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MEASUREMENT OF EFFECTS ON THE GORGE POWERHOUSE AND ITS EQUIPMENT AND TUNNELS DURING BLASTING IN THE ADJACENT ROCK FOR THE DEPARTMENT OF LIGHTING CITY OF SEATTLE, WASHINGTON

Structural Research Laboratory Report No. SP-24

RESEARCH AND GEOLOGY DIVISION

BRANCH OF DESIGN AND CONSTRUCTION
DENVER, COLORADO

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Subject: Measurement of effects on the Gorge Powerhouse and its equipment and tunnels during blasting in the adjacent rock.

SUMMARY

In order to insure the integrity and uninterrupted operation of the Gorge Power Plant of the City of Seattle Skagit Project while blasting was being conducted on the adjacent rock, measurement of various effects at critical locations were made during the blasting, with the result that limits were set on the magnitude of individual blasts. The intent was to allow the maximum rate of blasting compatible with the safety of the structure and its contents and auxiliaries.

The purpose of the investigation was strictly utilitarian, directed toward determining the maximum safe rate of excavation on the project. The results are not adapted to wide generalization; on the contrary, they appear to indicate that the only feasible method of handling such a problem is by measurement and observation, rather than by analysis in advance of construction. The problem occurs frequently in civil engineering, however, and the present test methods and results may be useful in determining the pattern for future investigations of a similar nature.

Based on an interpretation of the measurements made, a schedule was drawn up stating the maximum quantity of explosive that could be used at any given station. The schedule was revised in accordance with additional data which became available as the work progressed. Although considerable scattering occurred in the correlation of effect to weight of explosive divided by distance squared, a concept of varying effectiveness was used to define an upper boundary of the effect at maximum transfer effectiveness, and therefore the relationship to be used in the establishment of a conservative schedule.

It was found that the size of the charge could be increased several fold if milli-second delays were used, and that for delays of the order of seconds the size of the total charge could be increased almost without limit due to the variation in actual time of detonation for delays of the same nominal time.

No structural damage was observed although certain annoying disturbances in the delicate apparatus of the control room did occur.

BACKGROUND

Since 1945, the Bureau of Reclamation has had an informal agreement of cooperative research with the Department of Lighting of the City of Seattle and the Coast and Geodetic Survey for determining the best methods of measuring the effects of blasting and earth tremors on dams, powerhouses, tunnels, and similar structures.

The development of methods and equipment by the Bureau of Reclamation has been directed toward the direct recording and measurement of those effects at critical locations that can be most readily interpreted in terms of safety, such as strain, stress, pressure, and relative motion. The feasibility of this approach was demonstrated by measurements made of the strain in the concrete of powder storage igloos during large blasts at Arco, Utah, and of the strain in the concrete of Barker Dam while a small tunnel was blasted through its base.

THE PROBLEM

In September of 1948, the services of the Bureau of Reclamation were requested by the administration of the Lighting Department of the City of Seattle to assist in insuring the safety of the Gorge hydroelectric power plant while blasting was being conducted to prepare the foundations and drive the penstock tunnel for an addition to that powerhouse. It was desired to maintain the powerhouse in uninterrupted operation during the blasting.

The Gorge Power Plant, the lowest and oldest of the developments on the Skagit River, is at an elevation of approximately 500 feet in the Cascade Mountains of Washington, approximately 100 miles northeast of Seattle. It rests on a rock foundation at the confluence of Ladder Creek and the Skagit River.

It was arranged between the Department of Lighting, City of Seattle, and the Branch of Design and Construction of the Bureau of Reclamation by means of a special contract, that the Bureau of Reclamation would conduct measurements of significant effects at critical locations during the progress of the blasting, in order to determine the maximum rate of blasting consistent with the safety of the powerhouse, its equipment and appurtenant tunnels. Inasmuch as the power plant was at a distance from any metropolitan center where equipment or materials could be secured, practically all of the equipment required for the tests was shipped from the Denver laboratories of the Bureau of Reclamation to the Gorge Power Plant.

The plant is served by three steel-lined penstock tunnels 11.25 feet in diameter and approximately 400 feet long. The manifold section joining the three branch tunnels with the main tunnel is lined with reinforced concrete. The main tunnel, extending 10,715 feet from the manifold section to the Gorge intake, is 20.5 feet in diameter and lined with unreinforced concrete.

The addition to the powerhouse was to be attached to the north end of the existing powerhouse, and an additional branch tunnel 16 to 18 feet in diameter was to be driven 674 feet through the rock to intersect the existing tunnel 210 feet upstream from the manifold section. The rock in which the blasting took place was continuous with the rock upon which the existing powerhouse was built. The addition had been contemplated in the design of the existing structure, and the north wall of the main generator room was built of timbers and stucco so that it could be easily removed. Figures 1 and 2 show the situation of the Gorge Power Plant with the building addition and the tunnel indicated. The operating room of the powerhouse was situated in the north end of the building closest to the blasting. The apparatus of the control room was rather old, being the original equipment installed in 1924, and was particularly vulnerable to vibrations caused by pressure waves transmitted through the air.

Blasting was started on the afternoon of October 11 with only five sticks of dynamite being used at Station 0+10 G.T., a distance of approximately 240 feet from the closest generator. As expected, the effects of the blast were small in comparison to the vibrations to which the building was constantly subjected by the operating equipment, and in fact could not be separated from these continuous vibrations in the records obtained. The sizes of the subsequent blasts were increased regularly until on November 28 it was considered that the load increase on the thrust bearing of Generator No. 23 due to blasting had reached what was probably a reasonable limit of 80 tons. As the measured load increase on this bearing was the first effect to reach a magnitude approaching what was considered to be a safe limit, this effect was used to compute the schedule of powder quantity versus station in the subsequent blasts. However, other effects such as rotor displacement, hydraulic pressure on the scroll case, strains in the concrete lining in the tunnel, and accelerations in the subbasement of the building closest to the blast, were recorded in order to detect any change in the nature of the blasting that might shift the location of the greatest hazard. Table 1 shows the schedule used up to November 9, 1948.

The table shows quantities up to 60 sticks of 60 percent dynamite for Station 2+10 P.H. At locations beyond Station 2+10 P.H. quantities larger than 60 sticks of dynamite were permitted but the maximum quantity of dynamite permitted in these cases was arrived at by using an extension of the table plus considerations involving the type of material being blasted and the proximity of other structures. Frequently the quantities of dynamite actually used were less than the maximum limit set because the limits exceeded the quantity that the blasters would have used in those particular cases regardless of limits. The largest single blast was 150 sticks on the G. T. line where a charge of more than twice that amount could have been tolerated. As expected, the effects were slight. However, near the powerhouse the size of the charges was more critical and did limit the quantities of explosives that would otherwise have been used.

From the dimensions of the thrust bearing, it was calculated that the effective area of the babbit bearing was 1,164 square inches. The estimated load supported by the bearing was 290,000 pounds, giving a total static load on the bearing of 250 pounds per square inch.

The load was measured in terms of the strain on the spider arms supporting the bearing. A calibration in terms of tons of total load on the bearing per inch of trace deflection on the oscillograph record was obtained by jacking the rotor to completely relieve the load on the thrust bearing, and then restoring the load by releasing the jacks.

It was found that the load on the thrust bearing reduced from 145 tons under static condition to approximately 90 tons when the machine was operating at its rated load of 20,000 kva. (Figure 3). Thus, an increase of 80 tons in the load as a consequence of the disturbance caused by blasting would increase the bearing load over the static condition by only 17 percent. During the first part of the investigation this was considered a safe upper limit upon which to base the calculations, recognizing the possibility of a combination of factors which might allow the effect of any one blast to exceed the effects of the average blasts by as much as 100 percent. On November 4, a communication was received by the City engineers from the Westinghouse Electric Corporation, manufacturer of the Kingsbury type thrust bearings used, indicating that the maximum load on the thrust bearing should not exceed 350 pounds per square inch during continuous operation and 525 pounds per square inch during blasting. They considered the critical factor to be not the unit loading on the bearing surface but the strength of critical sections at the upper bracket and thrust collar mounting. However, in spite of their reassurance, some concern was felt for the ability of the babbit of the thrust bearing to withstand shock loading of this magnitude.

MEASUREMENT OF THE LOAD ON THE THRUST BEARING OF GENERATOR NO. 23

The load on the thrust bearing was determined by measuring the bending of the arms of the spider supporting the bearing. This bending was measured by means of an SR-4 bonded resistance wire strain gage attached to the top surface of one of the spider arms (Figure 4). A similar gage mounted on a steel bar insulated from vibration and thermal effects by resilient paper wadding was used as the reference gage. The gages were connected to an amplifier by means of a shielded cable. The amplifier was of the carrier frequency type using a 1,000-cycle current applied to the bridge. The amplifier contained two legs of the bridge, the ratio of which was adjustable over a narrow range by means of a calibrated micrometer screw acting on a cantilever beam on the surfaces of which were cemented the gages comprising the bridge arms. A diagram of the amplifier circuits is shown by Figure 5.

A phenomenon which was observed but not definitely explained was the presence of a continuous nearly sinusoidal indication from the gage measuring thrust bearing load (See Figure 6). The amplitude of the signal correlated very well with the power generated by the machine (see Figure 7), but the frequency varied from day to day between 64 and 72 cycles per second with no apparent correlation with any condition of load, bearing temperature, or excitation. Tests showed that the signal was associated with actual strain and was not due to electrical pickup. The presence of vibrations of these frequencies could not be explained in terms of forced vibration due to action of the generator or the turbine wheel since they would have to be even multiples of the speed of the machine, which revolved at 257 rpm. The explanation that the vibrations were due to the periodic building up and breaking down of ridges of lubricant in one of the bearings was supported by previous studies Mr. Cutler had made of similar action in different type bearings. The condition may have been due all or in part to misalinement. Since the problem was not directly related to the purpose of the tests, no further investigation was made beyond that necessary to demonstrate that the vibrational strains were real and that the indications on the record were not the result of pickup or malfunction of the amplifying or recording apparatus. However, an investigation of this phenomenon might result in some information of value.

INSTALLATION OF CARLSON STRAIN GAGES IN THE TUNNEL

In order to measure the strain in the concrete lining of the tunnel, Carlson strain gages were fastened directly to the inside of the tunnel by means of mounting brackets, illustrated in Figure 8. To make the installation it was necessary to unwater the tunnel, which was begun on the evening of Saturday, October 9. The installation was complete and the tunnel sealed about 10:00 p.m. October 10, and the powerhouse went back on the line at 12:40 a.m. October 11. The brackets were fastened to the concrete by means of anchor bolts, using lead anchors. A solid steel mandrel the same diameter as the flanges of the strain gages was substituted for the gages during the time the bolt holes were being located and while the set screws were being adjusted in order that bending of the Carlson gage would not occur while it was being secured in place. Figure 9 shows the manner in which the gages were attached to the surface of the tunnel.

The leadwires were brought down through the tunnel to a manhole cover that opened upward into the low-tension alley of the powerhouse. The wires were clamped to a steel cable every few feet and the steel cable was supported to the tunnel roof about every 10 feet. The wires were brought through the manhole cover by means of specially-constructed bushings shown in Figure 10. The bushings extending from the top of the manhole cover are shown in Figure 11. The bushings were so constructed that no continuous insulation extended through the bushing and thus no piping of water through the insulation could occur even if the insulation in the cable in the tunnel were broken. During the first weeks of the investigation each strainmeter was connected to a strain amplifier and the amplified output recorded. Later when higher sensitivity galvanometers became available due to the discontinuance of the accelerometer recordings a unit was built containing separate bridges for the strainmeters (Figure 12). The outputs of these bridges were recorded without amplification.

Four gages were initially installed in the tunnel serving Unit 23: two on the ceiling of the tunnel just beyond the adit plug, one on the side wall of the tunnel near the adit plug, and one bridging the joint between the steel penstock lining and the steel transition section to the Johnson valve (see Figure 1). The gage at the transition failed first, apparently because of severance of the lead wires by water-borne debris. Another gage, on the ceiling of the tunnel, failed after 4 days. The gage on the adit wall failed next. The exact cause of failure was not determined for these two gages or for the final gage mounted on the ceiling, which remained in operation for 38 days. After that portion of the investigation performed by the Bureau was concluded, the City Light engineers installed a new set of Carlson strain gages in the tunnel. They routed the lead wires along the bottom of the tunnel to reduce the hazard to the cable. Their experience was that under similar conditions of blasting they obtained essentially the same indications as were obtained from the original gages, but that when the blasting was conducted in the new tunneling the magnitude of recorded strain was negligibly small until the blasting was within a few feet of the gages.

A sample oscillograph record of tunnel strain is shown as Figure 6. The largest strain recorded was 133 microinches per inch, corresponding to approximately 400 psi assuming a modulus of elasticity for the concrete of $3x10^6$. As this stress was not considered critical, it did not constitute a limiting factor in determining the permissible size of the charges.

PRESSURE MEASUREMENTS

The hydraulic pressure in the scroll case of the wheel on Generator No. 23 was recorded by means of an electric pressure cell. The cell consists of a chamber connected by means of a tube to the source of pressure to be measured (Figure 13). One wall of the chamber is a diaphragm, and movement of this diaphragm causes an iron armature to displace between two coils. The coils constitute two arms of a 2,000-cycles-per-second a-c bridge so that the changes in inductive impedance caused by the movement of the armature cause changes in the output of the bridge. The a-c current is rectified to a signal proportional to the pressure by means of a phase-sensitive circuit so that the sense of the pressure change is preserved.

The pressure increases observed during blasting were not great enough to cause concern for the safety of the installation. The maximum pressure increase was 39 pounds per square inch. Figure 6 shows a typical record.

DISPLACEMENT OF ROTOR WITH RESPECT TO STATOR

In order to determine the vertical movement of the generator rotor with respect to the stator during blasting, a gage was devised using the coil assembly from one of the hydraulic pressure cells. The coil assembly was mounted on a bracket connected to the bottom stator supports in such a way that the air gap between the coil assembly and the top surface of the coupling cover varied as the rotor shaft displaced vertically with respect to the stator (Figure 14). It was found necessary to smooth the top surface of the coupling cover to reduce the variations during the rotation of the shaft. This smoothing was done with a rigidly supported portable electric grinder while the machine was in operation. The coil was made part of a bridge circuit in such a way that the output of the bridge depended on the air gap between the coil and the coupling cover. The output of the bridge was fed into one of the oscillograph galvanometers. Thus a displacement of the rotor with respect to the stator resulted in a deflection of one of the traces on the oscillograph record. A typical displacement trace is shown in Figure 6.

The displacement record was calibrated by jacking the rotor of the generator, measuring the displacement with a micrometer, and making a short record of the galvanometer trace displacement. The calibration factor was found to be 1.0 inch deflection on the record for each 0.020 inch displacement of the rotor shaft. The correlation between the rotor shaft displacement and the thrust bearing load measured statically is shown as Figure 15. The correlation of the rotor shaft displacement and thrust bearing load measured dynamically is shown in Figure 16. For the static condition a change of 50 tons on the bearing corresponded to a deflection of .016 inch while the same change in bearing load corresponded to only .008 inch measured dynamically.

The difference in the correlation factors can be accounted for in considering the difference in stress in the supporting members under the two conditions of load. When the load was removed from the thrust bearing by means of jacking, the point at which the jacks acted was near the point of deflection measurements; consequently, most of the rotor shaft involved was relieved of its tensile stress and actually placed in compression, so the change in strain of the shaft is added to the displacement. Possibly there was additional deflection in the supports to which the deflection gage was attached due to the action of the jacks. During dynamic loading the rotor acted as a seismic mass with increased load on the bearing resulting in increased tensile stress in the shaft, and the resulting strain then subtracts from the measured deflection. Any action of a hydraulic pulse on the wheel acting to increase the load would increase this tension.

MEASUREMENT OF STRAIN IN PENSTOCK

In order to measure the strains that occurred in the steel portion of the penstock exposed between the Johnson valves and that portion embedded in the concrete of the building, two SR-4 gages were installed on the outside surface of the penstock. One gage was oriented parallel to the axis of the penstock and the other gage was at right angles to the axis so that in effect the former gage would measure those strains resulting from stresses due to differences in the motion of the embedded portion of the penstock and the portion including the Johnson valve, scroll case, etc. The maximum strain measured at this point was 18 microinches per inch, corresponding to a stress of 540 psi, for a charge of 28 pounds of dynamite located at station 2/02. This stress was not considered significant, so this measurement was discontinued on October 30.

The gage mounted at right angles to the axis of the tunnel (or circumferentially) was sensitive to the expansion of the tunnel and therefore to changes of pressure of the water in the tunnel. The strains thus measured corresponded reasonably well to those calculated from increases in pressure of the water in the tunnel as measured by the pressure cell described previously. Therefore, after sufficient tests were made to determine that the correlation was reasonable, the recording of these strains was discontinued.

MEASUREMENT OF ACCELERATIONS AT GENERATOR NO. 23

A three-component carbon pile accelerometer, having a natural frequency of approximately 25 cycles per second, was located on the thrust bearing support spider of Generator No. 23 (Figure 17). A relay was used to permit closing the battery circuit from the location of the recording oscillograph. The output of the accelerometers was brought to the recording oscillograph and records were made up to October 30. The accelerations due to the blasts were smaller than those due to the vibrations of the machine operating in its normal fashion until the charges exceeded 6 pounds at a distance of 80 feet. Even with the largest blasts, the accelerations did not exceed three times the accelerations due to operation, and consequently it was considered impractical to attempt an interpretation of the record since the contribution of the normal vibrations could not be separated from the composite record with any reasonable accuracy.

An analysis of records taken on October 25 indicated that there was a reasonable correlation between the vertical component of acceleration measured at the thrust bearing of the machine and the increase in bearing load as measured by means of the strain in the support spider. For instance, record No. 422, which gave one of the most readable vertical acceleration records, indicated a vertical acceleration maximum of 0.275 g during the blast. The corresponding increase in measured bearing load was 38 tons. The increase in bearing load calculated as the reaction between the support accelerating at 0.275 g and the rotor acting as a seismic mass of 145 tons was 40 tons.

The accelerations recorded were very near the natural frequency of the accelerometer, 25 cycles per second, and consequently the calibration of the accelerometer in this range was very dependent on the damping.

The damping was by means of dash pots using a viscous fluid, and therefore was dependent on temperature. Lack of temperature control gave the measurements a low accuracy.

Since the measurement of bearing load by means of the increase in spider strain was a more direct measure of the forces acting on the bearing and was considered more reliable, the recording of acceleration at the bearing was discontinued in favor of recording penstock pressure and relative vertical motion between the rotor and stator.

DETERMINATION OF MAXIMUM FREQUENCY OF VIBRATIONS

An answer to the question of the maximum frequency at which energy was being transmitted to the powerhouse structures as a result of the blasting was obtained by means of a crystal acceleration pickup, a cathode ray oscilloscope, and a drum camera by which records were obtained of the trace on the oscilloscope screen produced by the crystal pickup. This combination would record accelerations up to the natural frequency of the crystal, which was 1,000 cycles per second, and displacements up to the limit of the oscilloscope amplifiers, which was 70,000 cycles per second. Thus, some record of vibrations at frequencies up to 70,000 cycles per second could be obtained with this apparatus. Figure 18 shows the apparatus set up in the Gorge Power Plant. However, the highest frequency component on the traces actually recorded was approximately 780 cycles per second. The point chosen for the measurement of these vibrations was the manhole cover on the penstock supplying Generator No. 23 (Figure 11). The location was chosen because the steel on the penstock at this point was mechanically coupled to the foundation rock, the building, and the water in the tunnel, and it seemed reasonable to assume that any vibrations reaching critical points in the powerhouse would have some component at this point. The information thus obtained was used as a criterion for determining the maximum frequency sensitivity to which the other elements would be carried. Because frequency response is obtained with recording galvanometers at the expense of sensitivity, it was decided to limit the upper frequency response of the other instrumentation to 1,000 cycles per second, a value just beyond the highest frequency to be expected.

LOCATION OF THE RECORDING INSTRUMENTS

After a brief survey of the problem, it was decided to locate the amplifying and recording equipment in the low-tension alley of the powerhouse. The bay in the low-tension alley containing the bus switches for Generator Unit No. 23 was chosen for the location of the amplifying and recording equipment. The reasons for this choice were proximity to the points at which pickups were to be placed, relatively low noise level, proximity to an oil filtration and storage room that could be used as a darkroom, and minimum interference with the normal traffic and operation of the powerhouse. The principal disadvantage of the location was the presence of overhead conductors carrying large currents which resulted in strong a-c magnetic fields in the area. It was found impractical to provide sufficient magnetic shielding for the transformers in the strain amplifiers, so the a-c pickup from the magnetic fields was reduced to a minimum by properly orienting the amplifiers. Thus, it was found necessary to have the amplifiers standing askew on end (Figure 19) rather than in their normal horizontal position (Figure 20). It was necessary to change the orientation from time to time as the current in the conductors was changed in adjusting the operation of the powerhouse to the power demands. Another disadvantage was the safety hazard due to the presence of the bus switches which were quite old. There had been instances when similar switches had failed with explosive violence. The risk was assumed to be small. However, during the conduct of the tests a similar switch in another bay did fail, splattering hot oil over that area.

MEASUREMENT OF MOVEMENT ACROSS CRACKS AND JOINTS IN THE BUILDING

In order to insure the safety of the powerhouse building during the blasting, an inspection of the building was made to locate the apparent points of weakness, and attention was concentrated on these points.

The western half of the north wall, closest to the open cut blasting, was of temporary timber and stucco construction, whereas the remainder of the structure was of reinforced concrete. The plans of the building showed that the temporary wall was tied into the permanent structure by tie bolts at the level of the crane rail. Where the temporary and permanent sections joined, a crack extended from the ceiling on both walls down to about 10 feet from the operating floor. The crack width was about 1/8 to 1/4 inch near the ceiling and narrowed gradually until it was no longer visible at about 10 feet from the floor.

DeForest scratch gages were installed across these cracks at the level of the crane rail.

The only other crack that appeared at all serious was located on the center partition wall near its south end. The crack was about 1/8 inch wide near the ceiling and extended downward toward the corner of the intersection of the partition wall and the south wall of the powerhouse, diminishing in width as it went down. A DeForest scratch gage was installed across this crack about 8 feet from the ceiling.

The DeForest scratch gage consists simply of a lightweight brass arm with an abrasive tip that bears against the polished surface of a small target in such a way that relative motion between the arm and the target is recorded in the form of a scratch on the polished surface of the target (Figure 21). The arm is held in contact with the target by means of a slot in the target plate. The slot allows the arm to move transversely over the width of the target surface and also longitudinally in an arc over the length of the target, which is approximately 1/2 inch. Initially the arm is bent away from its center position in an arc, and in the absence of vibration it will not move. However, when motion between the arm and target occurs the arm, in addition to moving in the direction of the strain, migrates toward the center of the target; so that, in effect, the separate vibrations are recorded on different parts of the target to give a crude time axis. There was some difficulty in adjusting the tension on the arms so that there would be no migration of the arm toward the center of the target due to the normal vibration in the building, and yet that the desired migration would take place during the slightly larger vibrations attending the blasting.

During the early part of the blasting, these gages indicated movement of 0.1 inch across the crack between the temporary and permanent sections. This was considered excessive for the small-size blasts that were being used. As a result, workmen were directed to break open small sections of the wall to gain access to the nuts securing the tie bolts anchored in the reinforced concrete section to the bearing plates in the timber section. It was found that the nuts were loose on the bolts, apparently due to shrinkage of the timbers and possibly also to sustained vibrations. The nuts were tightened down and no movements greater than 0.01 inch were observed during subsequent blasts, even though the size of the blasts was greatly increased. There was no definite evidence of movement across the crack near the south wall.

The scratch records were observed with a five power glass (Linen tester) and measurements made with a steel scale divided to 1/100ths of an inch.

In addition to the use of scratch gages, regular inspections were made of certain locations in the building which appeared vulnerable. These included the north portions of the parapet wall on the roof and certain cracks in the basement. As an aid to observation, existing cracks that had discontinuities were selected, and the limits of the cracks were marked and dated. However, no extensions of the existing cracks were noted and no new cracks were observed.

INSTALLATION AND MODIFICATION OF THE ACCELEROGRAPH

The City of Seattle purchased from the Peters Company of Washington, D. C. two Type S2 three-component strong-motion accelerographs to be located in Ross Dam and on the right abutment of Ross Dam. At the time that the Bureau tests were being conducted, the accelerographs were in the warehouse at Newhalem. The sites were not yet prepared at the dam, so it was decided by Mr. Cutler that one of the accelerographs would be installed temporarily in the Gorge Powerhouse in order to record the accelerations produced in the building due to the blasting. Consequently, one of the instruments was uncrated and installed in the subbasement in the corner of the powerhouse closest to the blasting. The instrument was calibrated by tilting to calculated angles, and it was found that the three accelerometers had approximately the same sensitivity of 10 percent of gravity for a 1-inch deflection on the record. In the first records obtained from the accelerograph, the vibrations decayed slowly, indicating a damping rate for the structure very much lower than was expected or in fact indicated by any of our other instruments. It was suspected that the trouble was due to the vibration of the plate on which the accelerometers were supported, and to test this supposition the space between the mounting plate and the base plate was filled with plaster. This, however, reduced the persistency of the vibrations by only a small degree, and time did not permit a complete solution of the problem. However, it was determined that the individual accelerometers had a damping factor of at least 10 and that the sustained vibrations were real, but since the instrument was to be used only in a relative manner for control purposes, this problem was considered unimportant. The slowly damped vibrations were suspected as being due to a nearby structural column.

The self-starting features of the accelerograph were not used since a delay of approximately 1/4-second occurred between the reception of the first strong motion and the beginning of the record. This delay, although tolerable in the recording of earthquake phenomena, was greater than the total duration of the vibrations caused by blasting and was therefore prohibitive. Instead, the instrument was wired for remote starting with the starter switch located next to the switch used for initiating the blasts. Thus, the City Light inspector who fired the blasts could start the accelerograph a few seconds before he fired the shot. The operation of the accelerograph was modified so that after starting it would run continuously for 18 seconds and then stop. A set of four oscillograph galvanometers and a light source were installed in the accelerograph so as to record on the same chart as the accelerometers. The galvanometers were connected to the outputs of Wheatstone bridges containing Carlson strain gages as their active arms, so that a record of the strains in the tunnel lining and on the spider supporting the thrust-bearing of Generator No. 23 could be obtained. This arrangement was not as satisfactory as desired, in that a considerable spurious trace deflection was obtained due to vibrations in the lamp support and galvanometers. Of course, it was impossible to insulate the accelerograph from these vibrations, since they constituted a part of the accelerograph record. Another shortcoming was that the paper speed of the accelerograph was too slow to resolve the individual waves of the phenomena recorded.

The commutator that determined the length of each accelerograph record was removed and a similar commutator having twice as many contacts was installed in order to keep lengths of record short and conserve paper. No recording paper was supplied with the instrument. In order to place the instrument in operation an adapter was made so that the 10-inch Linagraph paper used on the Hathaway oscillograph could be used in place of the regular 12-inch paper. To find the actual acceleration from its three components, the formula $A = \sqrt{A_L^2 + A_T^2 + A_V^2}$ was used, with the maximum amplitude of the longitudinal, transverse and vertical accelerations used for A_L, A_T, A_V, respectively. The resolution of the individual waves on the trace was not sufficient to take into account the phase differences that may have existed between the components of acceleration, and no practical method was available to increase the paper speed to give sufficient resolution. Consequently, the value of the computed accelerations represented an upper limit to the possible values of the acceleration, rather than the true values.

INCIDENTAL DAMAGE IN POWERHOUSE

The damage done to the contents of the powerhouse was confined to that part of the building closest to the blasting. The damage can be summarized as follows: The switches on the electric motors of the lubrication oil pumps in the subbasement fell open on several occasions. A cover glass on the governor indicator pedestal of Generator No. 23 fell out and broke on the floor. Indicating targets on the overload relays in the control room fell without the relays actually operating. The operation of the voltage regulators was disturbed on two occasions and the over-voltage breaker on Generator No. 22 fell open on one occasion. In every case the incidents could be explained by the direct action of the vibrations on an insecurely held part of the apparatus involved. Only in one case did actual damage result from these maloperations. That was the incident of November 10 when the overvoltage relay on Generator No. 22 opened. When the operator disconnected the generator from the low voltage bus the circuit breakers did not break cleanly but blew the bushing out of the switch on one phase and burned the contacts on two phases. This damage was not directly due to the blasting since the breaker should have handled the load without damage.

The other effects measured and the effects observed in the control room correlated only very approximately, and it appeared that the effects in the control room were due not so much to accelerations imparted to the building through its foundations as to the acceleration of the control panels directly by the pressure waves in the air.

Probably the best measure of the accelerations imparted to the control panels and associated equipment in the powerhouse control room was in the number of targets which fell on the integrating type overload relays. The number of targets that fell varied between 0 and 18. Inasmuch as a probability factor related the number of targets that fell to the accelerations present, and a different probability factor related the accelerations and the disturbance of other components, an exact correlation between the number of targets that fell and the number of other effects that occurred could not be expected. However, the number of targets that fell did indicate a trend as shown in Table 2. The falling of the targets indicated no more than that the target arms were moved by the action of the vibrations far enough from their quasi-stable position so that the action of gravity caused them to fall. There was no indication of any other action in the relays.

THE EFFECT OF THE USE OF DELAYS IN BLASTING

All of the blasting conducted prior to November 12 was done using instantaneous blasting caps wired together so that the whole charge went off simultaneously. When it became obvious that the size of the charges would have to be reduced below practical limits in the area closest to the powerhouse, the use of delays was investigated. At first, numbered delay caps were used, where the nominal delay of a cap in seconds is the number of the cap. Thus a Number 3 cap has a nominal delay of 3 seconds. When such caps were used, the measured effects were negligible and from the record it could be seen that there was sufficient variation in the actual time of detonation for caps with the same nominal delay that the actual detonations were separated far enough in time so that their effects were not additive. Thus, it appeared that the size of the charges could be increased practically without limit if this type of delay were used. However, the fracture of the rock was poor when these delays were used and consequently faster delays were investigated. The type of blasting cap designated by letters A, B, C, have a nominal delay of 1/2 of a millisecond per letter. Thus, an A cap has a nominal delay of 0.0005 seconds and a Type C cap has a delay of 0.0015 seconds. While the effects measured when blasting was done with these delays were greater than the effects when the longer delays were used, the effects were still very much less than those obtained with similar size charges using instantaneous fuses, and the fracturing of the rock was at least equal to if not superior to that obtained by instantaneous fuses. Consequently, subsequent to November 14 all of the shooting near the powerhouse was done with the millisecond delays.

CONCLUSIONS

It was apparent from all of the attempts that were made to correlate the magnitude of the effects measured with the size and location of the charges used that no simple relationship existed and that a correlation would have to include the condition of the rock, the effectiveness of the charges in breaking the rock, and a much more accurate description of the disposition of the charges than was actually obtained. In order to arrive at some working limits, the scattered data were considered to define an area the upper limit of which related the magnitude of the effect to the size and location of the charge under conditions favoring maximum transfer effectiveness. Figure 22 shows the relationship between the measured bearing loads and the size of the charge divided by D^2, where D is the distance from the center of the charged area to Generator No. 23. The justification for using this relationship was that the total charge was composed of a number of holes, each of which was loaded with approximately the same weight of powder, usually 1-1/2 sticks or 3/4 of a pound. Thus the effectiveness of the total charge was considered to be proportional to the simple sum of the individual charges rather than to the cube root of the mass of the powder, as is used where the variant is the size of the single charge. The effect of diffraction on the summation of the several single charges at the distance where the effects were measured was calculated and found to be negligibly small for the conditions obtaining. The D^2 factor was justified on the assumption that the energy would be propagated equally in all directions and that the effect at a point would be proportional to the energy reaching that point. No attempt will be made to further justify this assumption, other than that it fitted the data as well as, or better than, any of the other relationships tested.

It was apparent that the constant of proportionality entering into the relationship between the magnitude of the effect at any point and the size and location of the explosive charge could best be arrived at empirically. At the present state of the art our knowledge of the factors affecting the transfer of energy through materials is too meager to allow the solution of a problem of this complexity by purely theoretical methods. However, instruments and techniques are available with which the magnitude and character of the effects can be determined for conservative charges and from these measurements the magnitude of the effects for larger charges can be predicted with reasonable accuracy.

TABLE 1

SCHEDULE OF MAXIMUM POWDER QUANTITY
PERMITTED AT ANY STATION

Station on PH Line	Powder in sticks of 60% Dynamite	Distance to Generator No. 23
2 ≠ 10	60	90 ft.
2 ≠ 23	56	77 ft.
2 ≠ 28	48	72 ft.
2 ≠ 33	40	67 ft.
2 ≠ 38	32	62 ft.
2 ≠ 43	25	57 ft.
2 ≠ 48	20	52 ft.

Larger quantities permitted beyond station
2 ≠ 10 computed for each location

<u>TABLE 2</u>

Relay Targets Tripped and Incidental Damage
Done by Blasting

November	3	No Targets	No damage	2:12 pm
November	3	No Targets	No damage	3:03 pm
"	3	5 Targets dropped	Lube. oil pumps dropped out	3:10 pm
"	3	1 Target dropped	glass on Gen. No. 23 pedestal knocked off.	10:09 pm
"	4	No targets		9:40 am
"	4	2 Targets	No damage	4:15 pm
"	4	No Targets		10:50 pm
"	4	No Targets		11:06 pm
"	5	6 Targets	No damage	10:26 am
"	5	9 Targets	Lube pumps out	12:04 pm
"	5	11 Targets	Lube pumps out	1:58 pm
"	5	7 Targets	No damage	3:50 pm
"	5	2 Targets	No damage	6:20 pm
"	5	No Targets	Boulder into carpenter shop	11:55 pm
"	6	6 Targets	Lube pumps out Glass window out	9:05 am
"	6	2 Targets	No damage	8:00 pm
"	6	8 Targets	Lube pumps out Window blown out	11:55 pm
"	7	7 Targets	No damage	2:00 pm
"	7	4 Targets	No damage	11:26 pm
"	8	13 Targets	No damage	9:30 am
"	8	1 Target	Blast close under window	4:45 pm

November	9	5 Targets	No damage	1:18 pm
"	9	1 Target	No damage	6:55 pm
"	10	10 Targets	Lube pumps out Generator No. 23 Voltage regulator broken.	8:33 am
"	10	18 Targets,	Over voltage brkr. on Gen. No. 22 Opened by blast.	4:05 pm
"	10	2 Targets	Close to bldg.	9:54 pm
"	11	13 Targets	No damage	3:03 pm
"	11	7 Targets	Knocked out lube oil pump	11:55 pm
"	12	1 Target	Light blast no damage	11:25 am
"	13	9 Targets	No damage	1:32 pm
"	14	9 Targets	No damage	11:00 am
"	14	11 Targets	RKVA to zero on Gen. No. 21 RKVA to full scale on Gen. No. 22&23 Voltage Regulator on No. 21 Broken	1:05 pm
"	15	2 Targets	No damage	12:05 pm

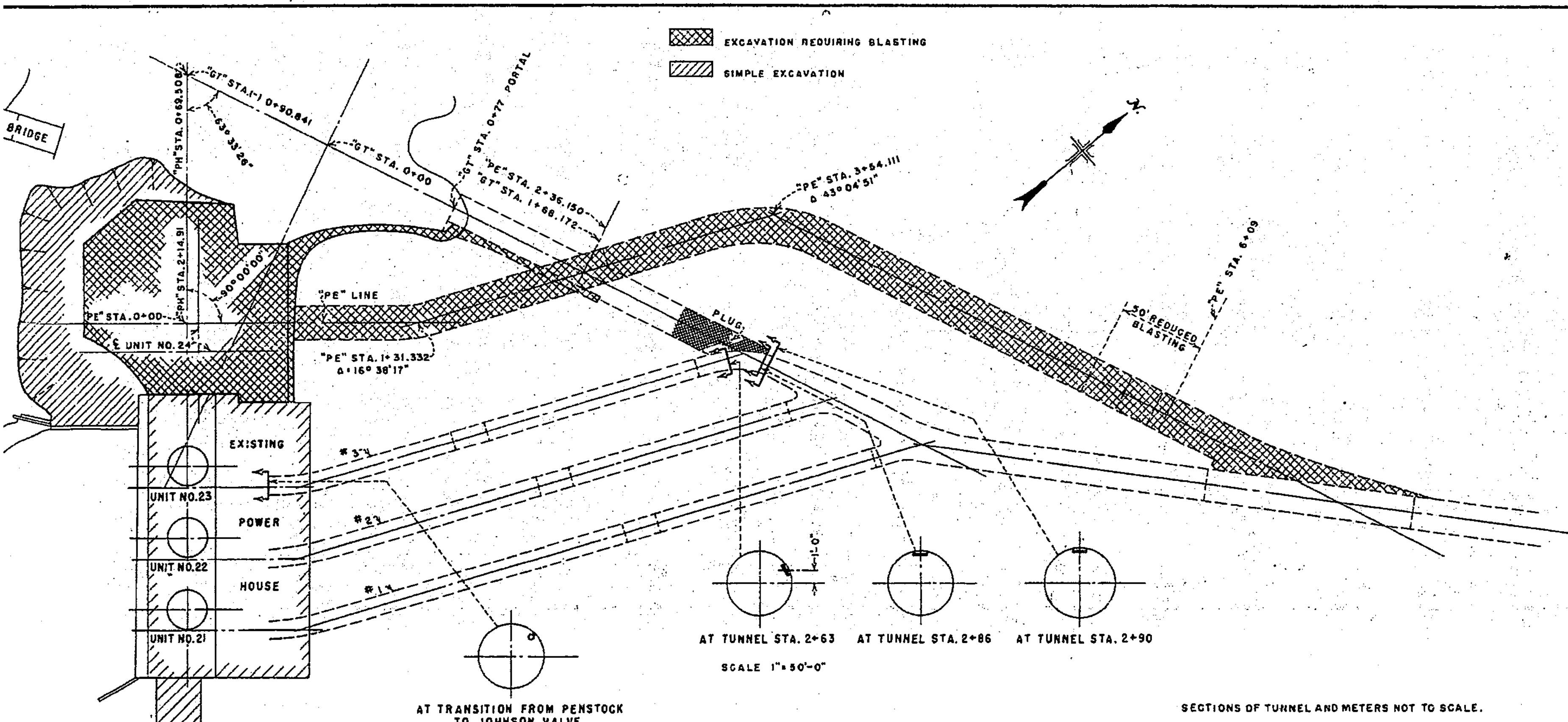


FIGURE 1

PLAN OF GORGE POWERHOUSE SHOWING AREAS OF ROCK EXCAVATION FOR ADDITION TO POWERHOUSE AND LOCATION OF CARLSON STRAIN METERS IN UNIT No. 23 TUNNEL

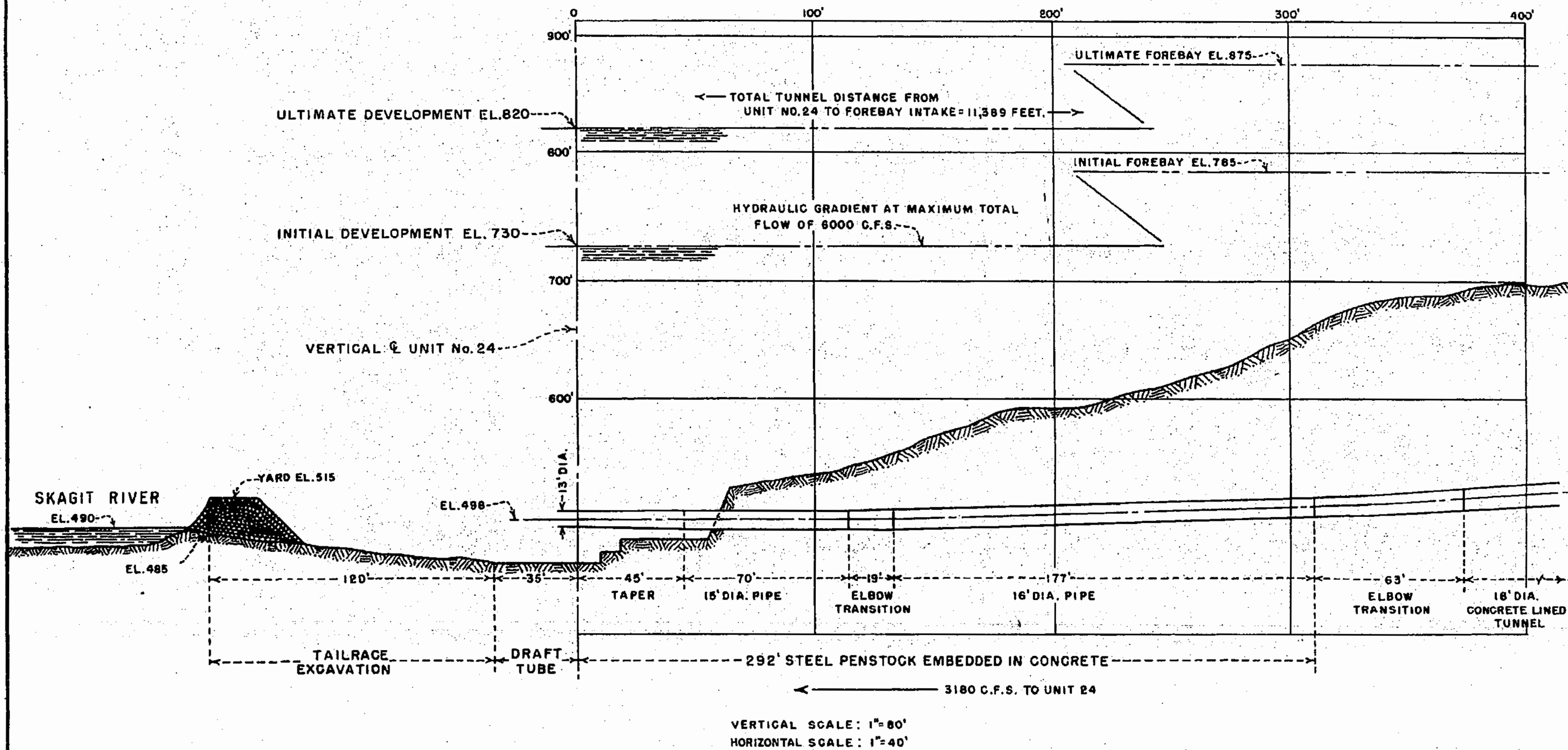


FIGURE 2

PROFILE OF TUNNEL UNIT No. 24 — GORGE POWER PLANT

MACHINE LOAD	AVERAGE TOTAL LOAD	DYNAMIC LOAD	
M.V.A.	TONS	TONS	FREQUENCY CYCLES / SEC.
21	97	53	75
10	127	42	73
5	137	26	72
0	142	23	74
−2	140	22	68

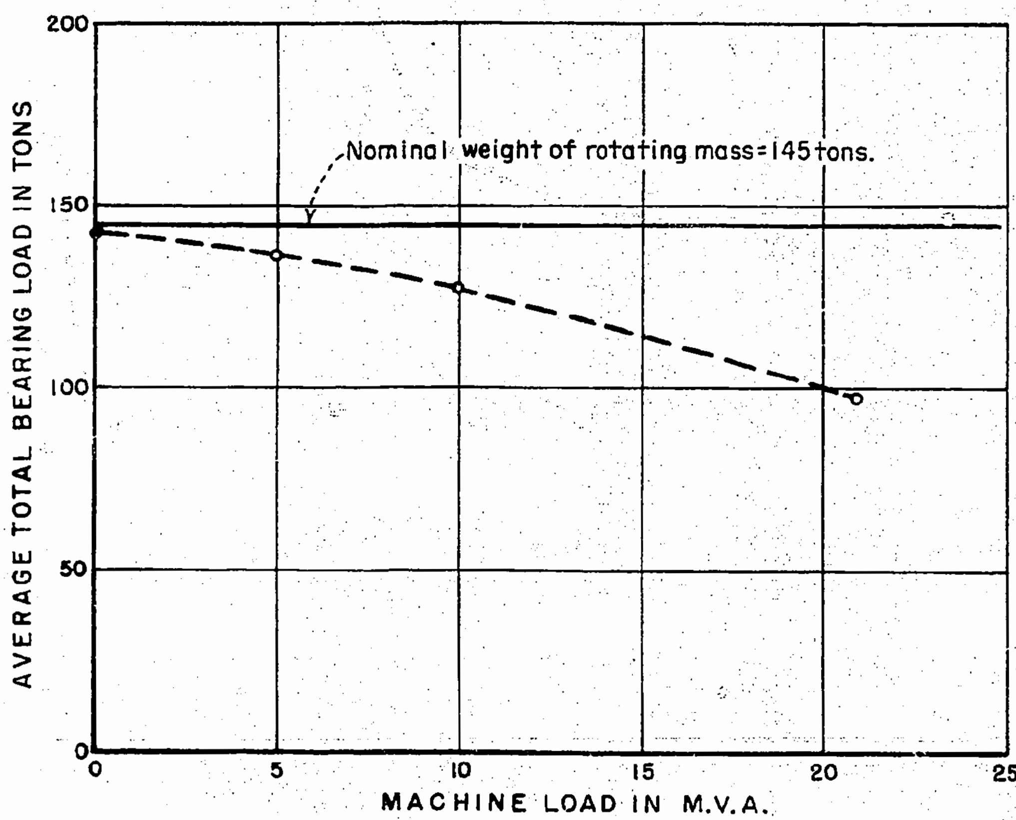


FIGURE 3

AVERAGE TOTAL BEARING LOAD VS. MACHINE LOAD
(AS MACHINE LOAD IS REDUCED BY CLOSING WICKETS)

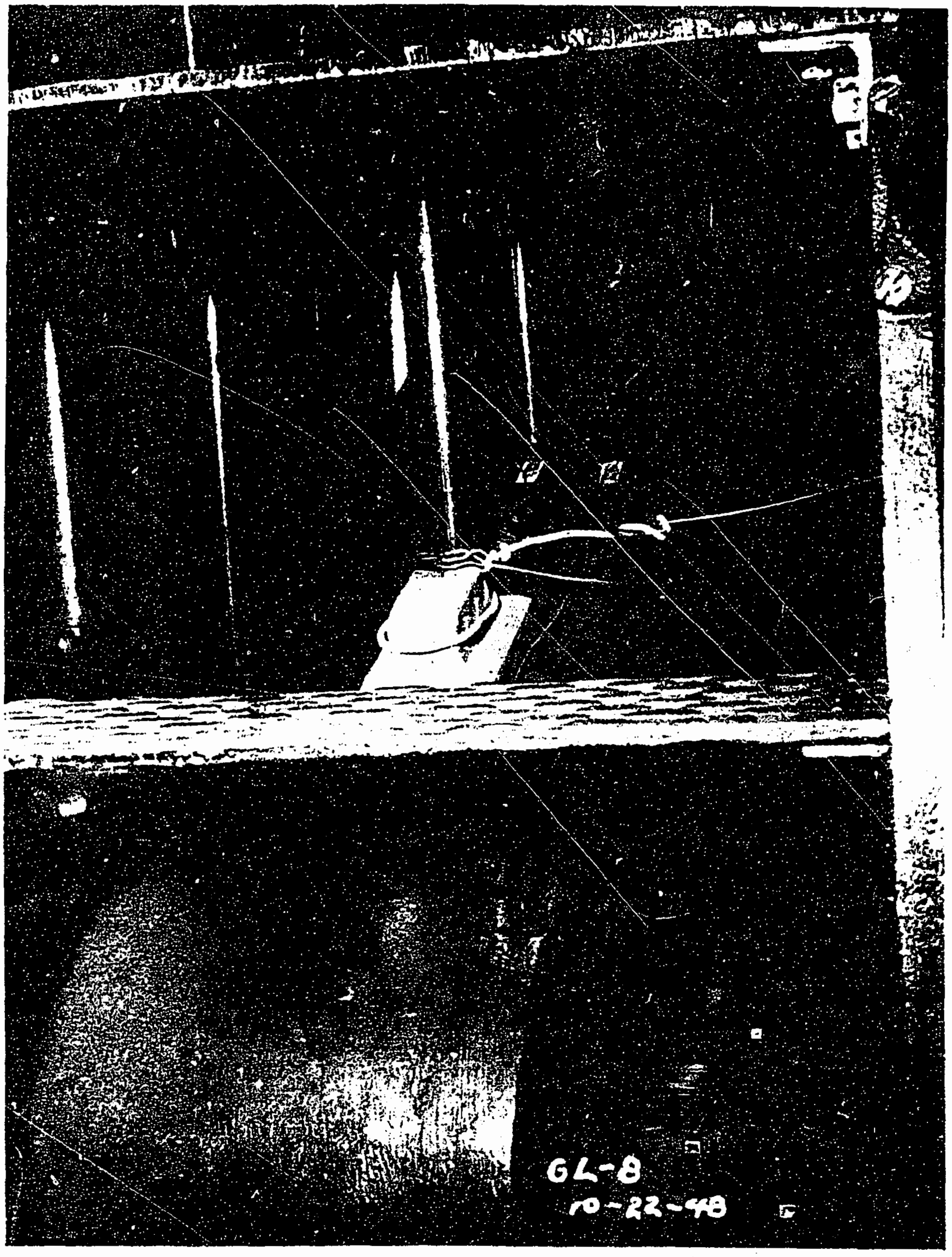
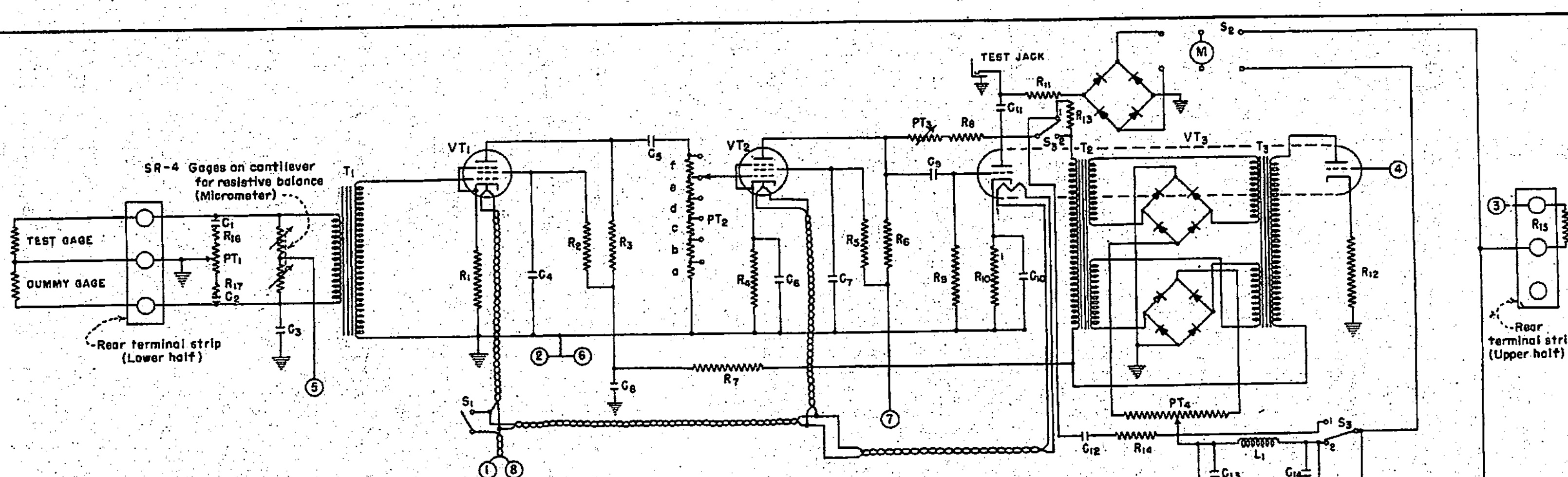


Figure 4

SR-4 strain gages attached to upper surface of thrust bearing support arm of Generator No. 23. Two gages were cemented to the arm, one for a spare in case of damage to the other. The dummy gage is mounted on a bar inside the junction box and insulated from the vibrations.



R_1	200Ω	C_1	0.01 μf
R_2	240,000Ω	C_2	0.01 μf
R_3	51,000Ω	C_3	0.004μf
R_4	1,000Ω	C_4	0.5 μf
R_5	1,100,000Ω	C_5	1.0 μf
R_6	470,000Ω	C_6	10.0 μf
R_7	10,000Ω	C_7	0.5 μf
R_8	100 000Ω	C_8	8.0 μf
R_9	1,100,000Ω	C_9	0.1 μf
R_{10}	1,000Ω	C_{10}	10.0 μf
R_{11}	50,000Ω	C_{11}	0.005 μf
R_{12}	1,000Ω	C_{12}	1.0 μf
R_{13}	10,000Ω	C_{13}	100.0 μf
R_{14}	100,000Ω	C_{14}	100.0 μf
R_{15}	1,000Ω		
R_{16}	5,000Ω		
R_{17}	5,000Ω		

PT_1	Capacitive balance 0 - 5000Ω	
PT_2	Sensitivity adjustment	
a	1000 Ω	.02
b	1500 Ω	.05
c	2500 Ω	.1
d	5000 Ω	.2
e	15,000 Ω	.5
f	25,000 Ω	1
PT_3	Feedback control 0.5 megohm (Lower rear of unit)	
PT_4	Discriminator output control 50Ω (Upper rear of unit)	

S_1	S.P.S.T. Filament supply switch-"ON-OFF"
S_2	D.P.D.T Meter switch -"BAL-GALV."
S_3*	2 S.P.D.T. mechanically ganged - at rear of unit.
VT_1	6SJ7
VT_2	6SJ7
VT_3	6SN7

* Position 1 - Use as carrier amplifier for strain measurements, etc.
Position 2 - Use as straight A.C. amplifier without carrier for geophysical work.

Connections made to octal plug at rear of unit.

1 → 6.3 Volt Filament Supply
2 → B-
3 → Galvanometer
4 → Discriminator Signal - 1000~
5 → Gage Supply Amplifier 1000~
6 → Ground
7 → B+, regulated 250 volts
8 → 6.3 Volt Filament Supply

FIGURE 5
STRAIN AMPLIFIER - CIRCUIT DIAGRAM

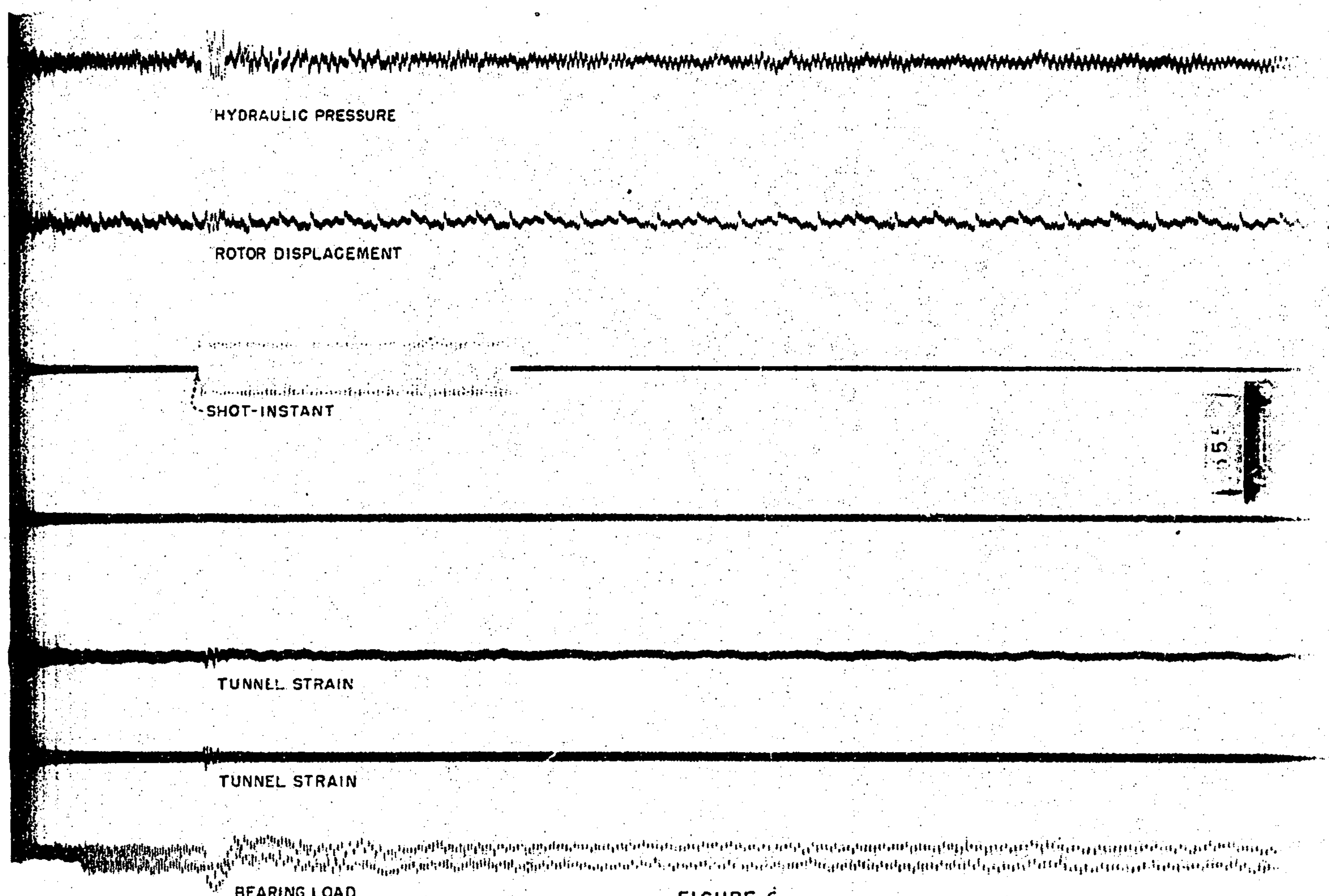
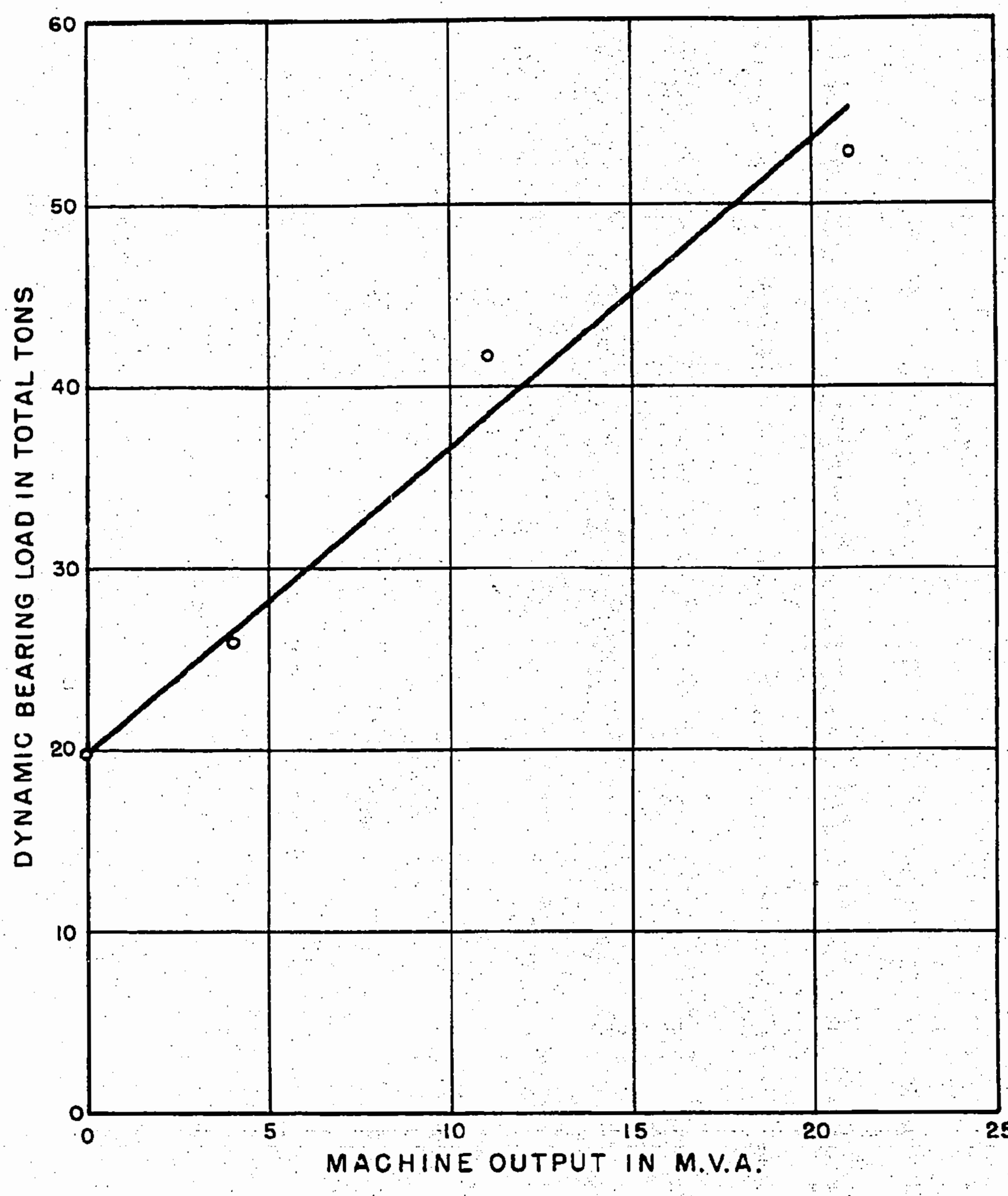


FIGURE 6
OSCILLOGRAPH RECORD OF THRUST BEARING LOAD, TUNNEL STRAIN, ROTOR DISPLACEMENT AND HYDRAULIC PRESSURE IN SCROLL CASE



NOTE: Dynamic load is defined as the peak to peak variation in the indicated load over intervals of time less than 1/50 sec. and which are present in normal operation.

FIGURE 7

DYNAMIC BEARING LOAD VS. MACHINE LOAD

BASED ON DATA TAKEN 10-30-48

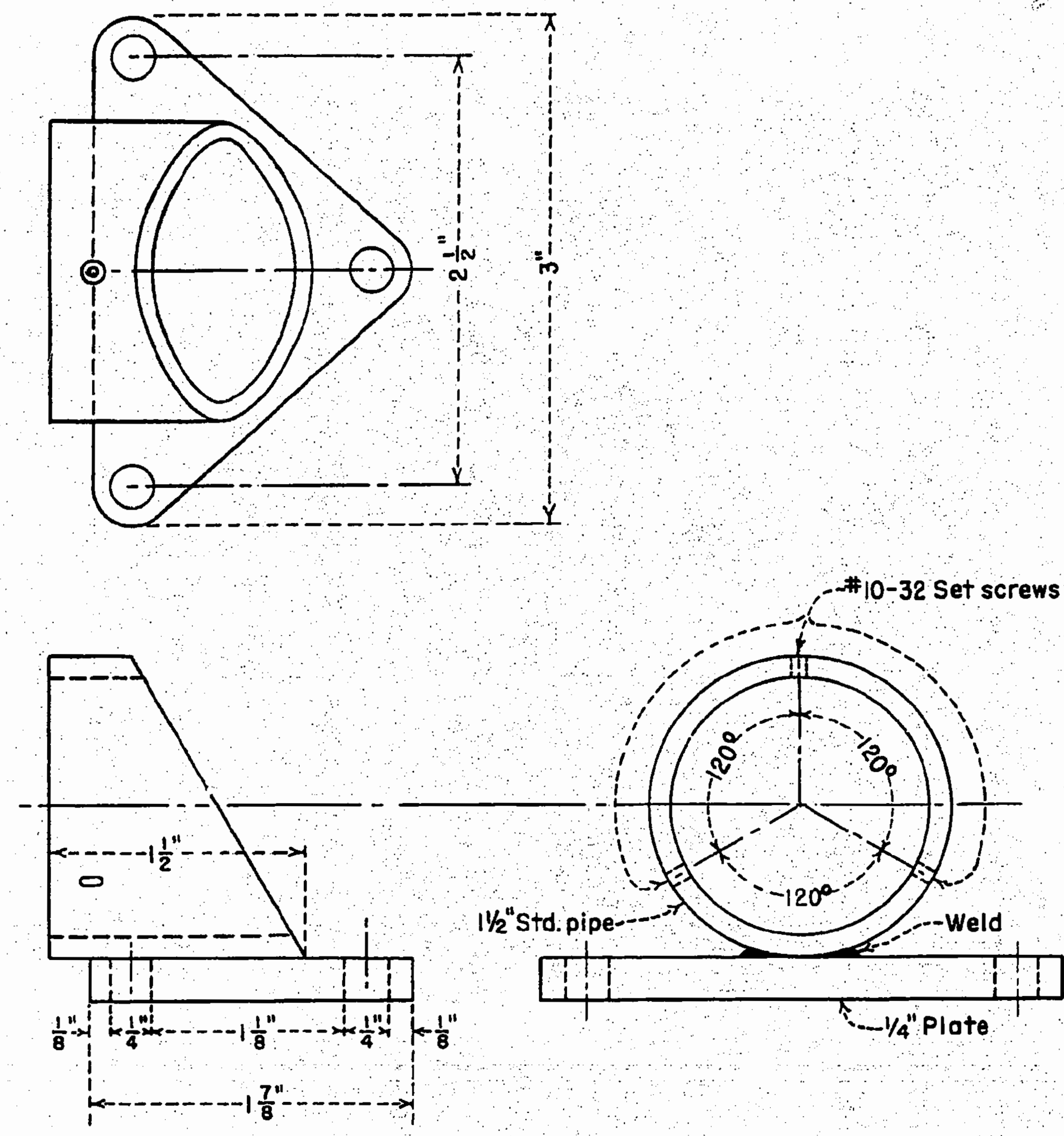


FIGURE 8

CARLSON METER ATTACHMENT BRACKET

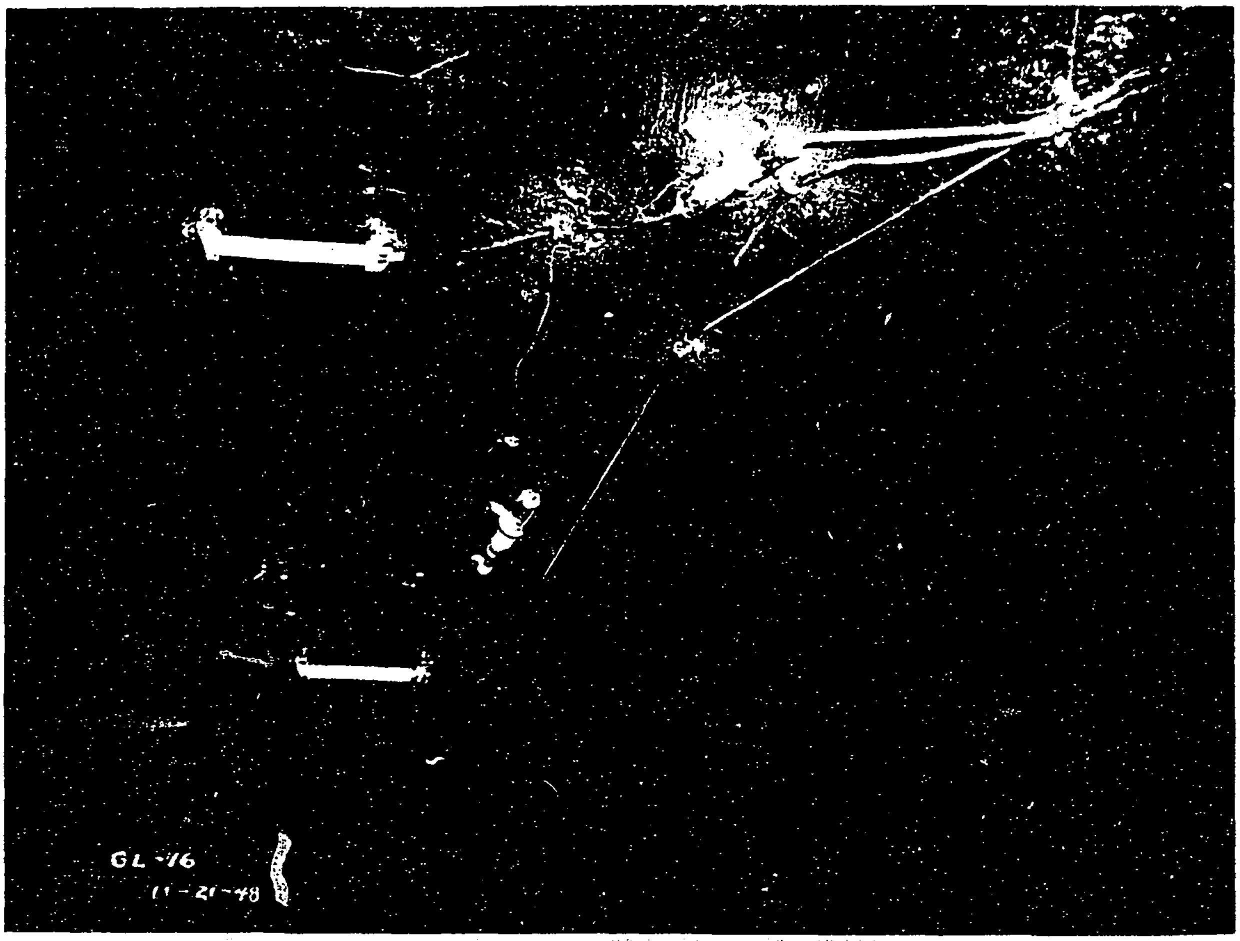
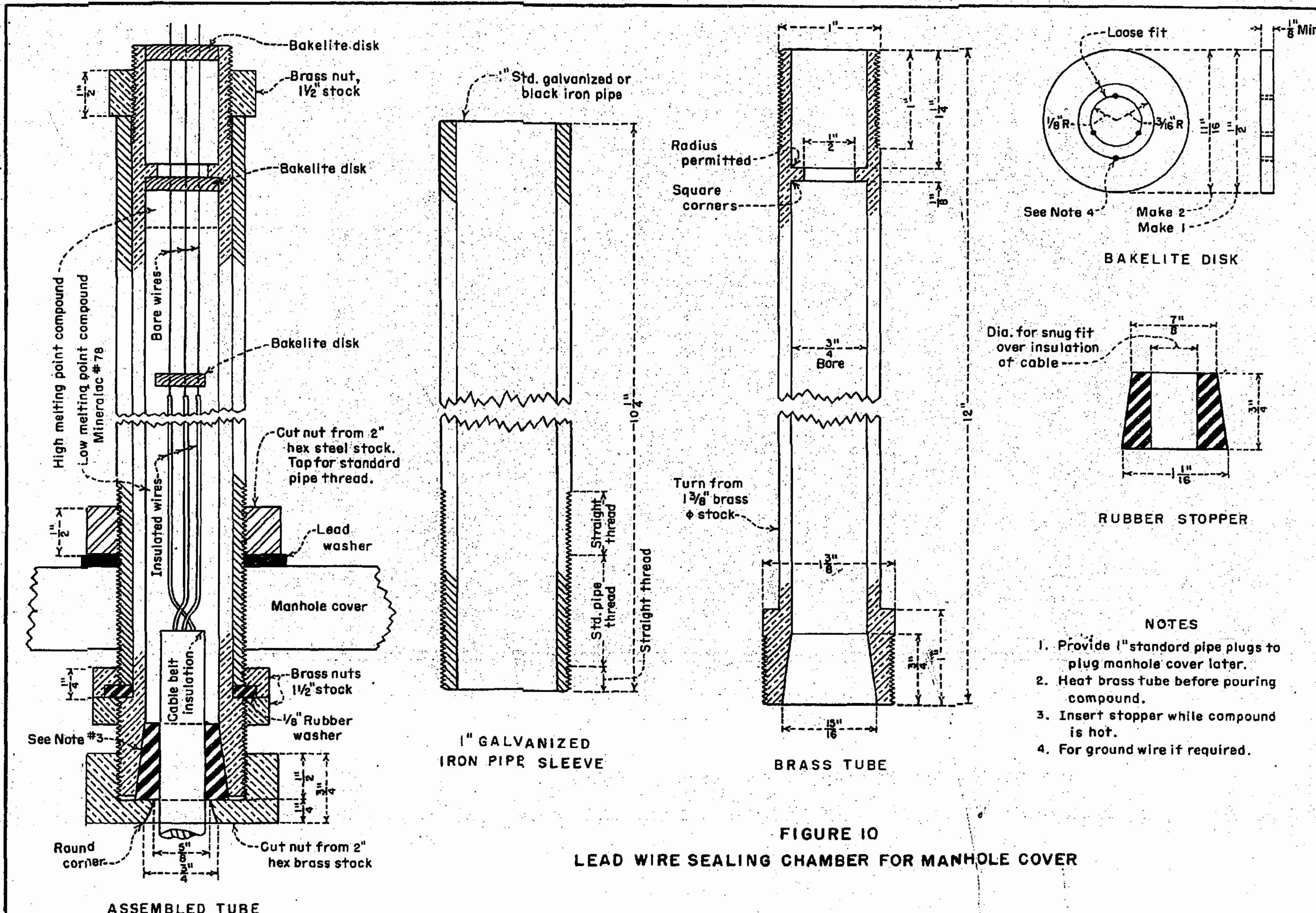


Figure 9

Carlson strain gages attached to concrete lining of tunnel. Cable splices are enclosed in sleeves. Steel messenger wire is used to support the cables.



NOTES

1. Provide 1" standard pipe plugs to plug manhole cover later.
2. Heat brass tube before pouring compound.
3. Insert stopper while compound is hot.
4. For ground wire if required.

FIGURE 10

LEAD WIRE SEALING CHAMBER FOR MANHOLE COVER

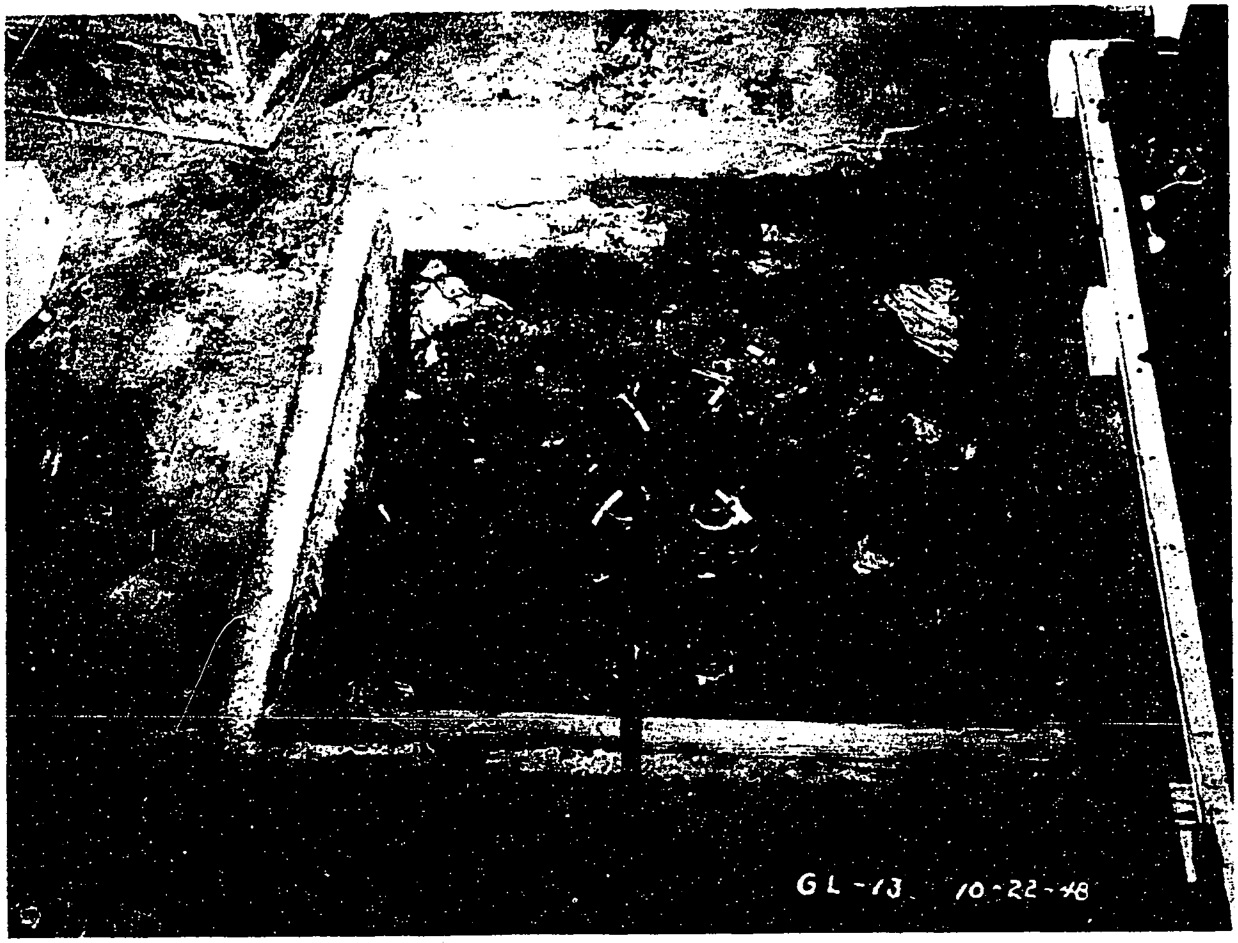


Figure 11

Lead wire sealing chambers mounted in manhole cover to penstock of Unit No. 23.

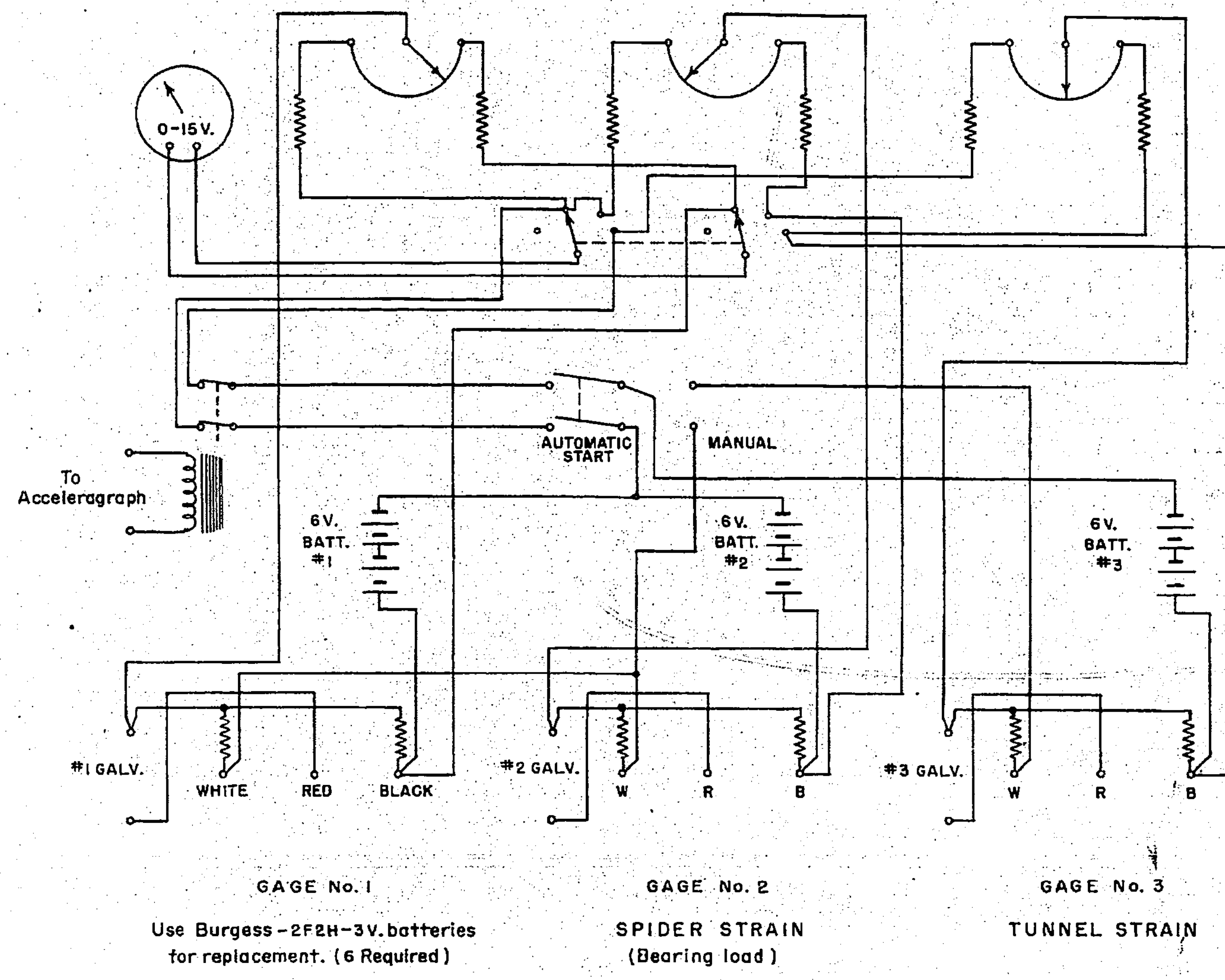


FIGURE 12

WIRING DIAGRAM OF THREE CHANNEL BRIDGE FOR CARLSON STRAINMETERS

Figure 13

Hydraulic pressure transmitter mounted to measure dynamic pressures in the scroll case of Unit 23.

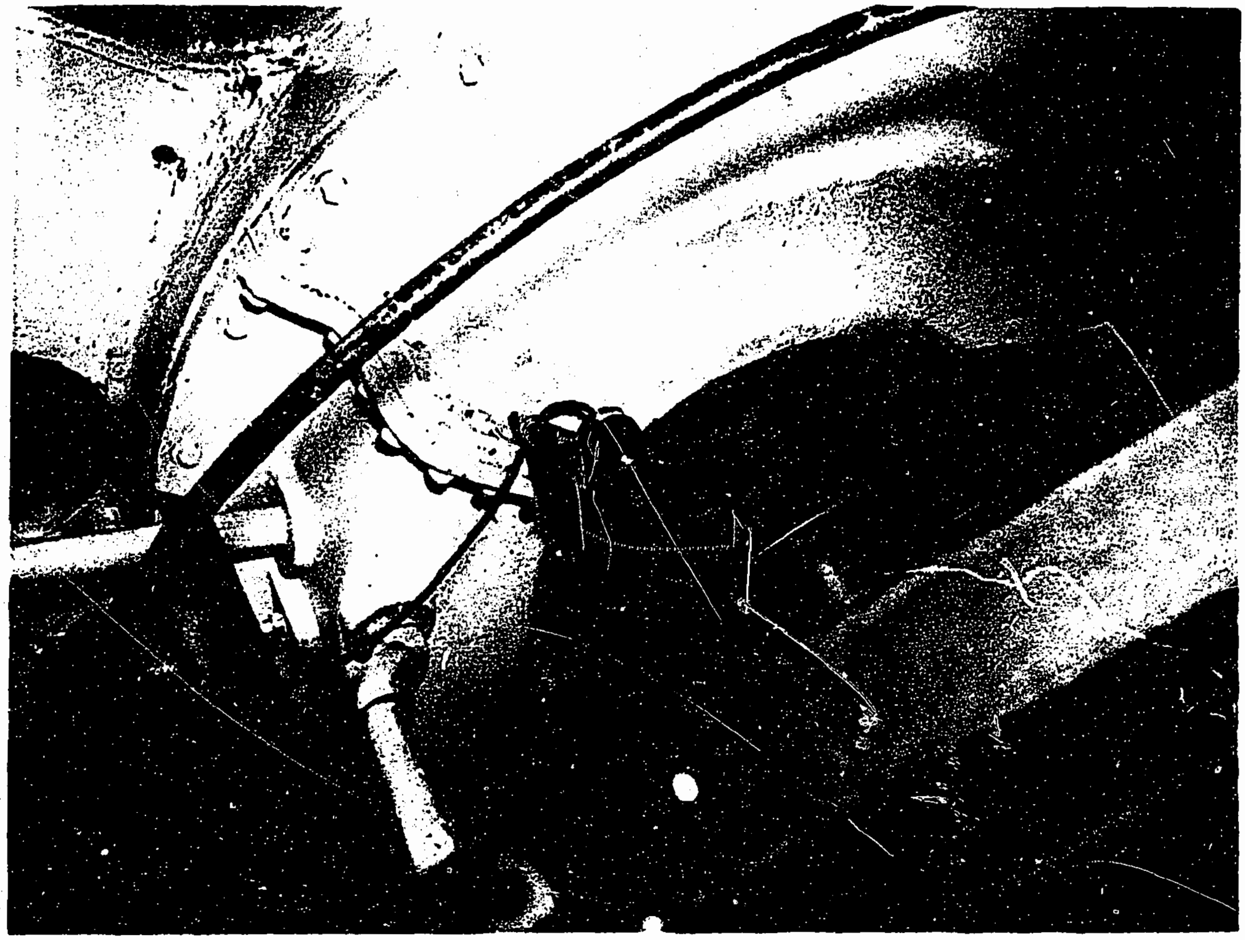


Figure 14

Position transmitter mounted to measure the relative motion between the rotor and stator of Unit No. 23.

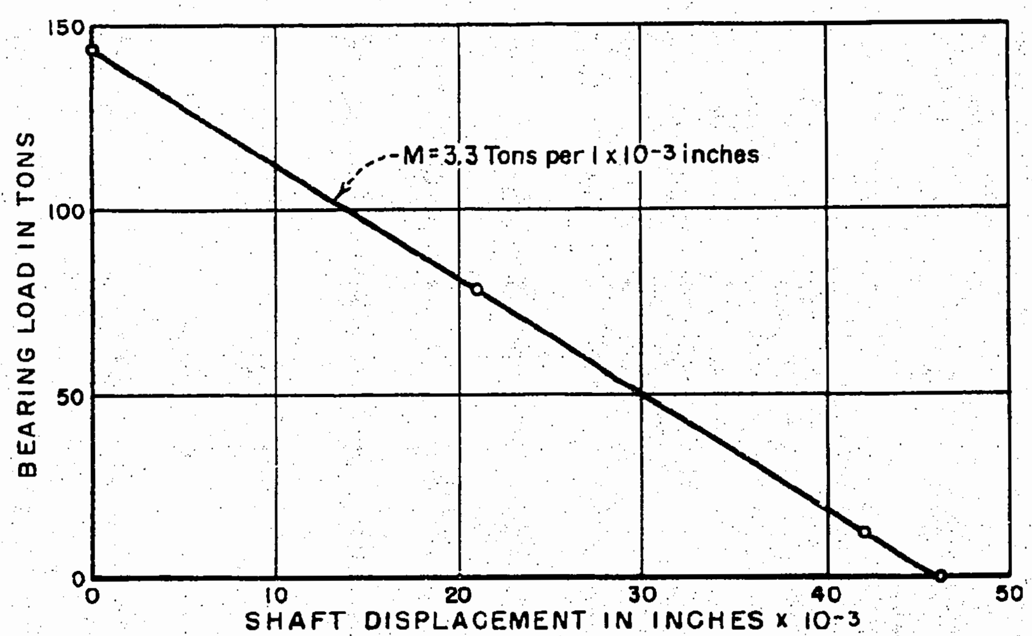


FIGURE 15
BEARING LOAD VS. SHAFT DISPLACEMENT RELATIVE TO STATOR FRAME— MEASURED STATICALLY

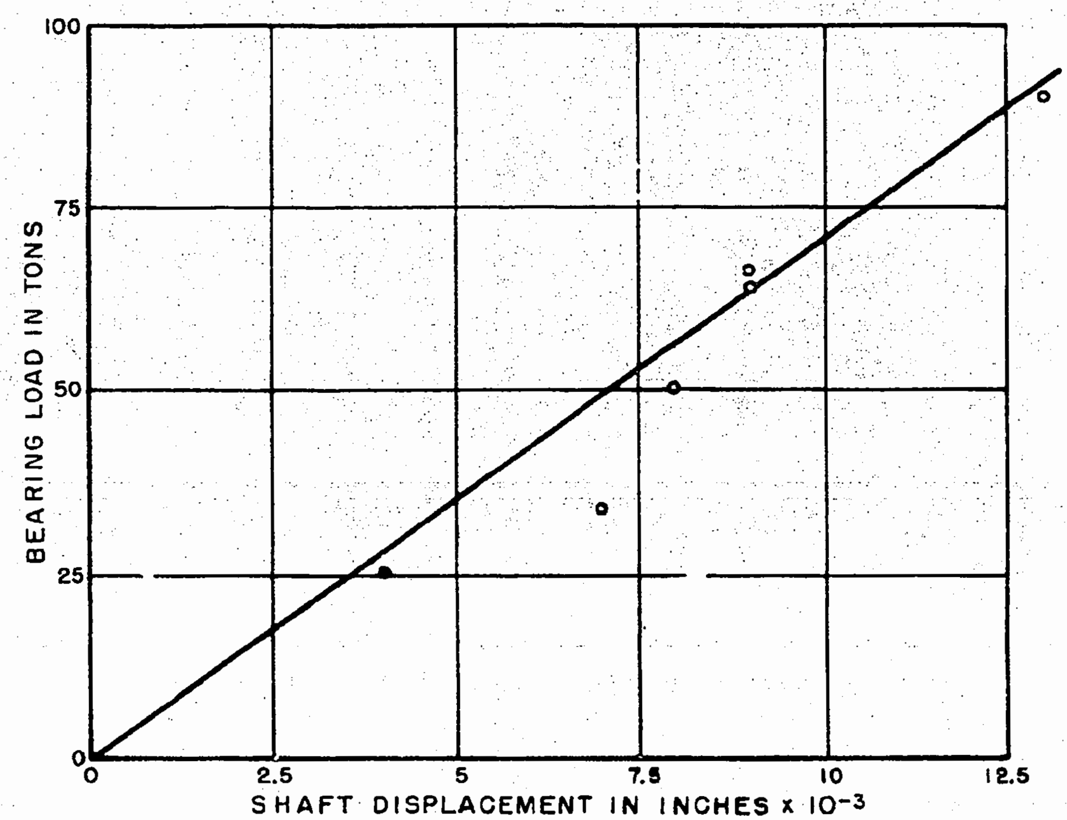


FIGURE 16
BEARING LOAD VS. SHAFT DISPLACEMENT RELATIVE TO STATOR FRAME— MEASURED DURING BLASTS

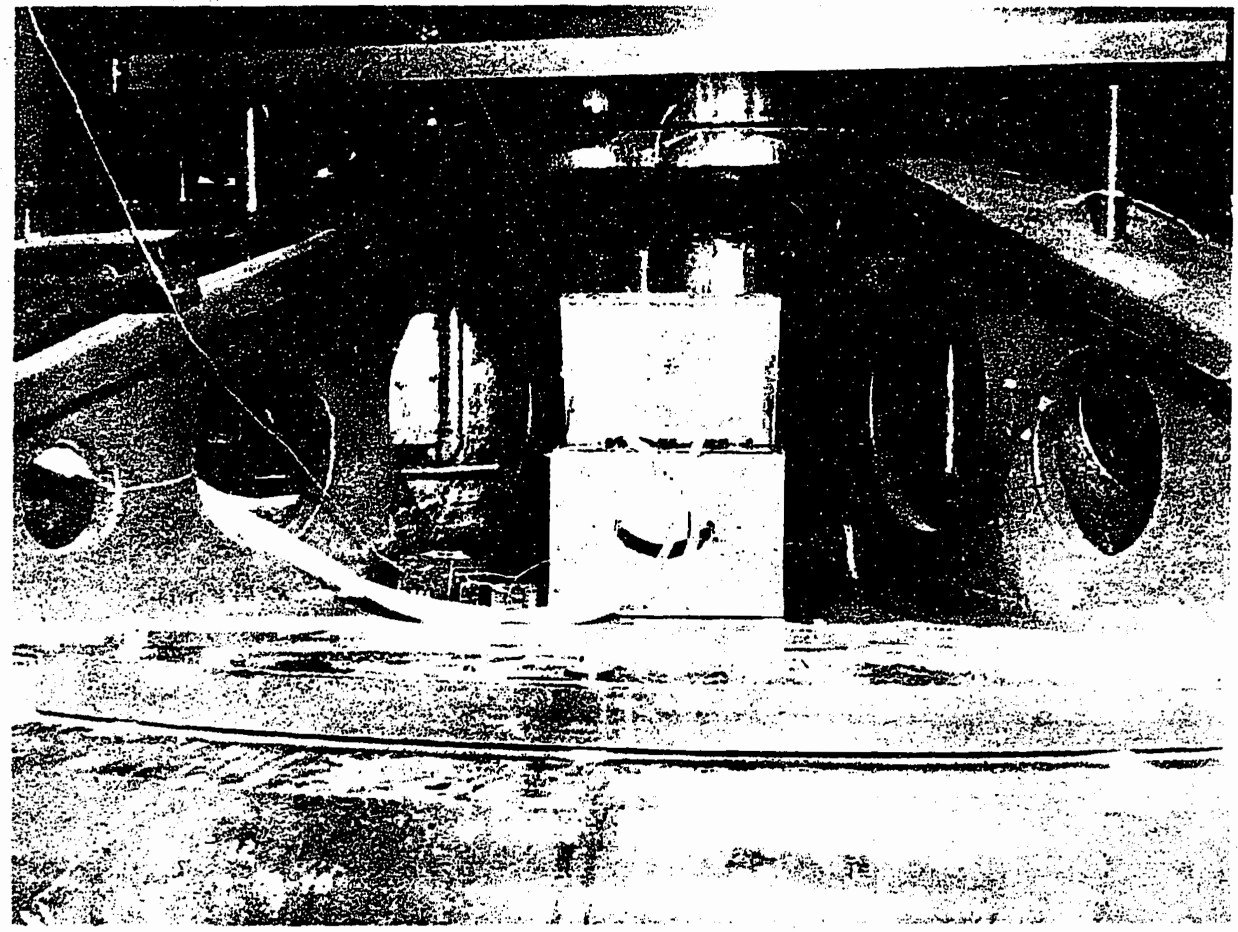


Figure 17

Three component accelerometer mounted on spider of Unit No. 23. Relay to energize the accelerometer is in the box to the left of the accelerometer.

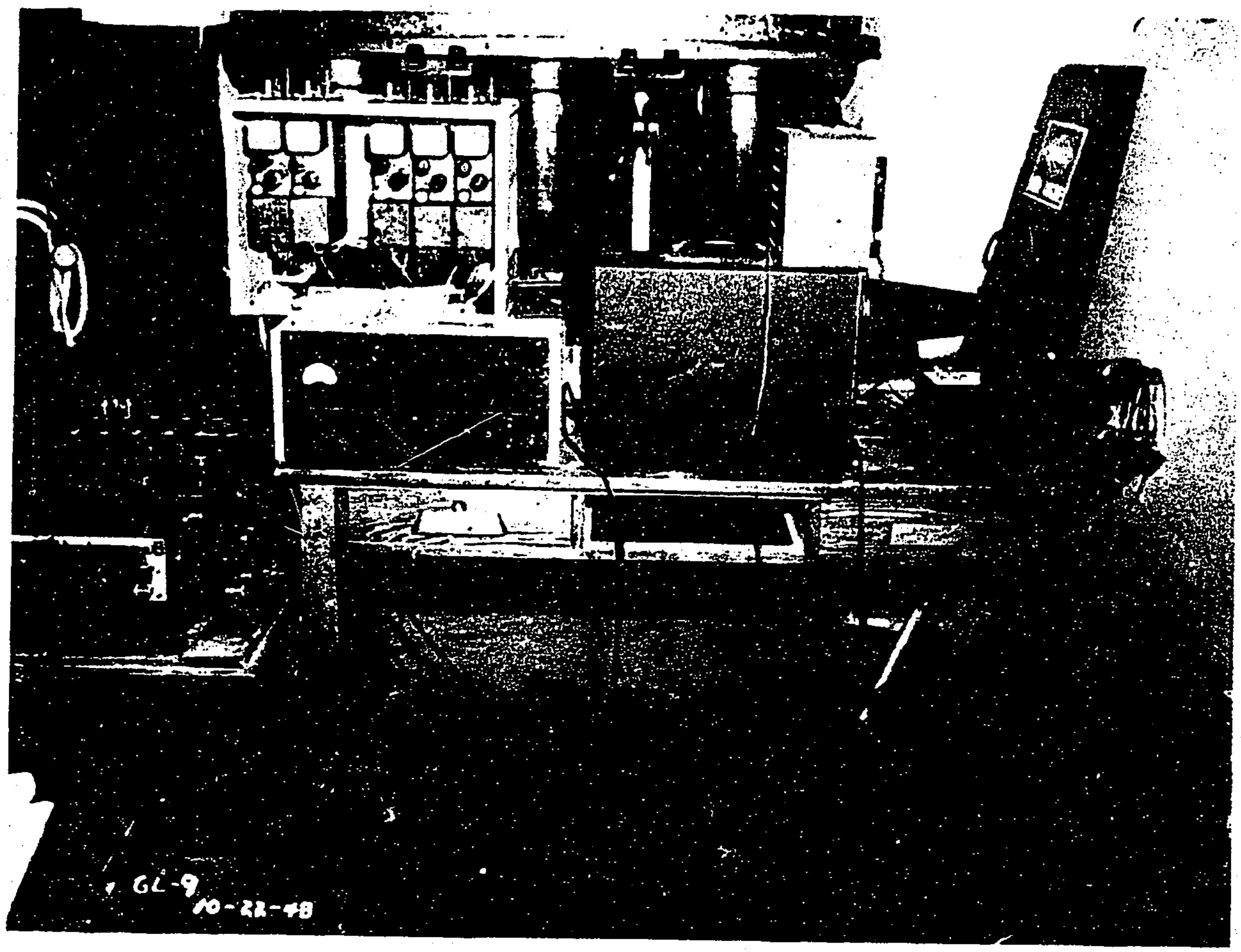


Figure 18

Amplifying and recording apparatus used in tests. Cathode ray oscilloscope and drum camera set up in operating position on right-hand side of table.

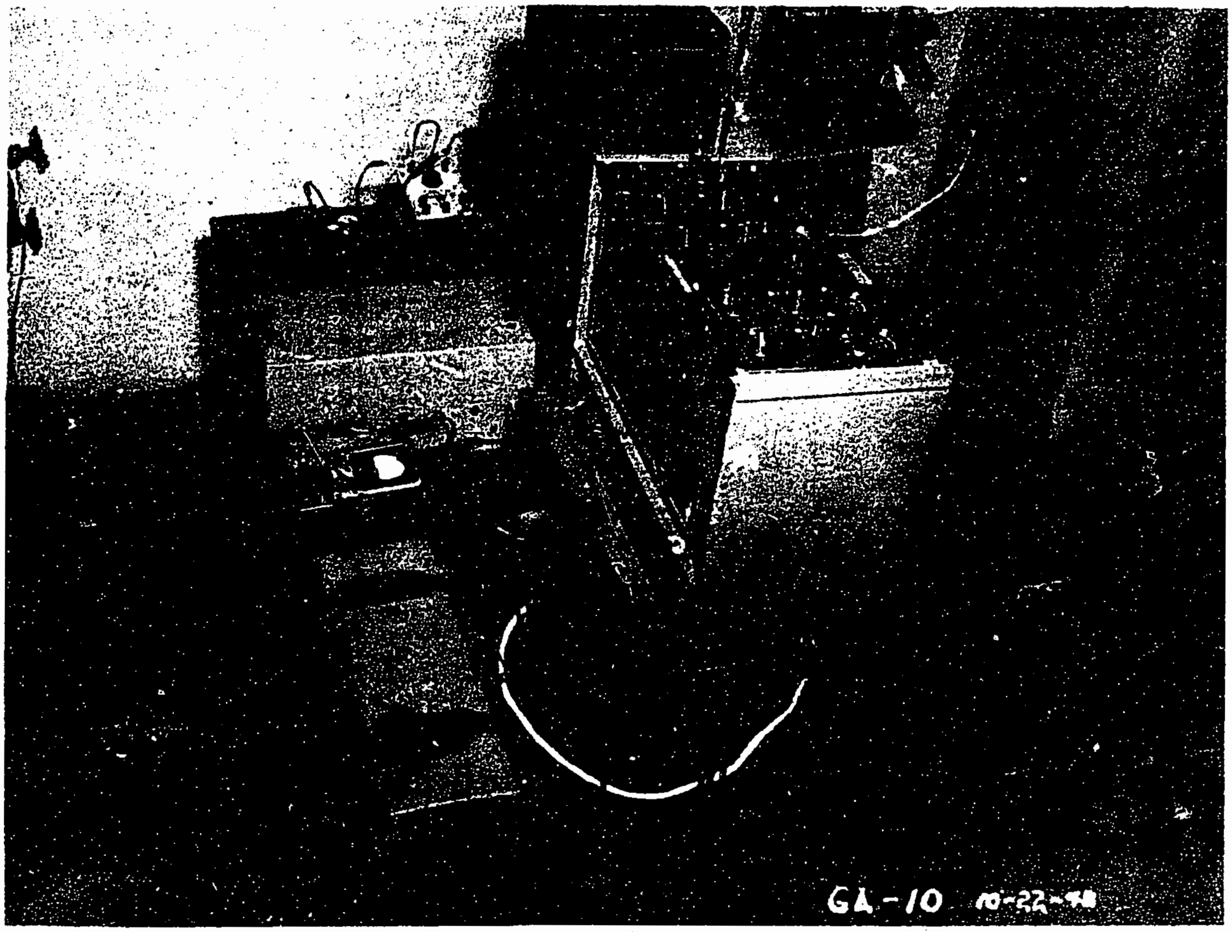
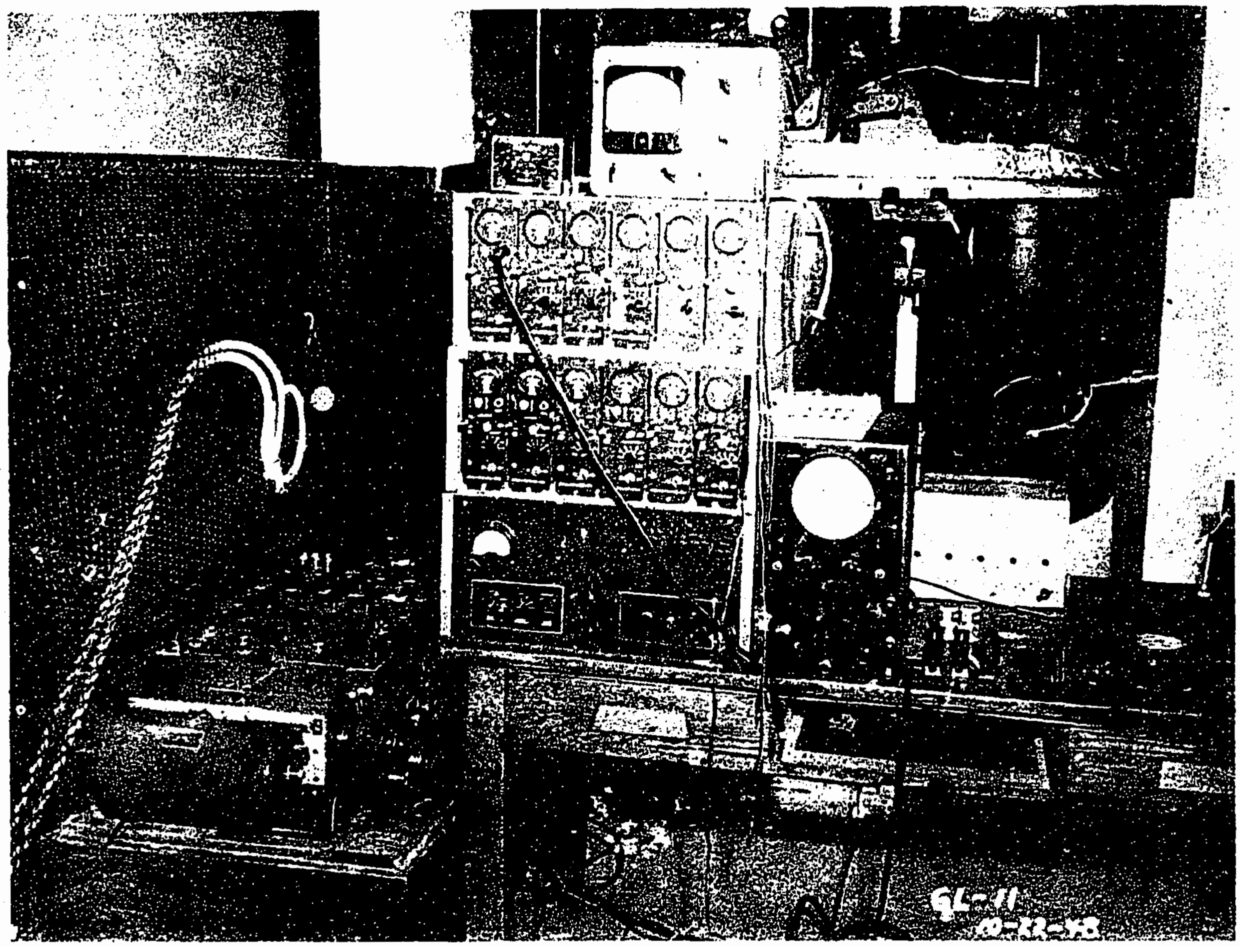


Figure 19

Amplifying and recording apparatus used in tests. Strain amplifiers, right foreground, are oriented to minimize the effects of the magnetic fields in the area. The oscillator and bridges for the pressure gage and relative position transmitter are in the left foreground.



<u>Figure 20</u>

Amplifying and recording equipment used in tests. Left to right: signal lights from blaster; 12-channel recording oscillograph; 12-channel strain amplifiers and power supply; cathode ray oscilloscope.

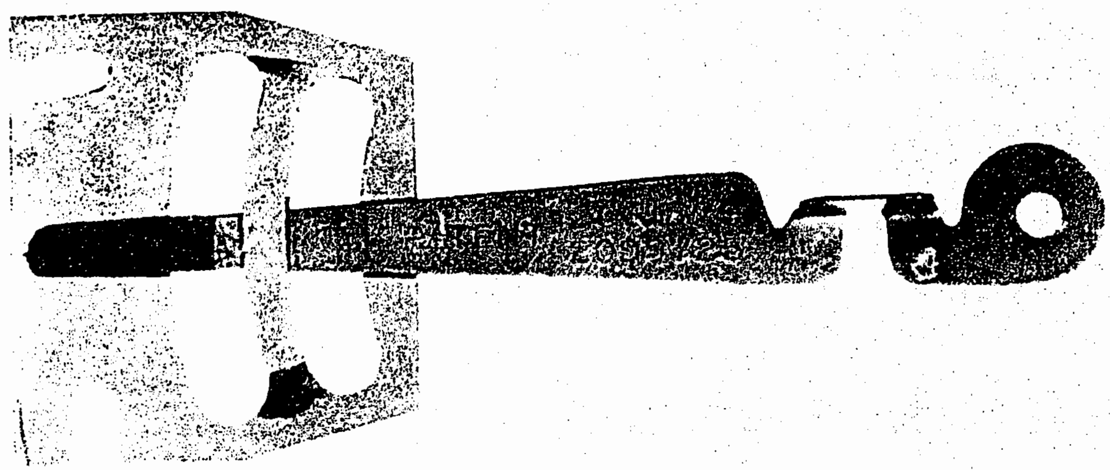


FIG. 21 DE FOREST SCRATCH GAGE

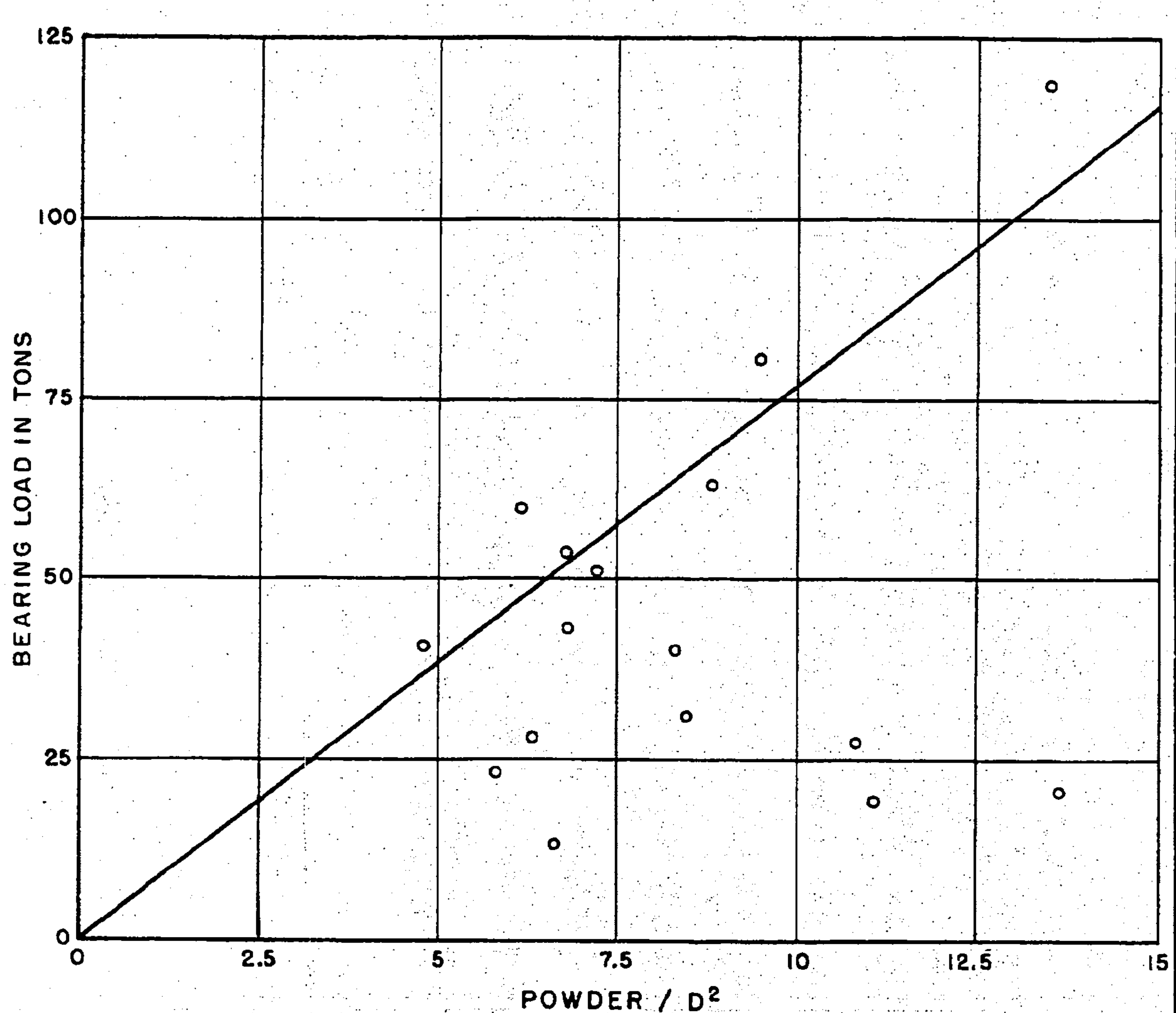


FIGURE 22
BEARING LOAD VS. POWDER / D^2