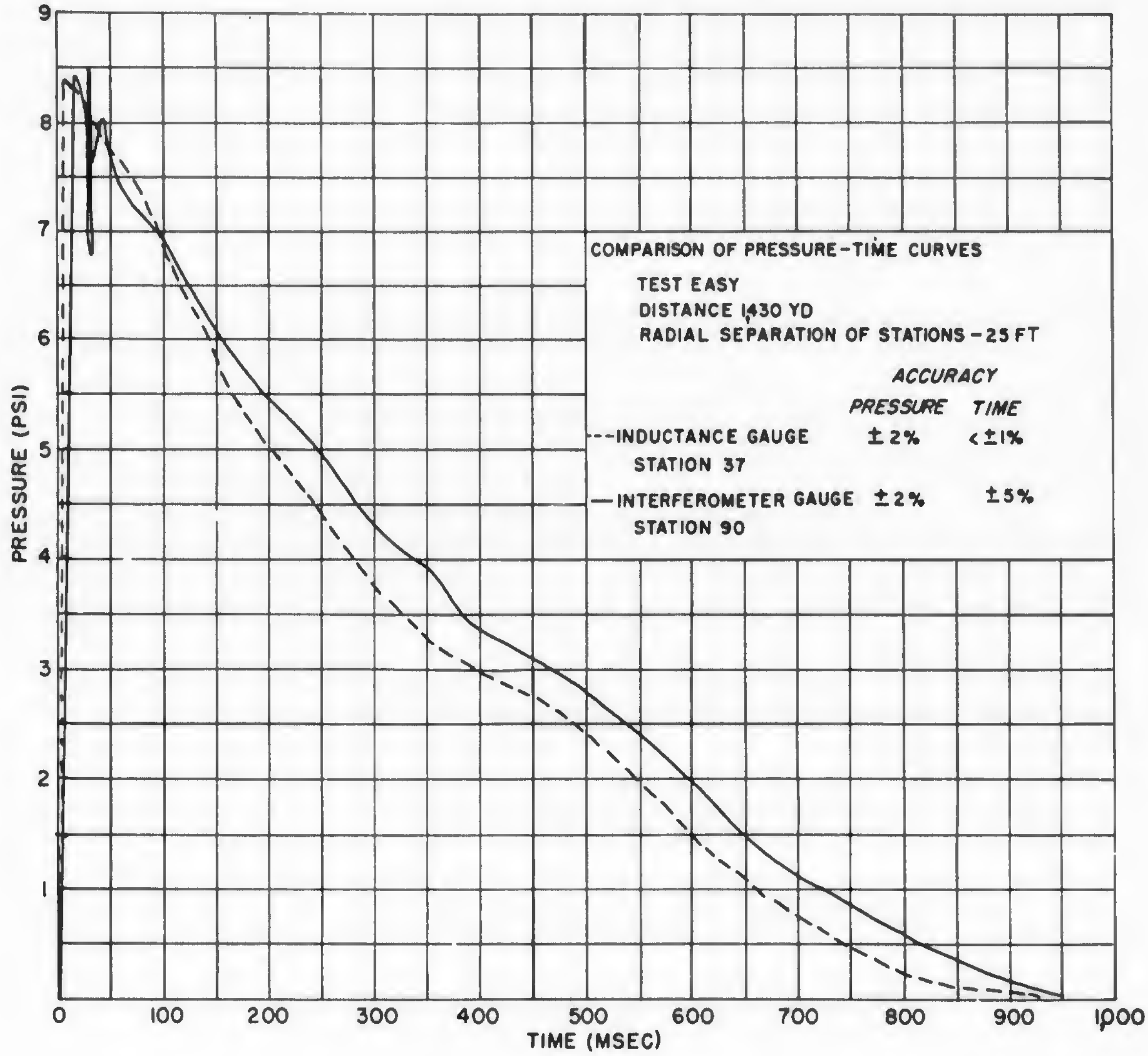

Fig. 5.4 Inductance Gauge; Interferometer Gauge; Test Easy, 1,430 yd

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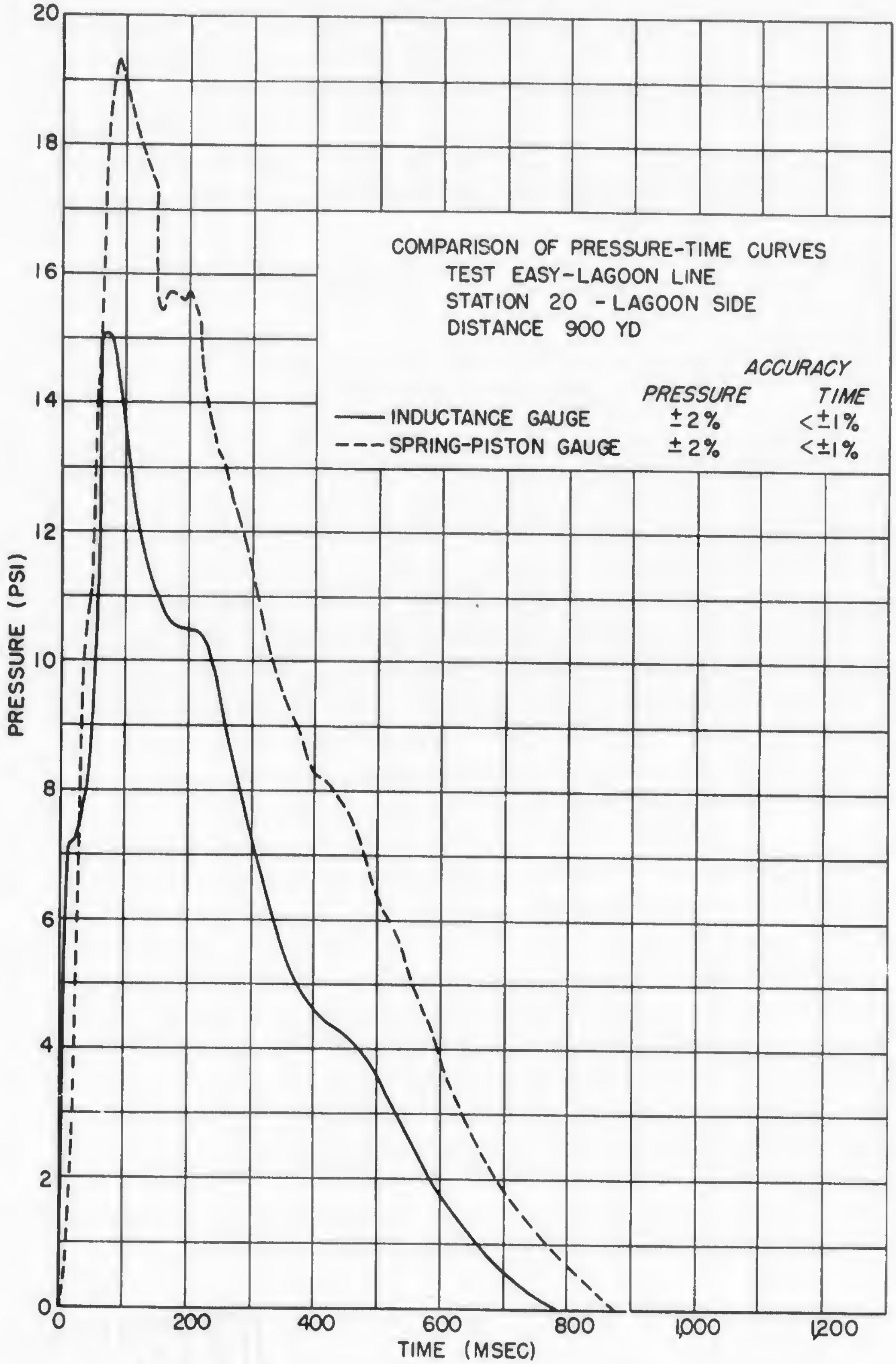

Fig. 5.5 Inductance Gauge; Spring-piston Gauge; Test Easy, Lagoon Line, 900 yd

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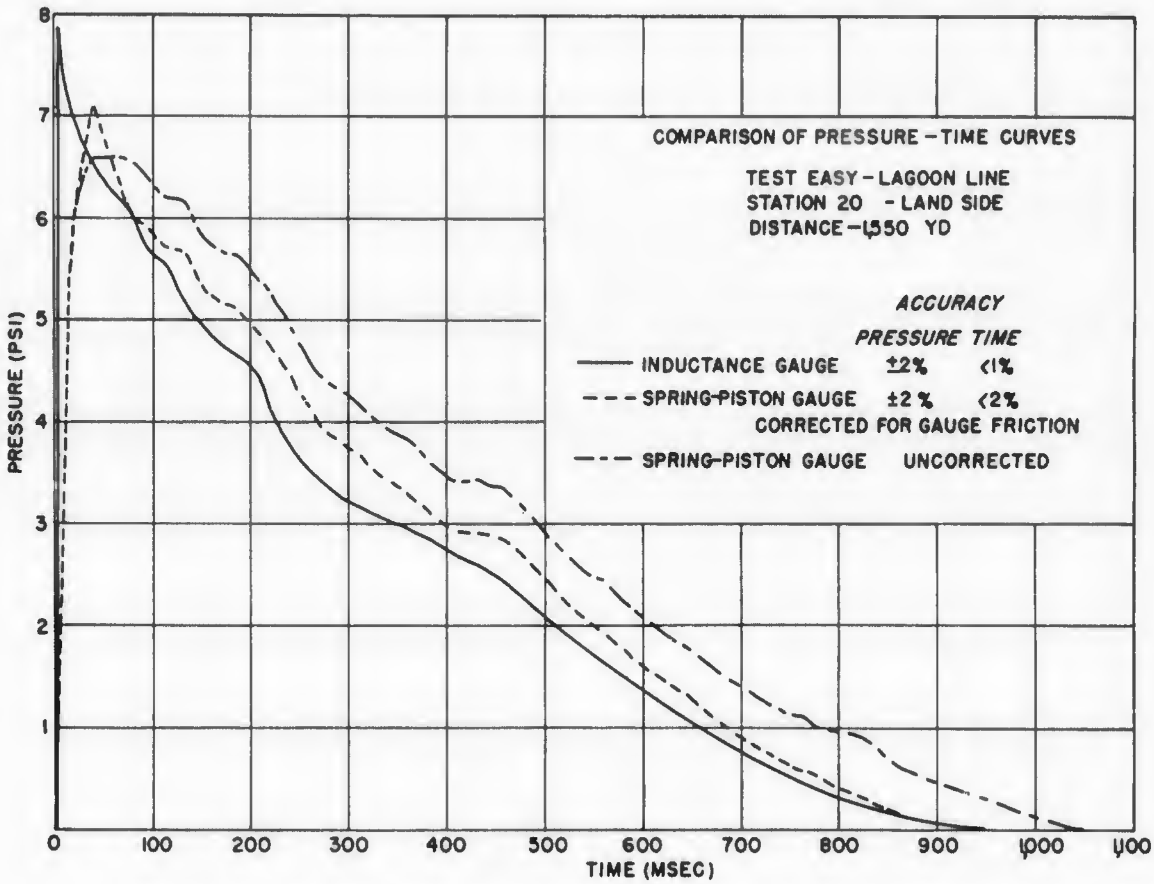

Fig. 5.6 Inductance Gauge; Spring-piston Gauge; Test Easy, Lagoon Line, 1,550 yd

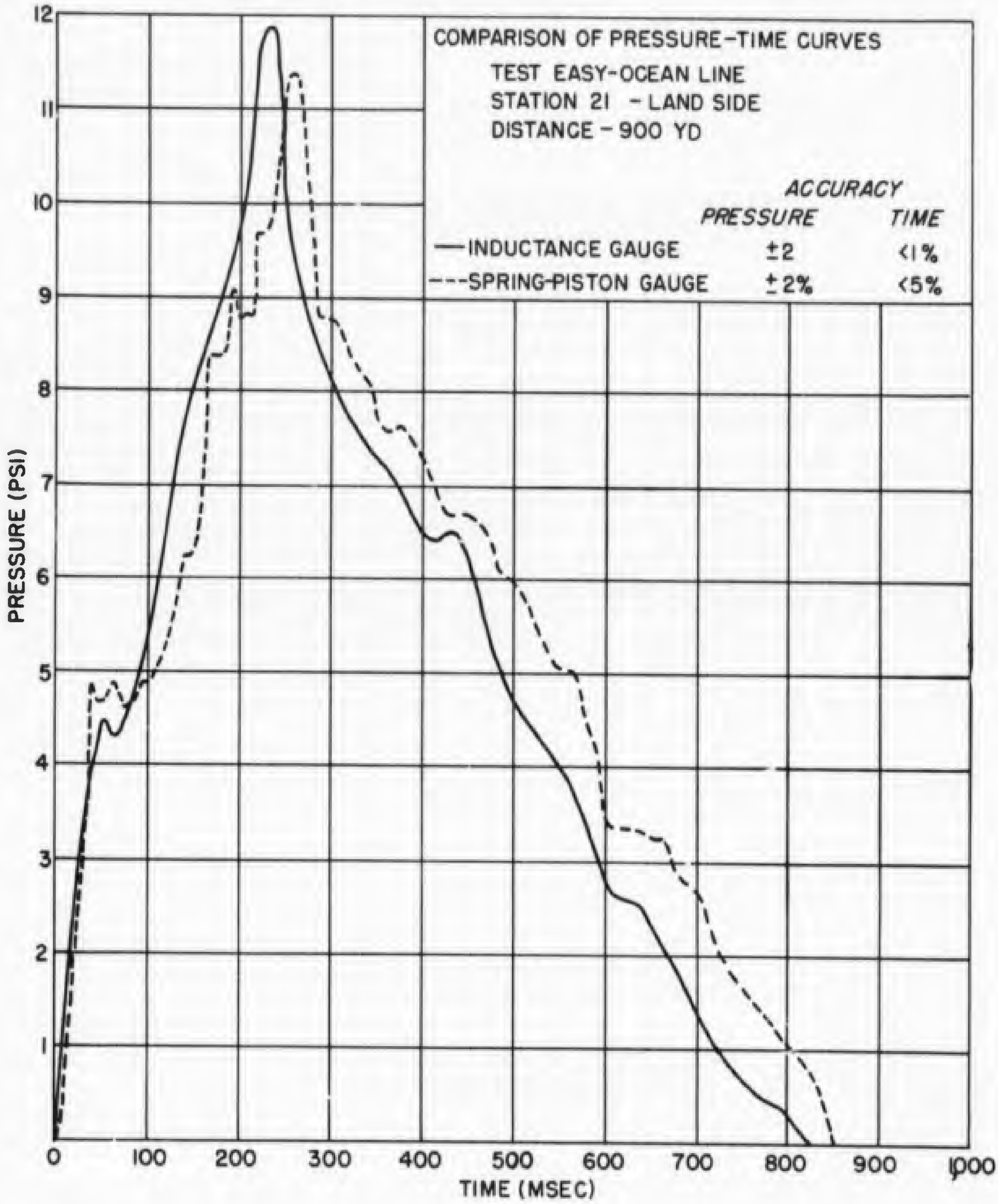

Fig. 5.7 Inductance Gauge; Spring-piston Gauge; Test Easy, Ocean Line, 900 yd

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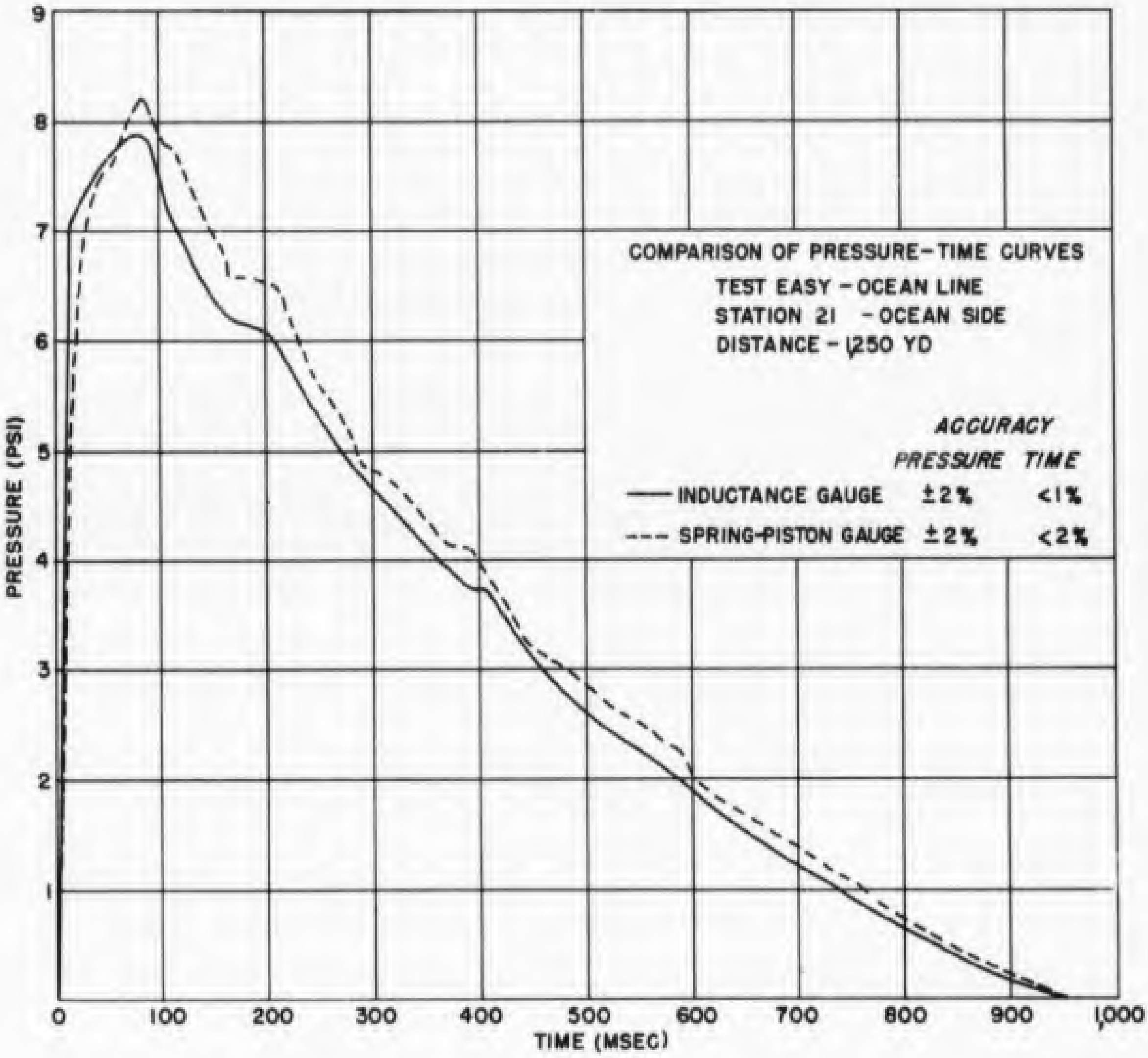

Fig. 5.8 Inductance Gauge; Spring-piston Gauge; Test Easy, Ocean Line, 1,250 yd

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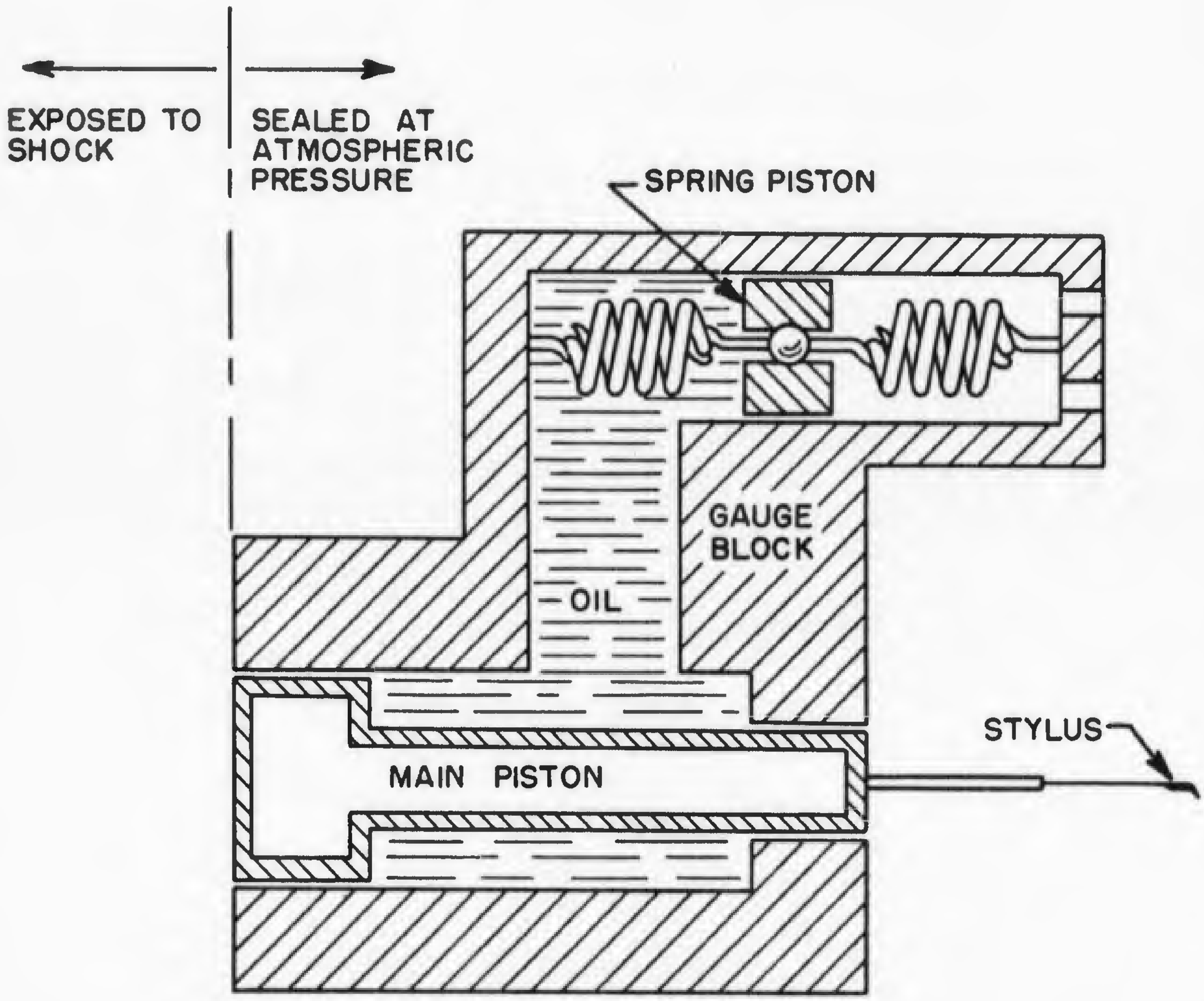

Fig. 6.1 Schematic Diagram of Spring-piston Gauge

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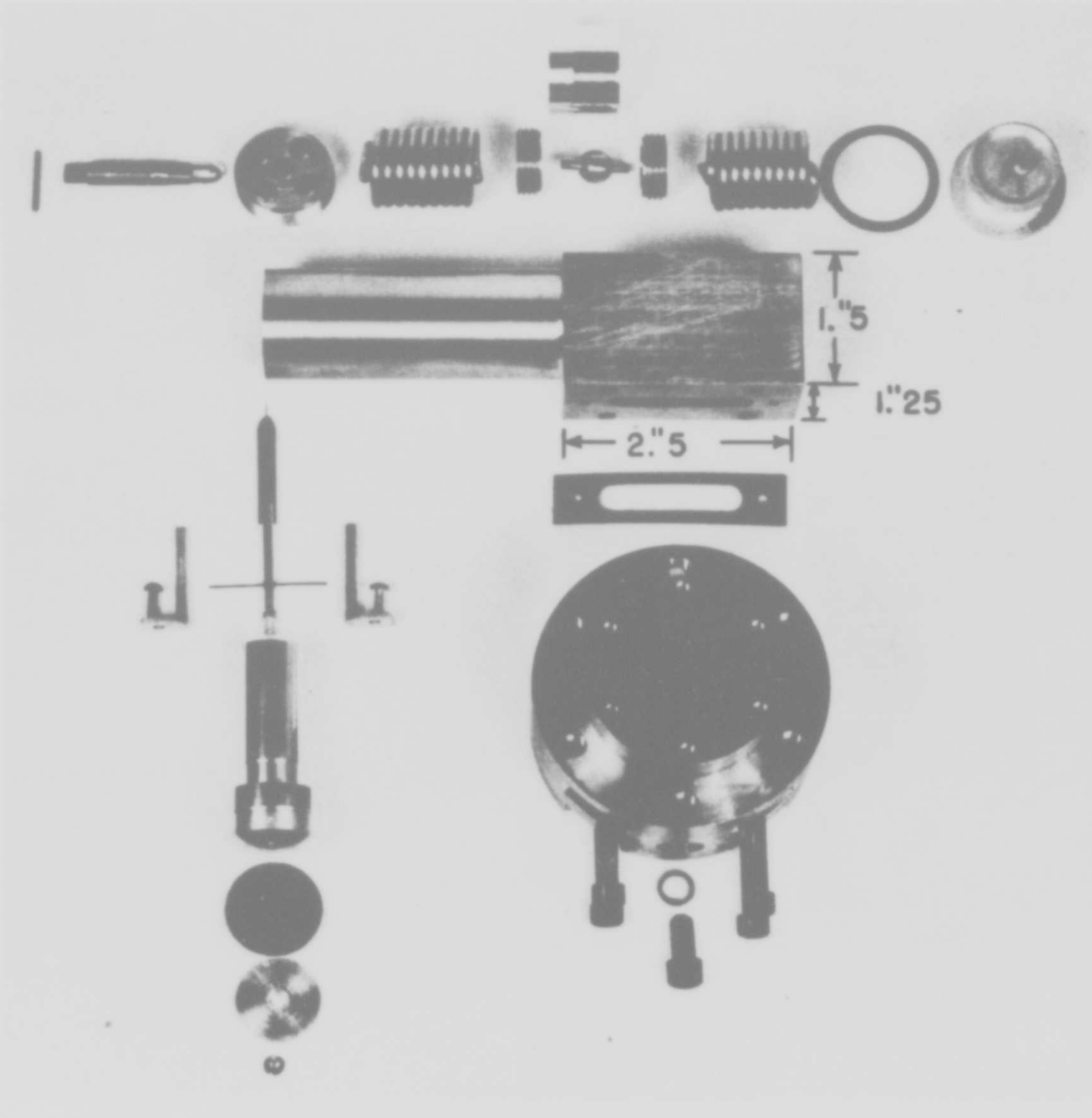

Fig. 6.2 Unassembled Low-pressure Gauge

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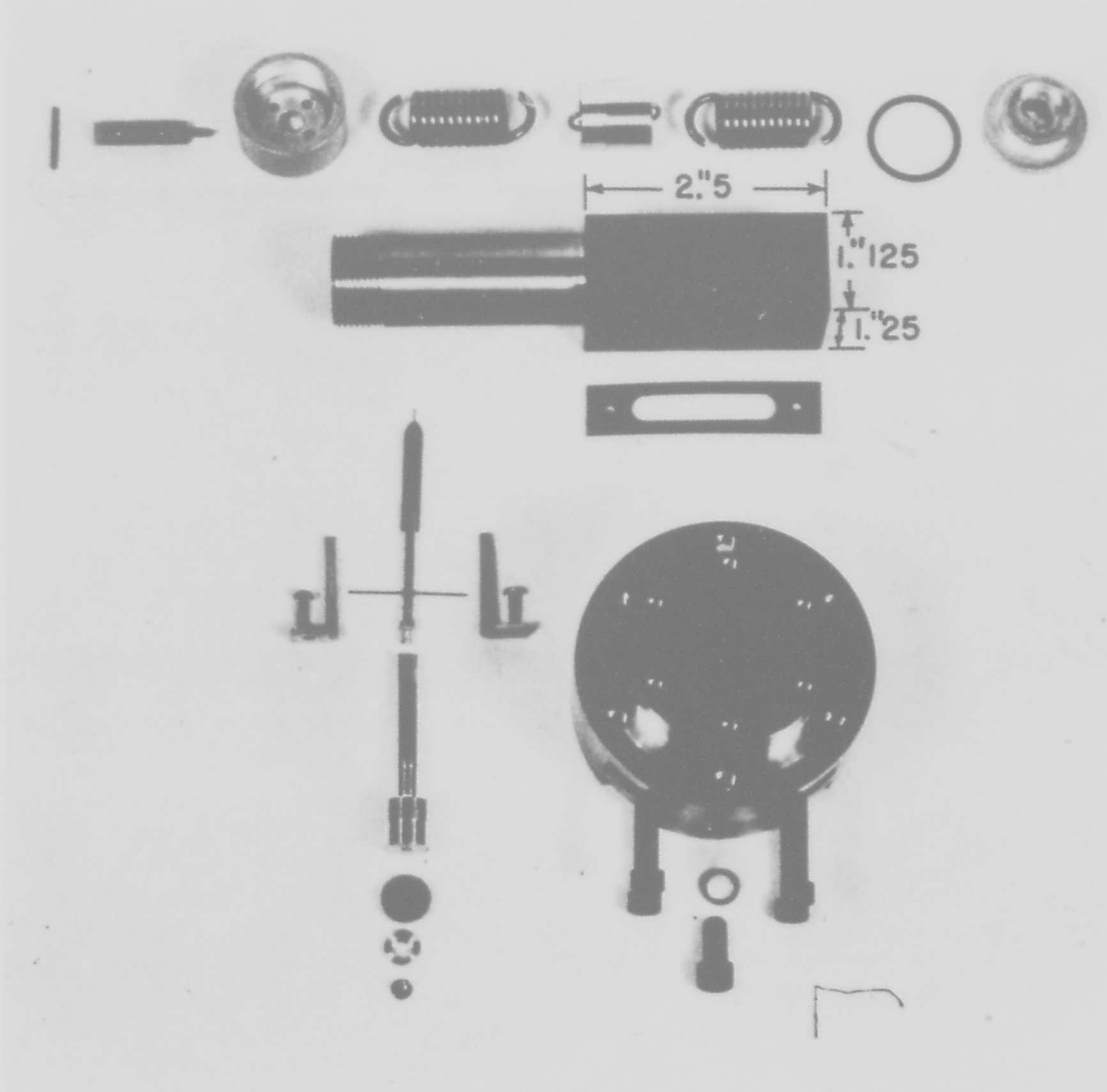

Fig. 6.3 Unassembled High-pressure Gauge

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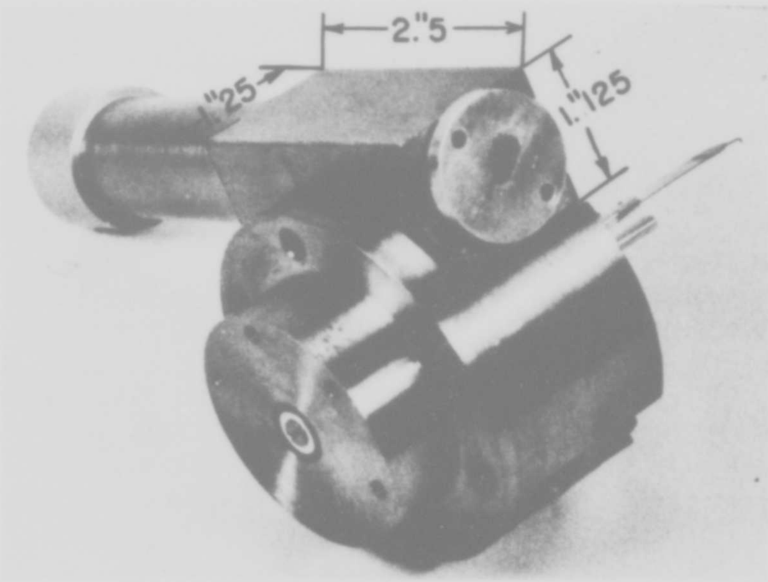

Fig. 6.4 Assembled High-pressure Gauge

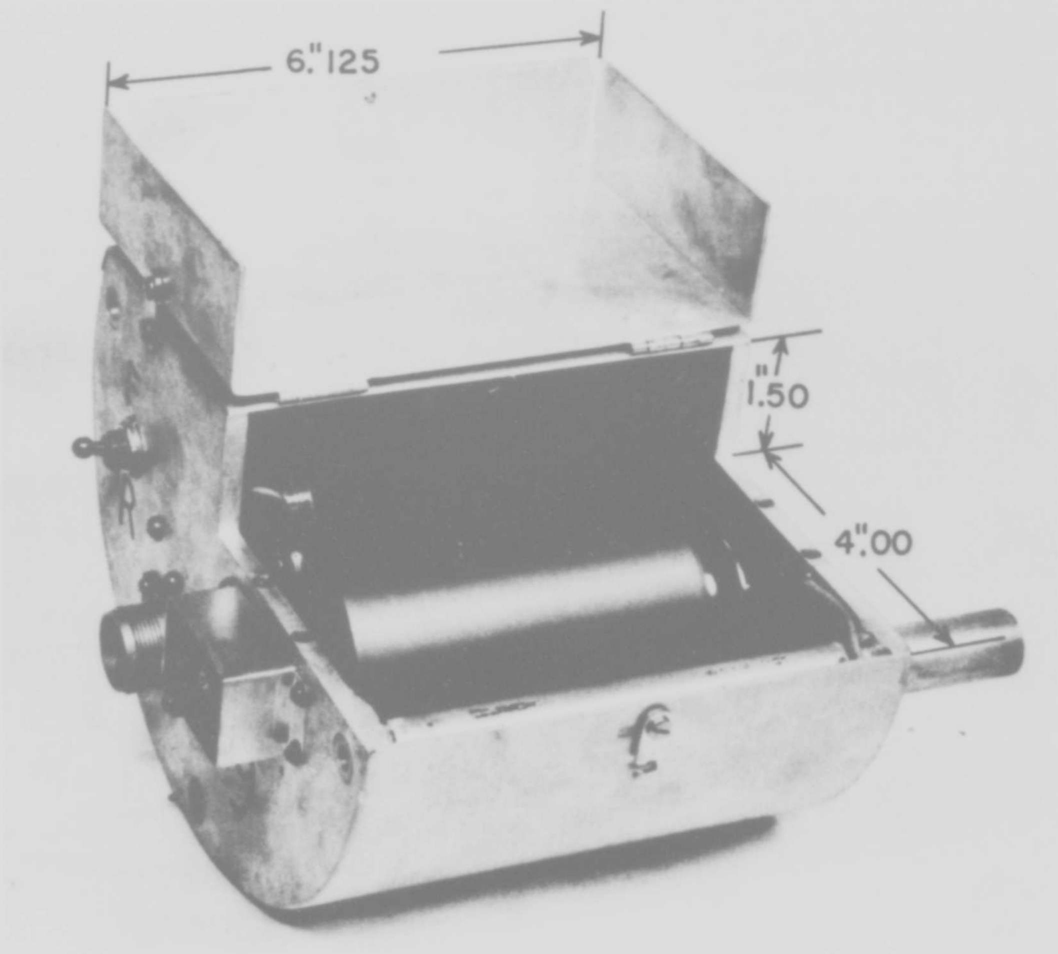

Fig. 6.5 Recorder

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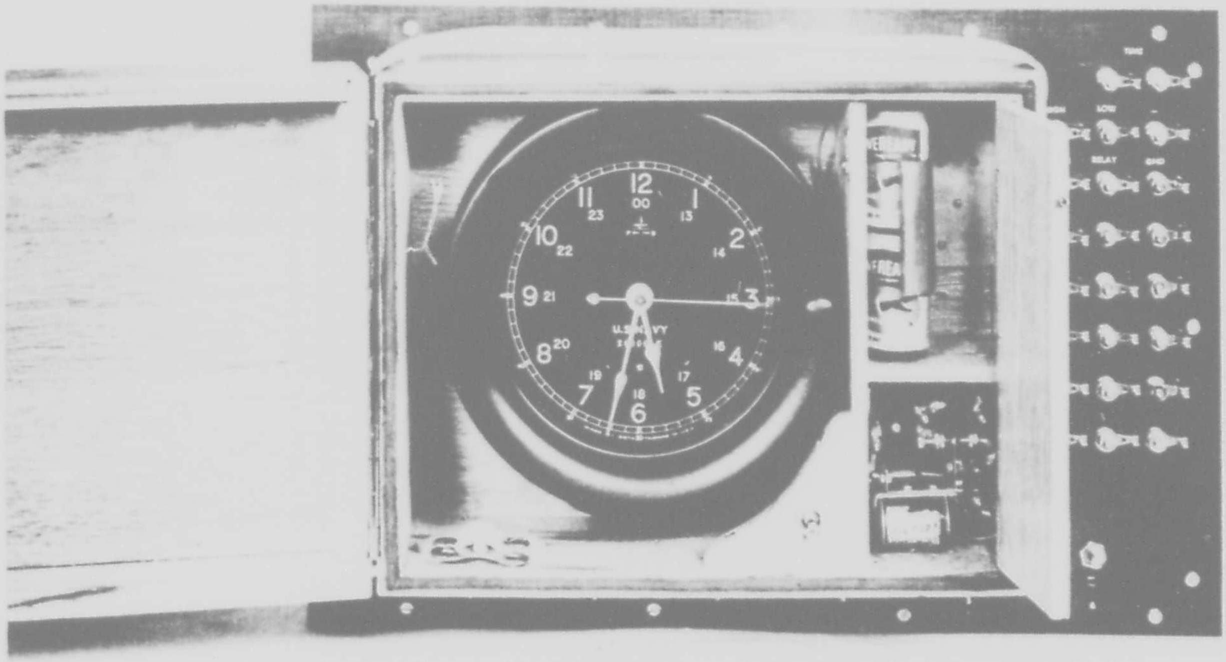

Fig. 6.6 Timing Clock and Junction Box

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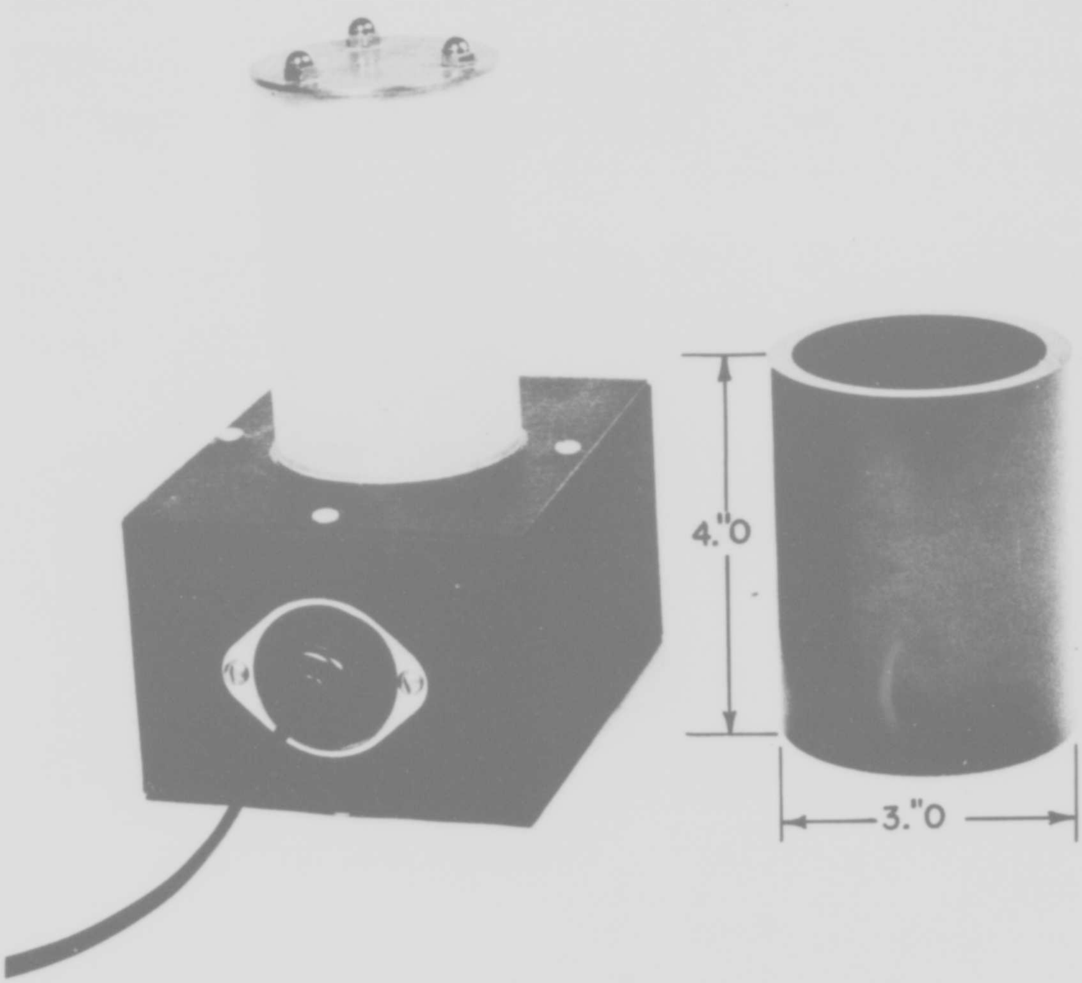

Fig. 6.7 Record Light Source

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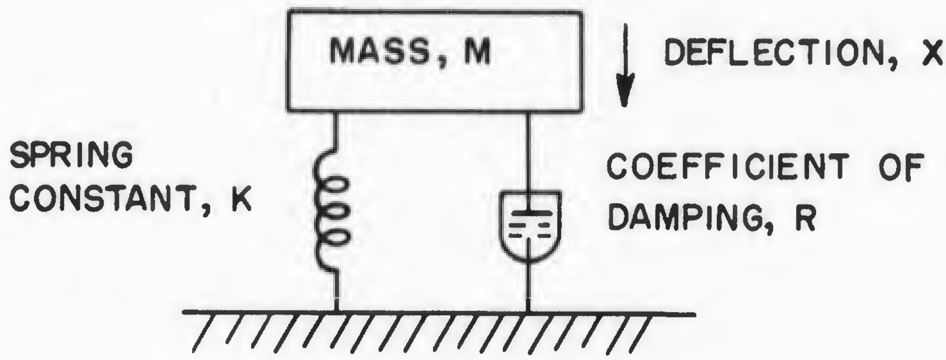

Fig. 7.1 Simplified Mechanical Circuit

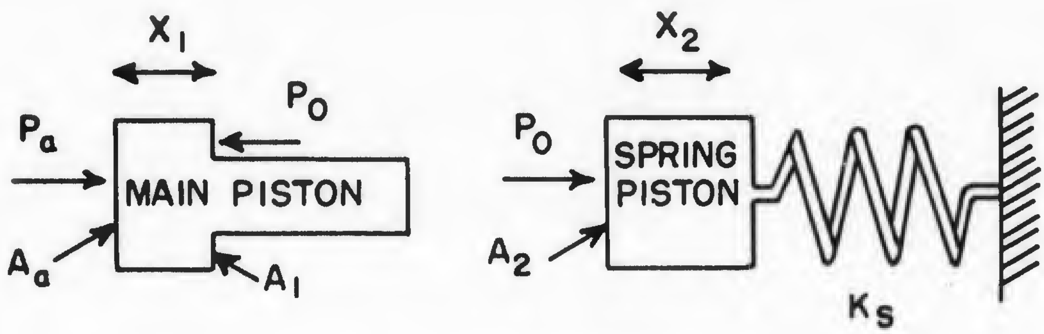

Fig. 7.2 Oil-coupling Schematic Diagram

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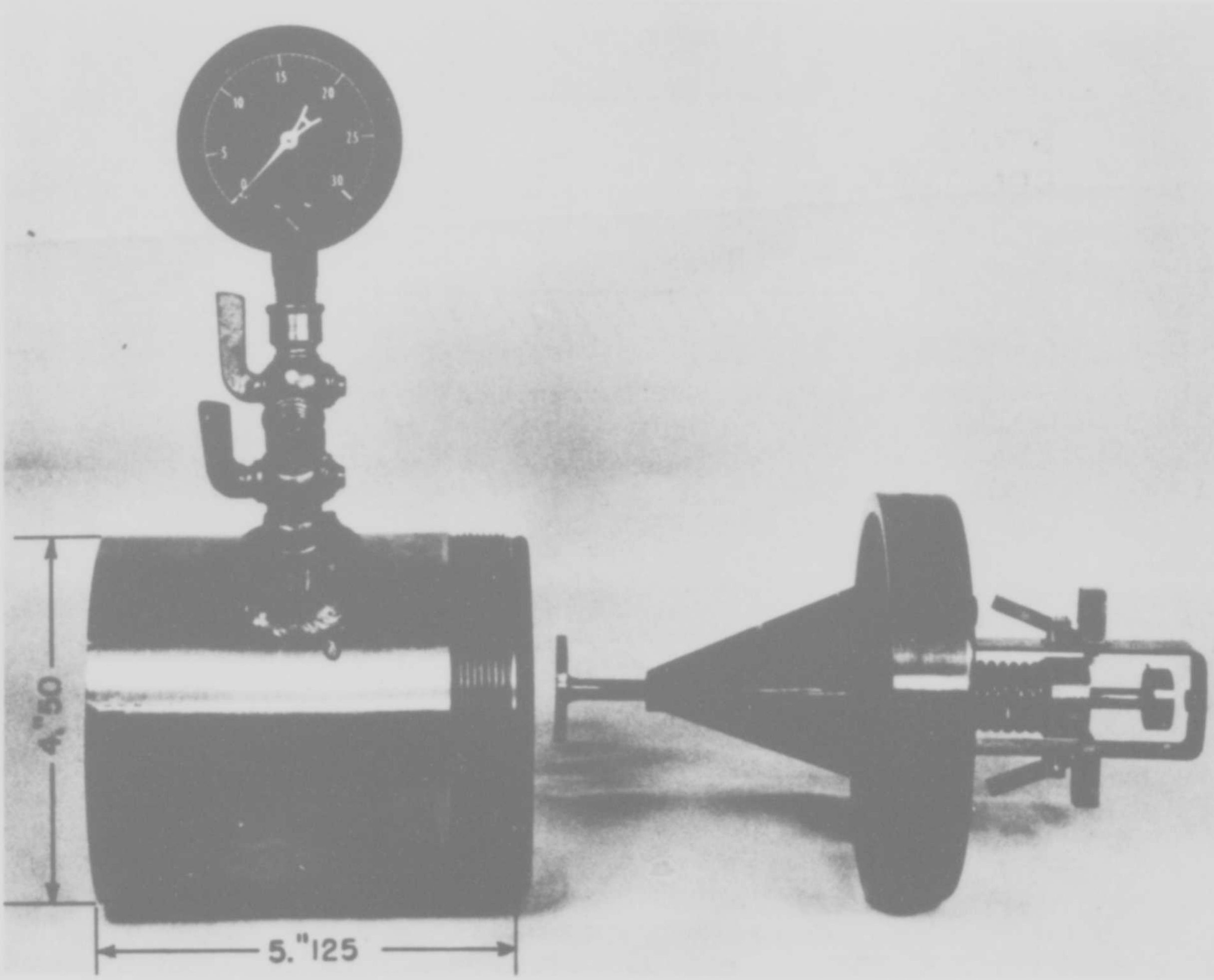

Fig. 8.1 Test Pot

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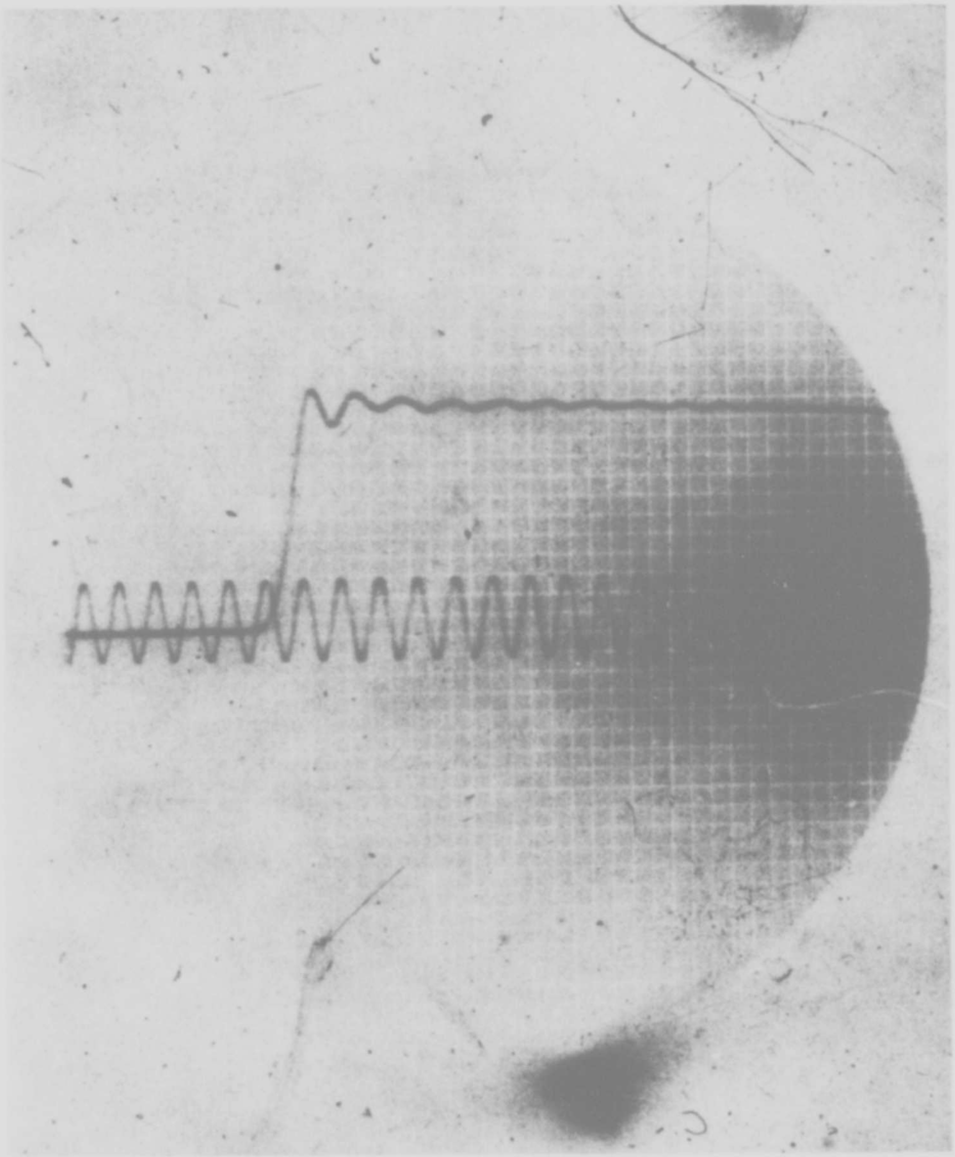

Fig. 8.2 Pressure Rise of Test Pot Measured by Diaphragm-type Inductance Gauge

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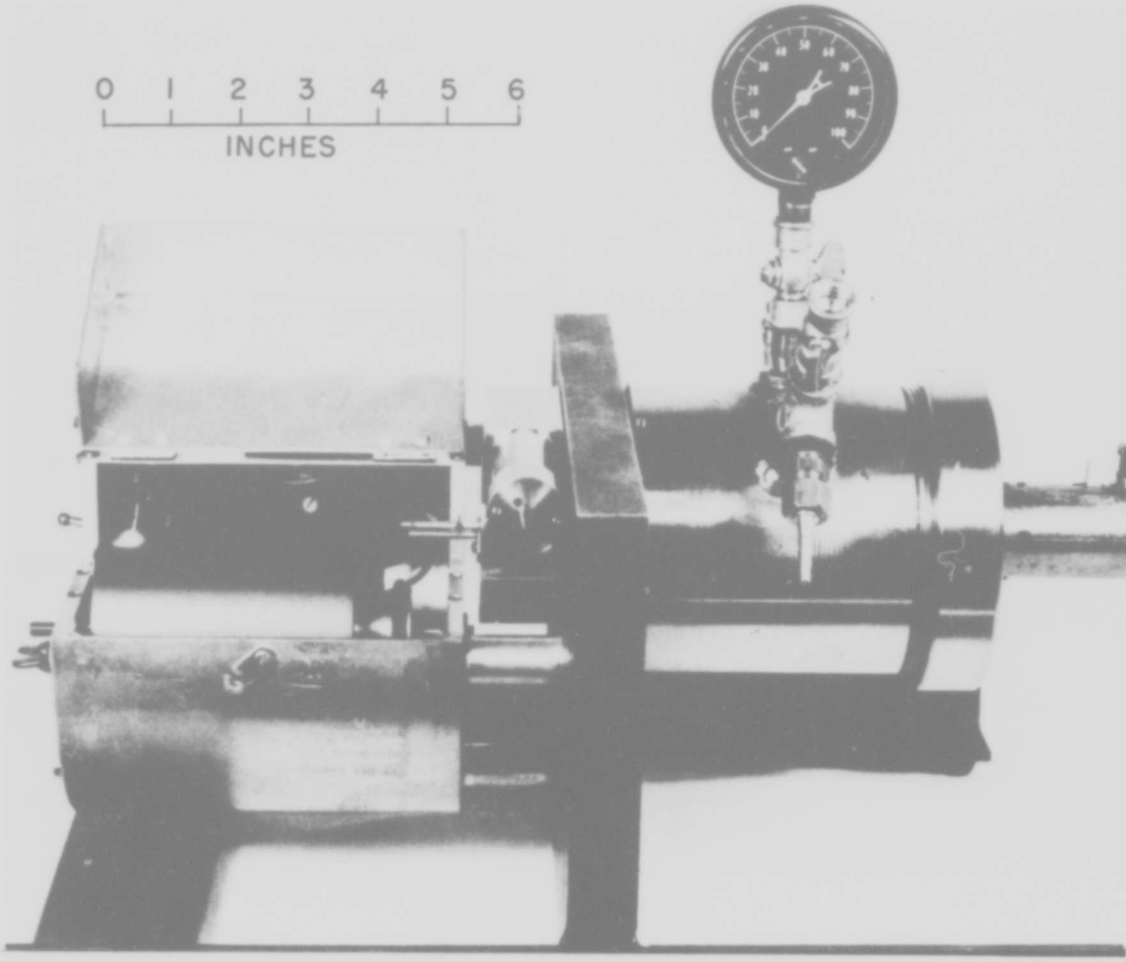

Fig. 8.3 Calibration Assembly

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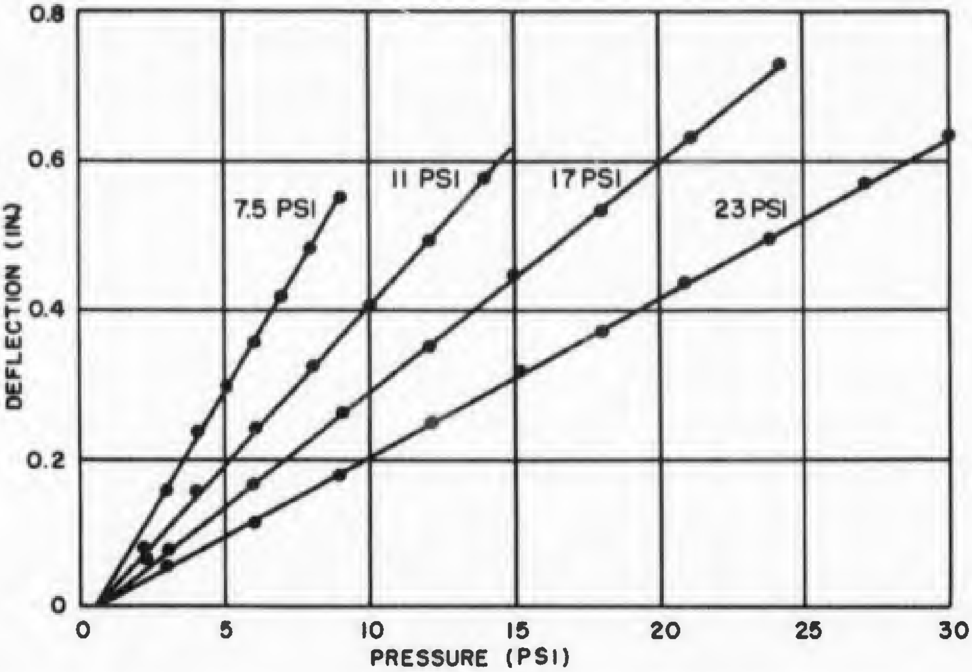

Fig. 8.4 Typical Calibration Curves, Low-pressure Design, Showing Gauge Design Pressures

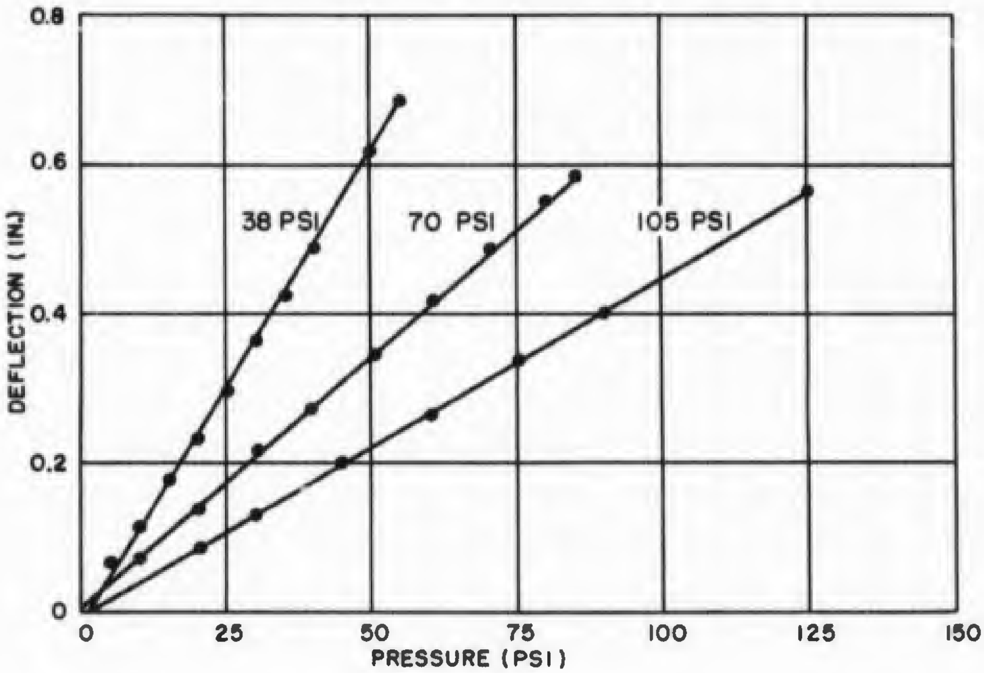

Fig. 8.5 Typical Calibration Curves, High-pressure Design, Showing Gauge Design Pressures

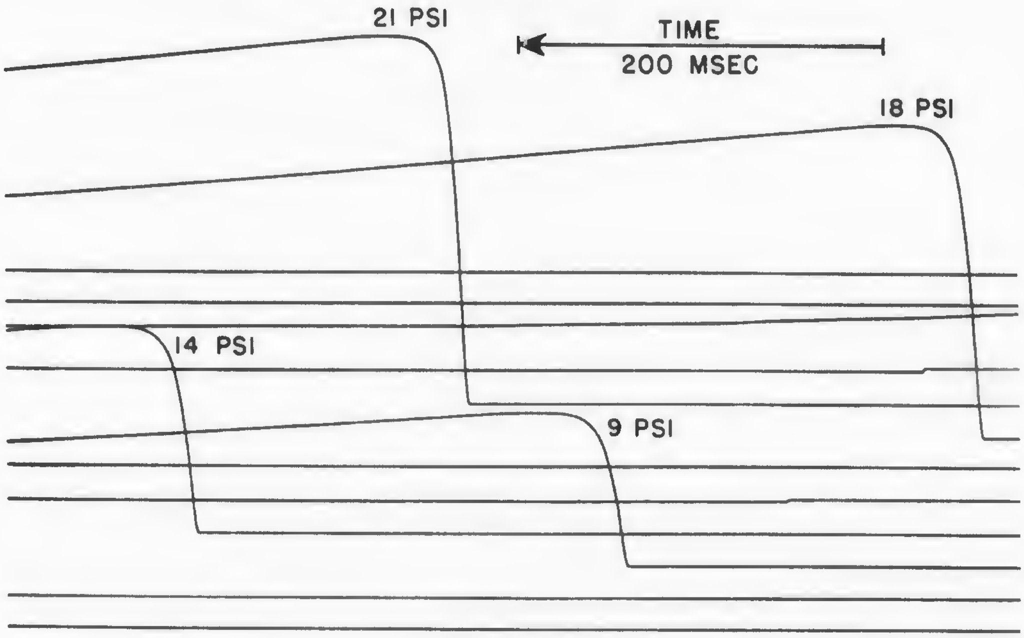

Fig. 8.6 Typical Calibration Records, Gauge 9L, 17-psi Design, Enlargement 3×

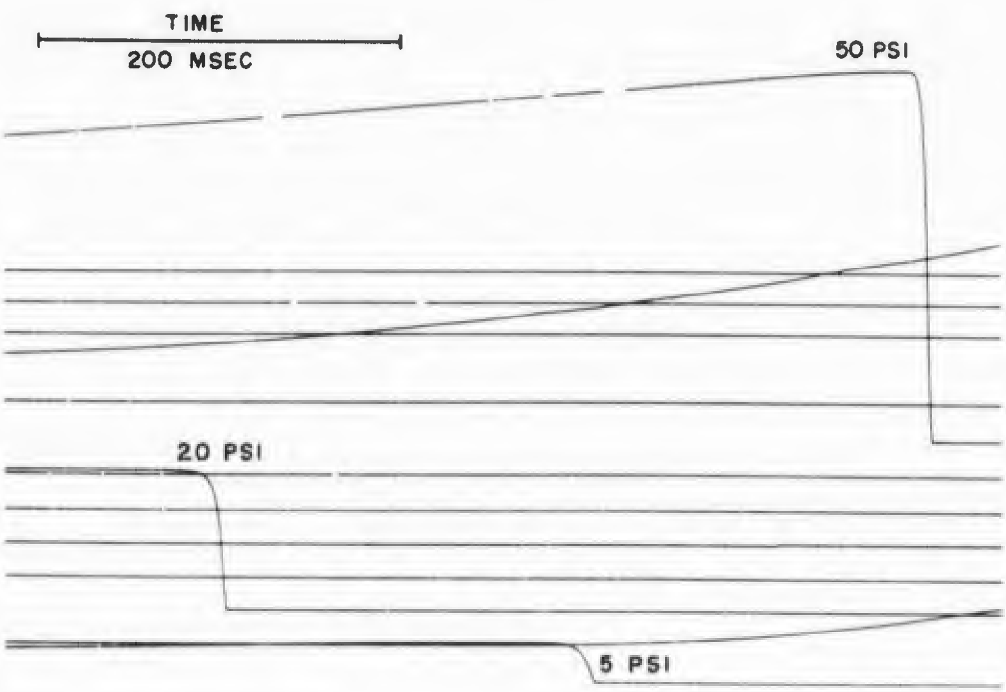

Fig. 8.7 Typical Calibration Records, Gauge 11H, 38-psi Design, Enlargement 3×

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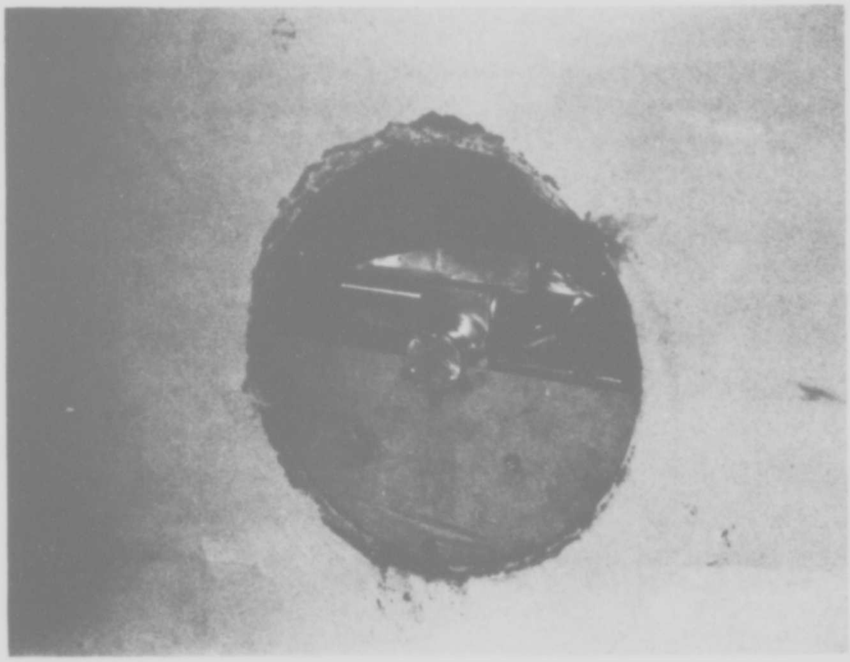

Fig. 9.1 Wall Station with Inspection Plate Removed

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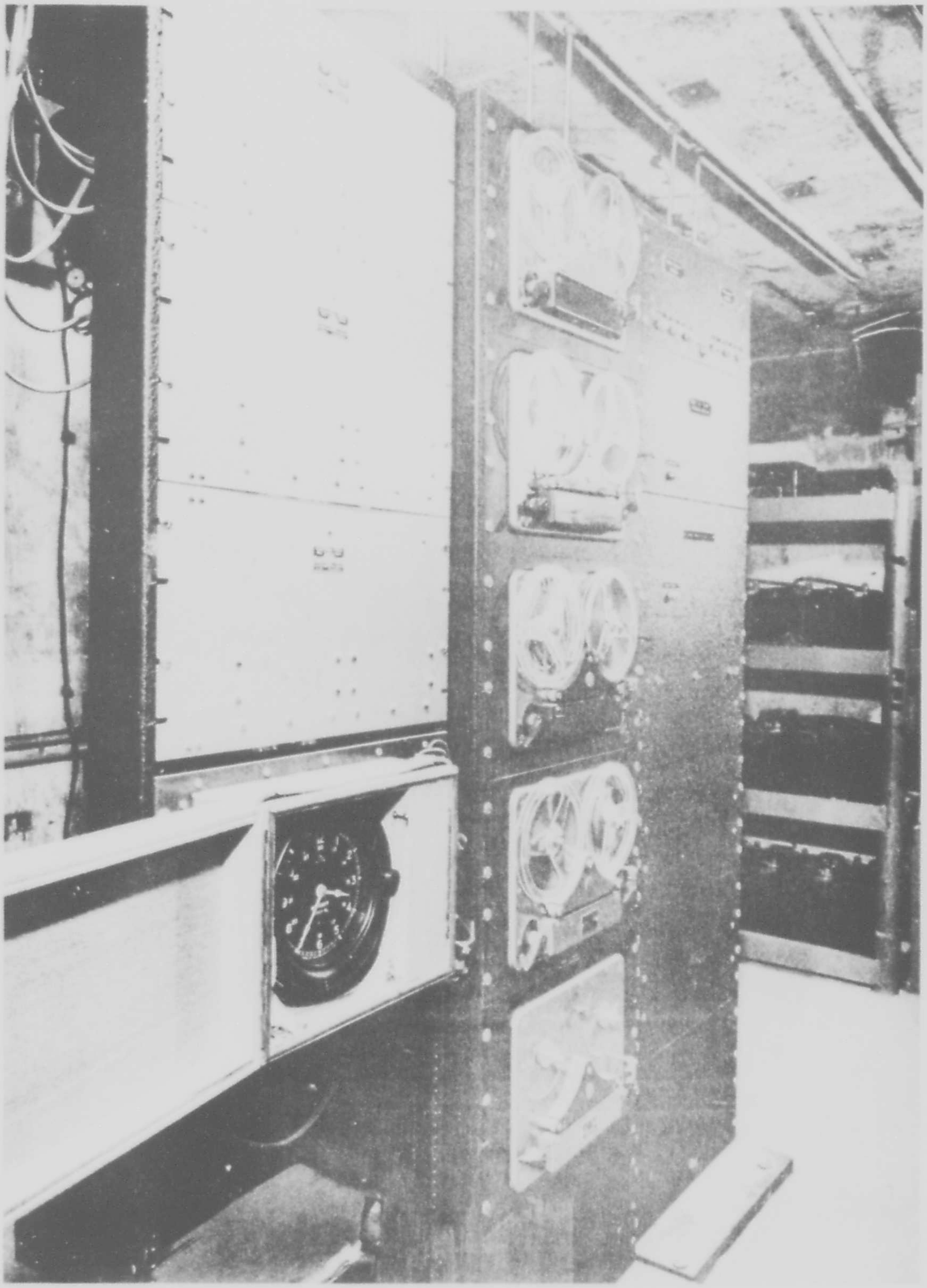

Fig. 9.2 Clock and Junction Box Mounted in Blast Hut

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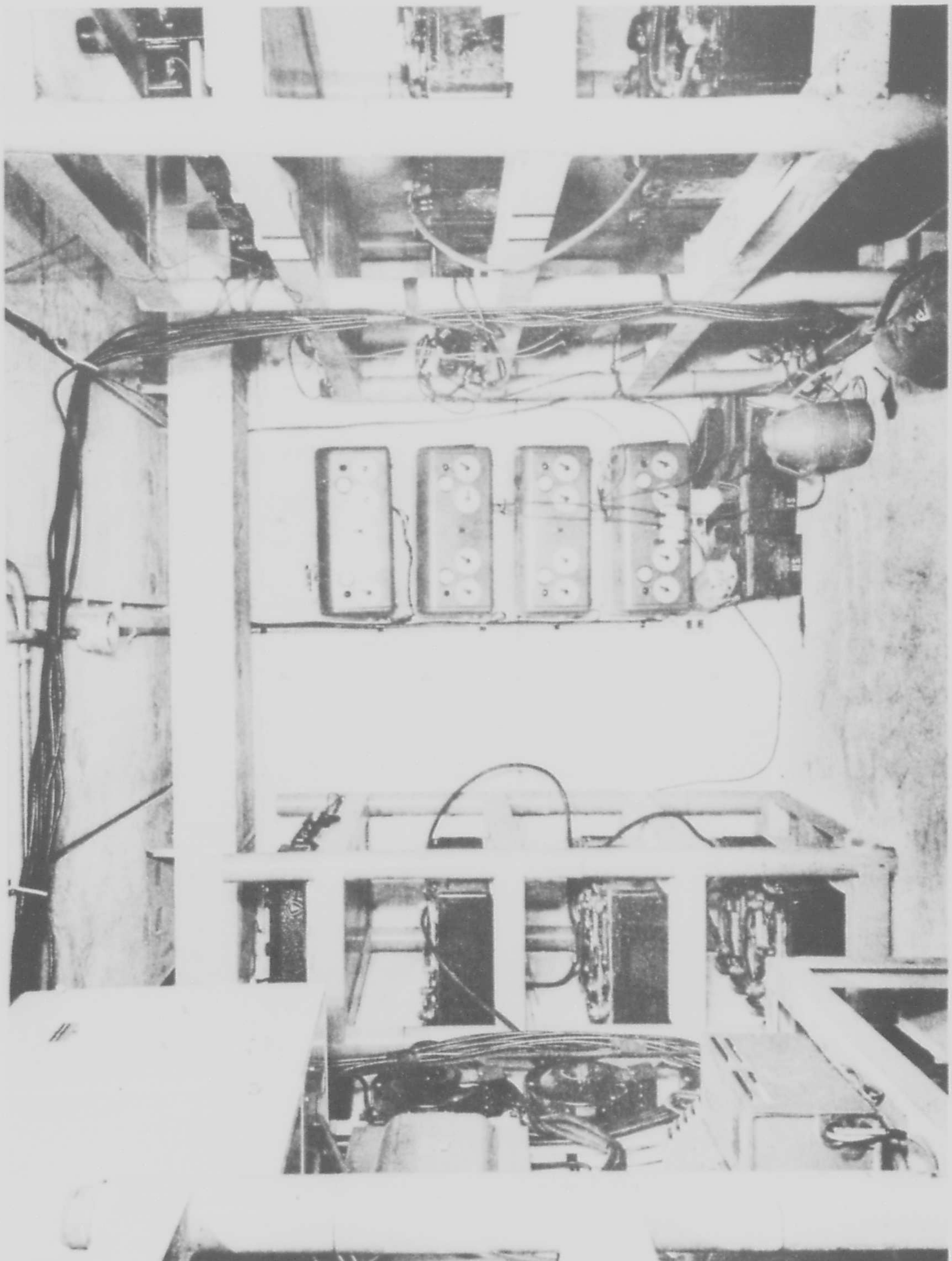

Fig. 9.3 Battery Racks in Blast Hut

FORMERLY RESTRICTED DATA
HANDLE AS RESTRICTED DATA IN
FOREIGN DISSEMINATION
SECTION 144b, ATOMIC ENERGY ACT 1954

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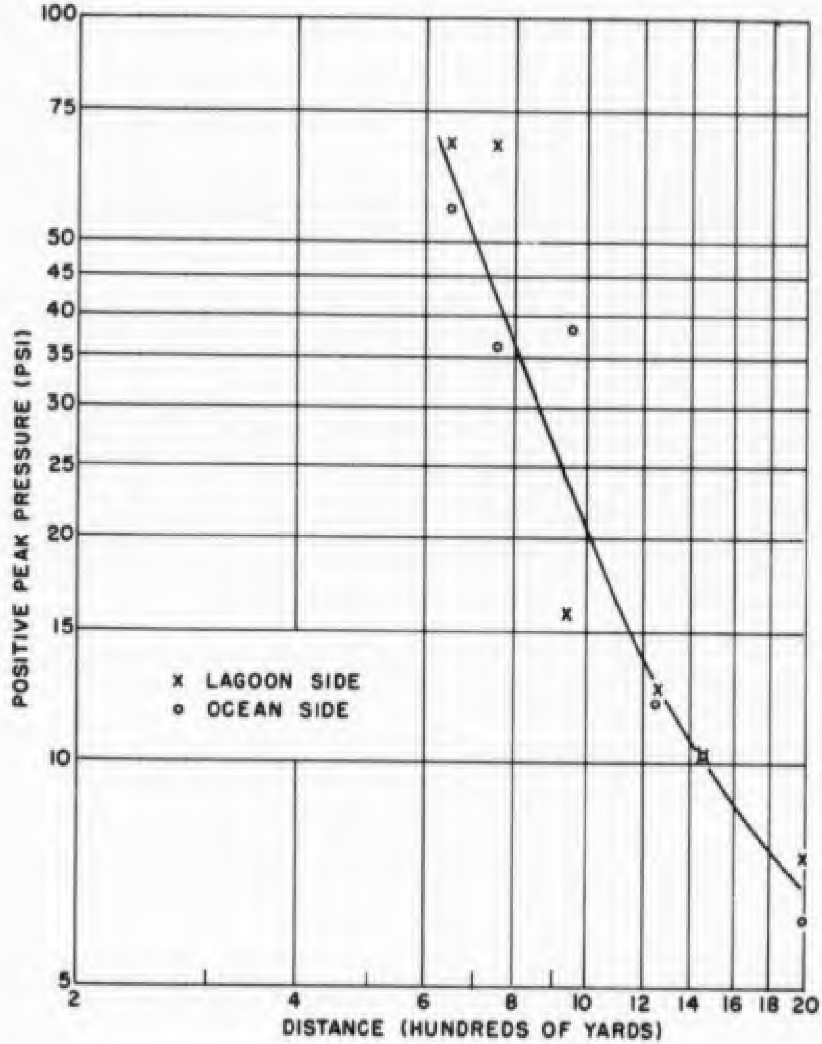

Fig. 9.4 Maximum Positive Pressure, Test Dog

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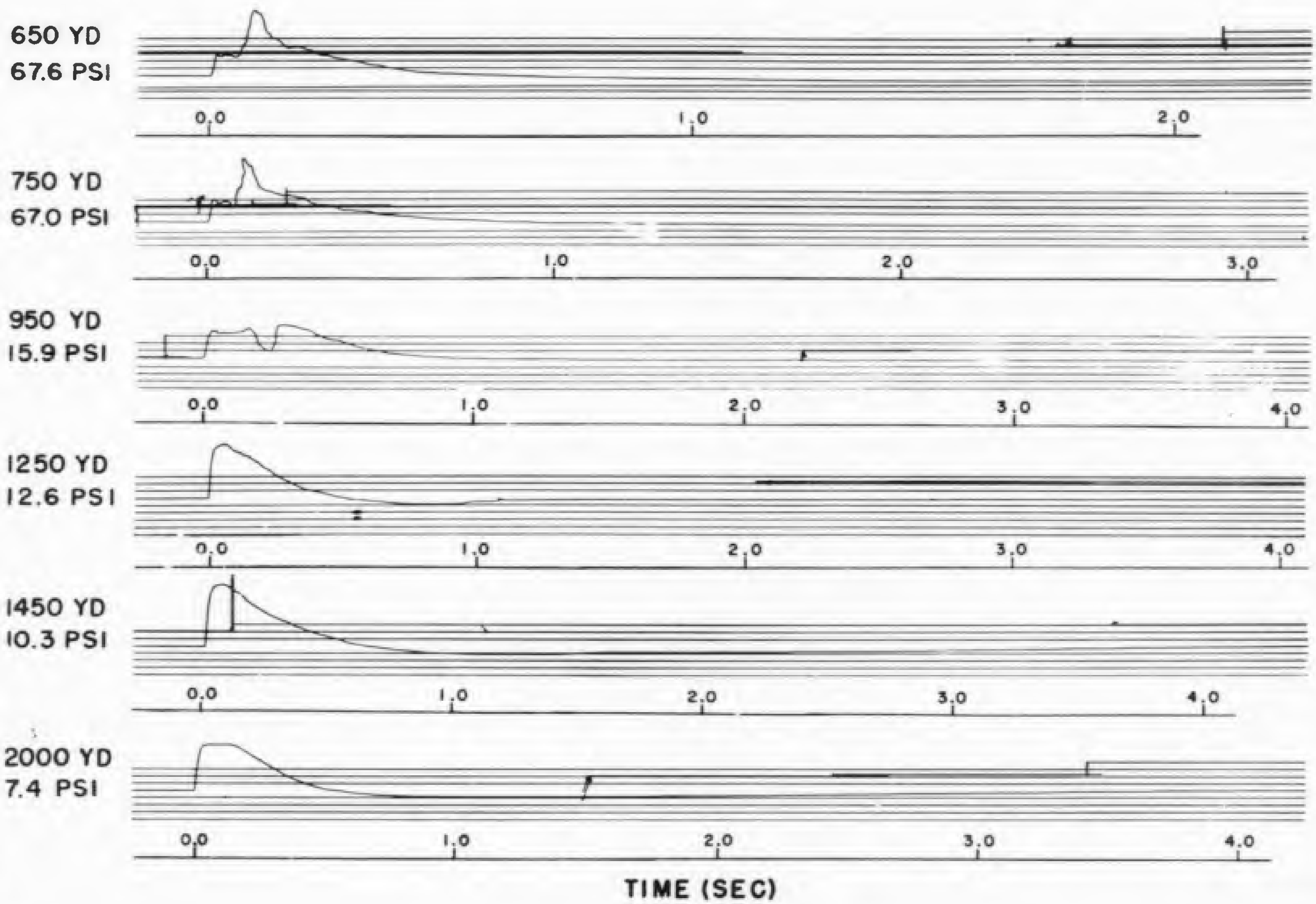

Fig. 9.5 Pressure-Time Records, Test Dog, Lagoon Side

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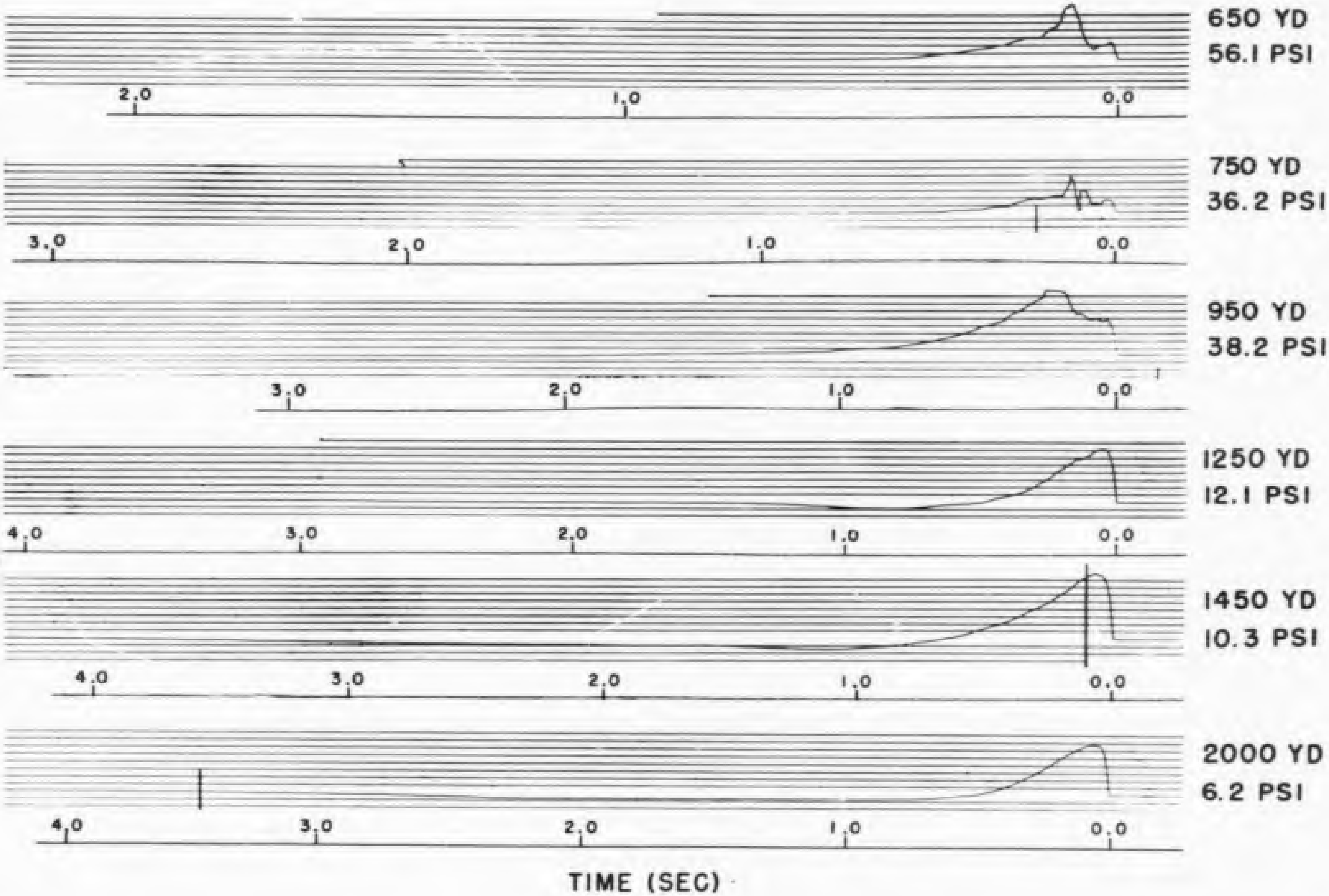

Fig. 9.6 Pressure-Time Records, Test Dog, Ocean Side

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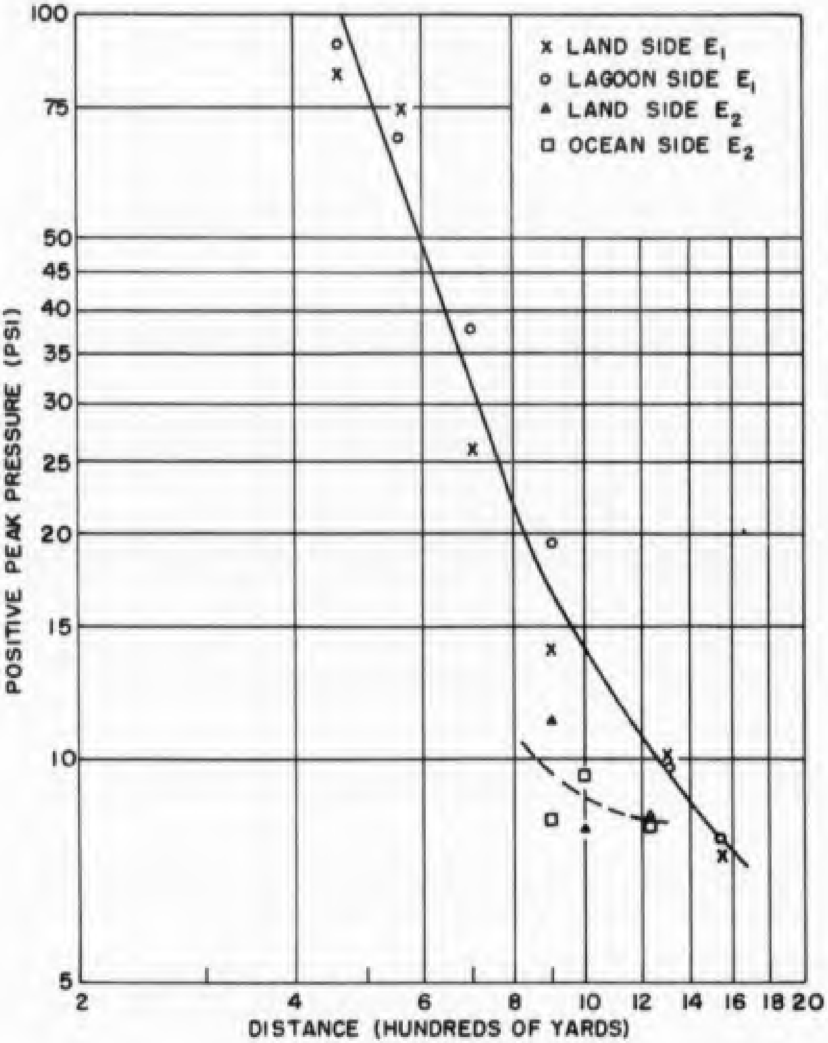

Fig. 9.7 Maximum Positive Pressure, Test Easy

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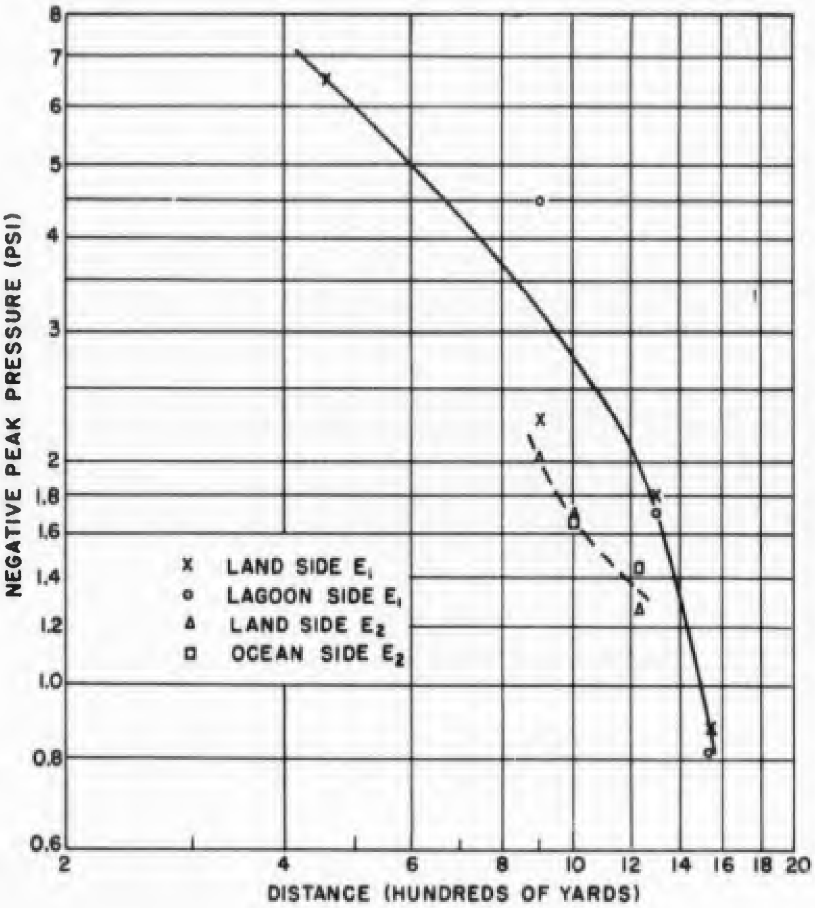

Fig. 9.8 Maximum Negative Pressure, Test Easy

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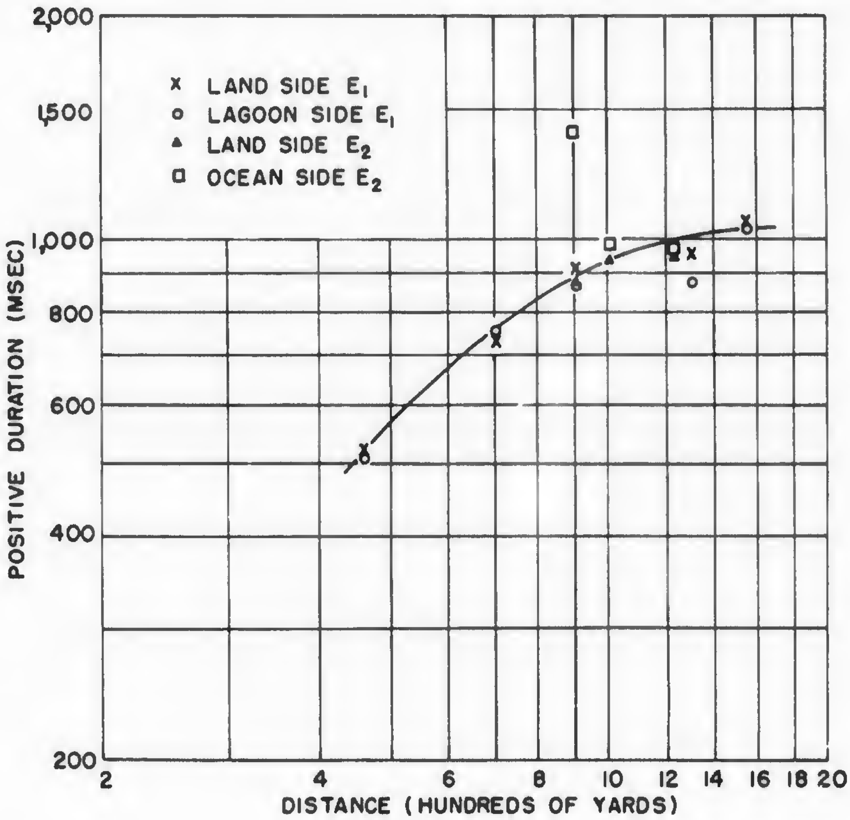

Fig. 9.9 Positive Duration, Test Easy

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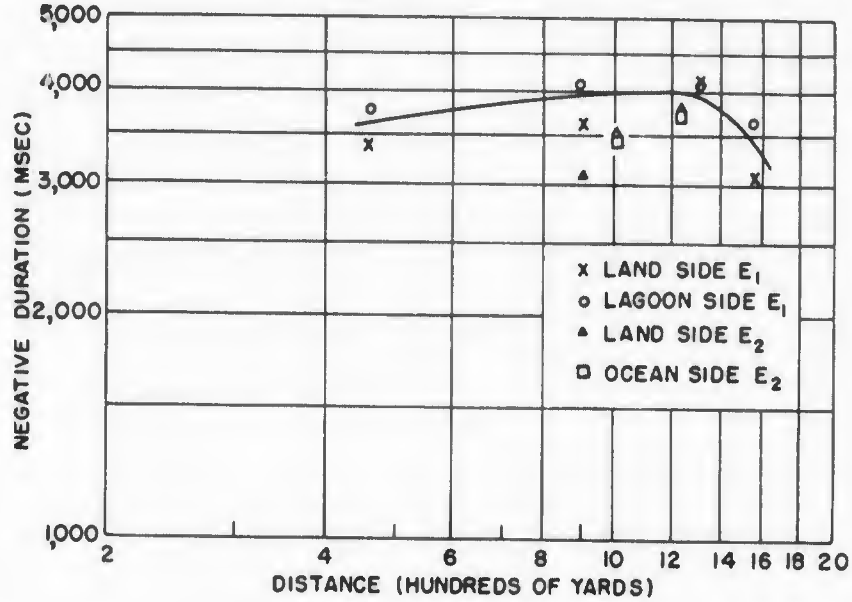

Fig. 9.10 Negative Duration, Test Easy

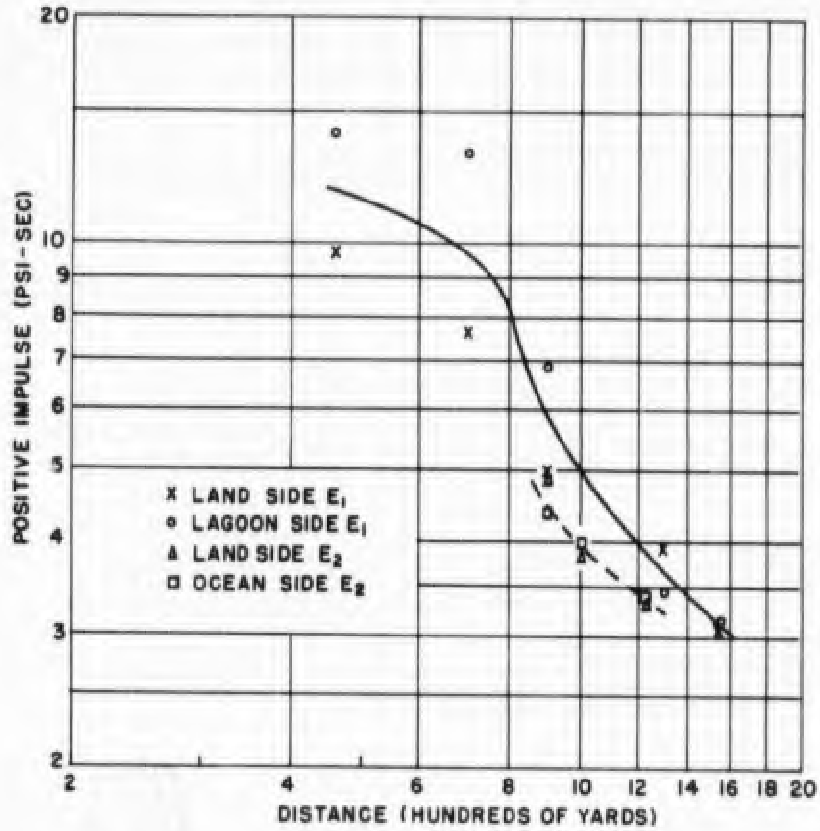

Fig. 9.11 Positive Impulse, Test Easy

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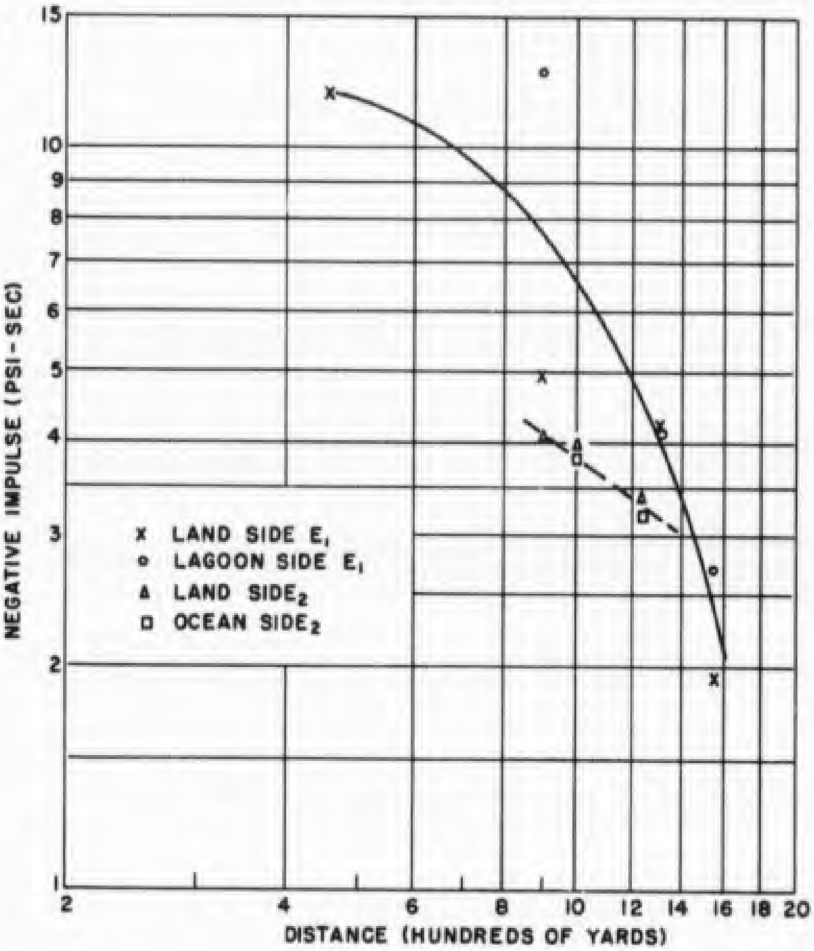

Fig. 9.12 Negative Impulse, Test Easy

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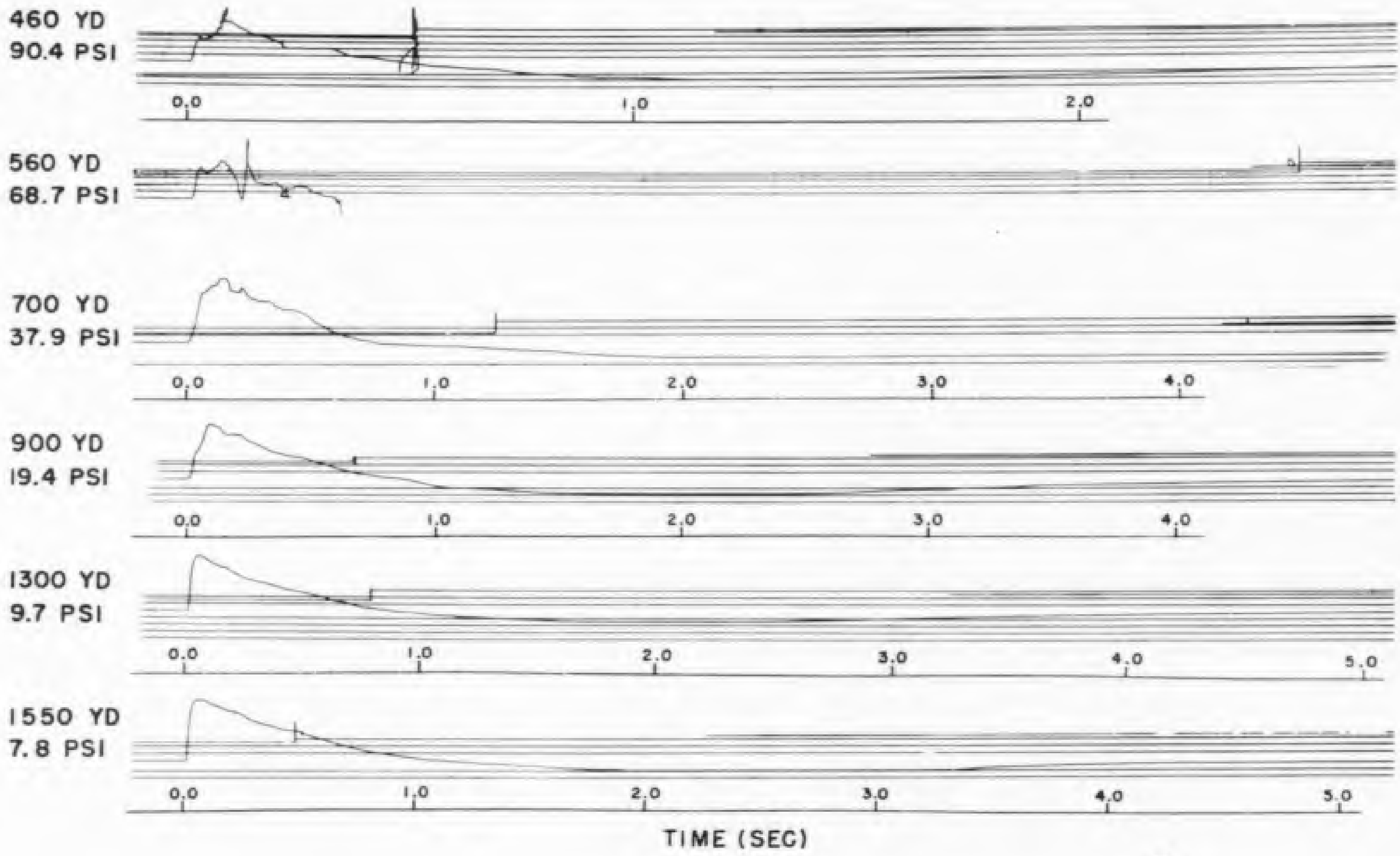

Fig. 9.13 Pressure-Time Records, Test Easy, E_1, Lagoon Side

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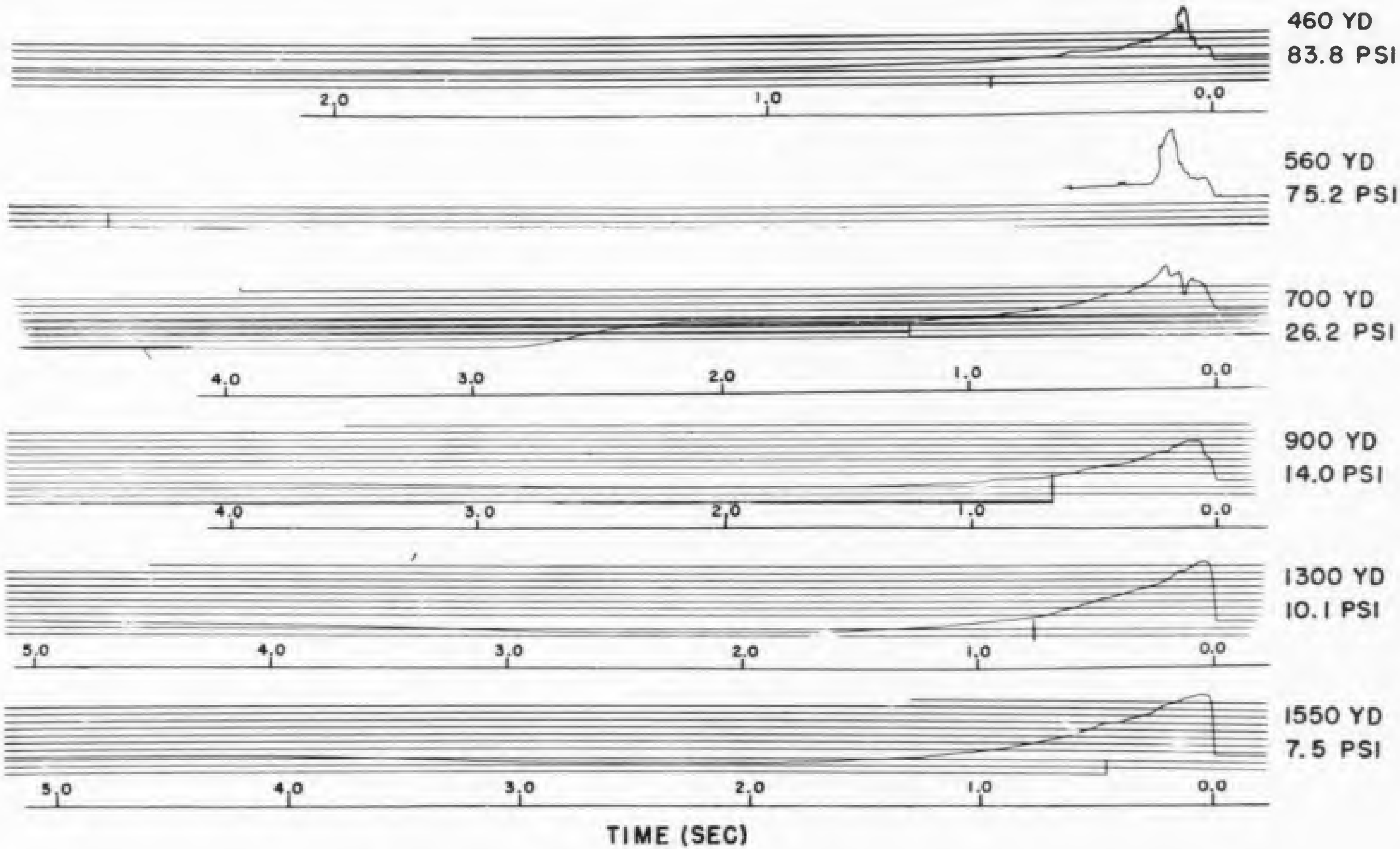

Fig. 9.14 Pressure-Time Records, Test Easy, E_1, Land Side

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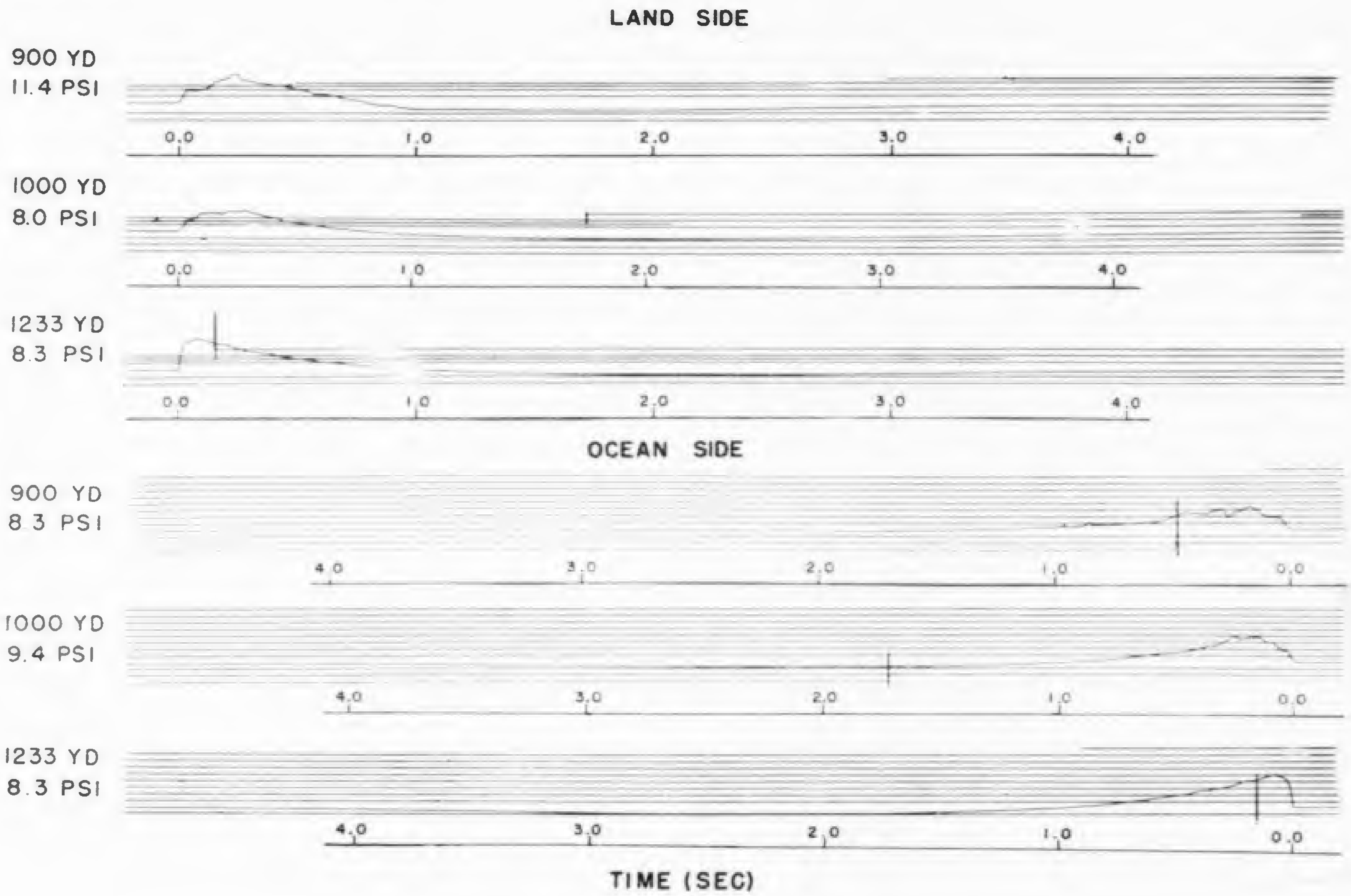

Fig. 9.15 Pressure-Time Records, Test Easy, E_2, Land and Ocean Sides