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PROTOTYPE GATE VIBRATION TESTS BARKLEY DAM, CUMBERLAND RIVER KENTUCKY

by

E. Dale Hart, John E. Hite, Jr.

Hydraulics Laboratory
U. S. Army Engineer Waterways Experiment Station
P. O. Box 631, Vicksburg, Miss. 39180

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This report presents data obtained during prototype tests concerned with the vibration of the 50- by 55-ft spillway tainter gates at Barkley Dam. The gates vibrate during flow passage in which the gate lip is submerged by high tailwater.

Field tests were conducted on two of the gates during high tailwater. Three pressure transducers were placed near the lip of the gate. In addition

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20. ABSTRACT (Continued).

14 accelerometers were attached at preselected locations on the gate. The second gate was instrumented with five accelerometers only for a limited data comparison.

Data reduction indicated that many components vibrate at the same frequency as the gate lip pressure fluctuations. Computations and ring tests indicate that this frequency approaches at least one component's natural frequency. The gate seal at the lip was removed and the test repeated under identical conditions. The measured vibrations were all dramatically reduced. By varying the opening of the gates, under identical conditions, it was found that vibration severity decreased with increasing tailwater submergence.

Remedial measures in design and operation of the gates were recommended.

PREFACE

The prototype tests described in this report were conducted during March 1977 by the Hydraulics Laboratory of the U. S. Army Engineer Waterways Experiment Station (WES) under the sponsorship of the U. S. Army Engineer District, Nashville.

Acknowledgment is made to the individuals of the Nashville District who actively participated in this investigation. Mr. E. D. Hart, Chief of the Prototype Evaluation Branch, was test coordinator for WES. This report was prepared by Mr. Hart with the assistance of Mr. J. E. Hite, Jr., under the general supervision of Messrs. E. B. Pickett and M. B. Boyd, Chiefs of the Hydraulic Analysis Division, and Mr. H. B. Simmons, Chief of the Hydraulics Laboratory. Mr. Pickett and Dr. Frank M. Neilson provided assistance in the preparation of the report.

Commander and Director of WES during the investigation and the preparation and publication of this report was COL John L. Cannon, CE. Technical Director was Mr. F. R. Brown.

CONTENTS

CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U. S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
acre-feet	1233.482	cubic metres
cubic feet per second	0.02831685	cubic metres per second
Fahrenheit degrees	5/9	Celsius degrees or Kelvins*
feet	0.3048	metres
feet per second	0.3048	metres per second
feet per second per second	0.3048	metres per second per second
inches	25.4	millimetres
inches per second	2.54	centimetres per second
miles (U. S. statute)	1.609344	kilometres
pounds (force) per square inch	6894.757	pascals

* To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: C = (5/9)(F - 32). To obtain Kelvin (K) readings, use: K = (5/9)(F - 32) + 273.15.

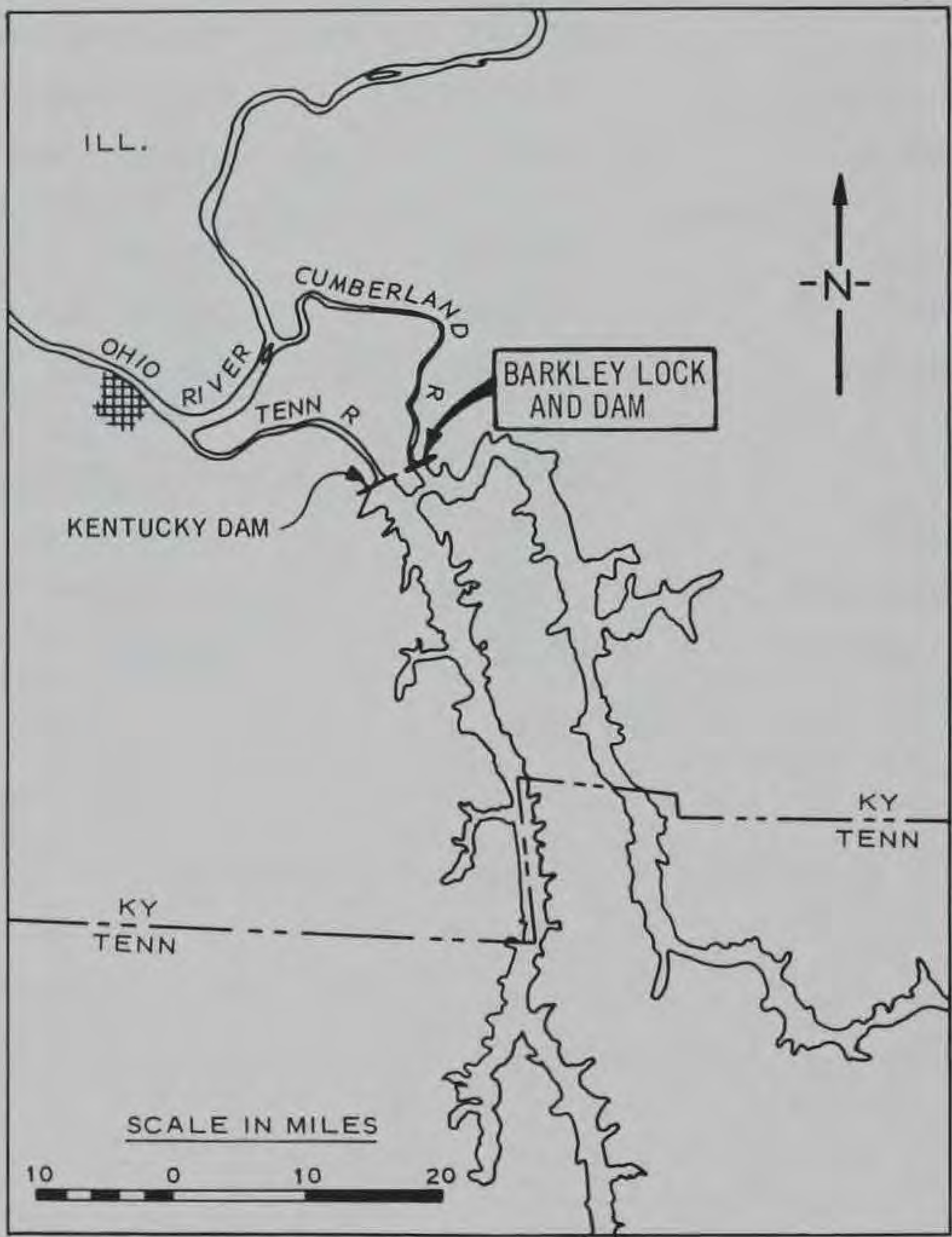

Figure 1. Vicinity map

PROTOTYPE GATE VIBRATION TESTS, BARKLEY DAM
CUMBERLAND RIVER, KENTUCKY

PART I: INTRODUCTION

Pertinent Features of the Project

1. Barkley Lock and Dam is located 30 miles* above the confluence of the Cumberland and Ohio Rivers (Figure 1). The completion of the project in 1966 eliminated five smaller obsolete locks and dams along the Cumberland and provided a 9-ft-deep navigable waterway up to mile 308. About 2.5 miles above Barkley Dam, a 1.5-mile-long canal extending through the narrow ridge between Lake Barkley and Kentucky Lake permits navigation from one reservoir to the other as well as diversion of flow as required for flood control or power production.

2. The project consists of a 12-bay, 804-ft-long concrete spillway (Plate 1), a 130,000-kw powerhouse, an 8,725-ft-long rolled earth-filled dam, and a 110- by 800-ft lock (Figure 2). Total storage

Figure 2. Barkley project

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* A table of factors for converting U. S. customary units of measurement to metric (SI) units is presented on page 3.

capacity of the reservoir is 2,082,000 acre-feet of which 1,472,000 acre-feet is reserved for flood-control storage at pool el 375.*

Background

3. Gate vibrations at Barkley Dam were first observed in March 1967. From observations it was concluded that the gates vibrate when the lower portion of each is submerged by high tailwater and between openings of approximately 0.5 to 6.0 ft. A number of alterations have been tried in an effort to reduce or eliminate the vibrations. These included aerating the gate bottom, removing the gate seal, and filling the bottom seal support void with tar. While partially successful, these efforts have not reduced gate vibrations to an acceptable level or have resulted in other unacceptable conditions.

Purpose and Scope of Tests

4. The primary objectives of the prototype tests were to (a) determine the magnitude and frequency of vibrations at specified locations on two spillway tainter gates; (b) determine pressure fluctuation magnitudes and frequencies at and near the gate lip; (c) compare vibration and pressure fluctuation magnitudes with and without the gate seal; (d) analyze gate lip pressure fluctuations and gate vibrations to determine if the former caused the latter; and (e) make recommendations for reducing or eliminating gate vibrations, based on results of the analysis and field observations. In order to accomplish these objectives, 18 data-sensing transducers were installed on the gates tested. Test measurements consisted of the following.

- a. Strut transverse acceleration.
- b. Skin plate radial accelerations.
- c. Gate frame acceleration.
- d. Gate lip pressure fluctuations.

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* All elevations (el) cited herein are in feet referred to mean sea level (msl).

The data were recorded on magnetic tape and oscillograph charts. Data records were reduced and analyzed, using both the digital and analog computer facilities available at the U. S. Army Engineer Waterways Experiment Station (WES) to provide the results presented herein.

Related Studies and Model Investigations

5. Vibration of the tainter gates has been reported at several dams on the Arkansas River navigation project. A model study was conducted at WES to investigate these vibrations. A 1:12-scale model that reproduced one 60-ft-wide gate bay and the adjacent half bays was used for the study. During this study the Barkley gate lip configuration and seal were reproduced in the model and this gate did not vibrate in the model. WES is currently conducting a model study to test gate "bouncing" experienced at Barkley during extremely high tailwater conditions. This phenomenon is created when large gate openings are combined with the high tailwater. A partial reverse flow effect is believed to be created causing a portion of the discharging water to move back upstream and exert an uplift pressure on the bottom girder of the gate (Plate 2).

PART II: TEST FACILITIES, EQUIPMENT, AND PROCEDURES

Gate Lip Pressures

6. Three 25-psia pressure transducers (PGC, PGL, PGS) were mounted in the lip area of gate 3 as shown in Plate 2. Table 1 lists all transducers, their locations, measurement, and range. The transducers were housed in special adapters and secured with either a locknut or a setscrew. Transducer PGS measured pressure fluctuations on the upstream side of the skin plate about 6 in. above the lip. Transducers PGL and PGC measured fluctuations upstream and downstream, respectively, of the gate seal. In addition, a 25-psia pressure transducer (PGP) was mounted flush with the underside of the lower gate girder in the event gate "bouncing" conditions were experienced. Location of transducers PGC, PGL, and PGS is also shown in Figure 3.

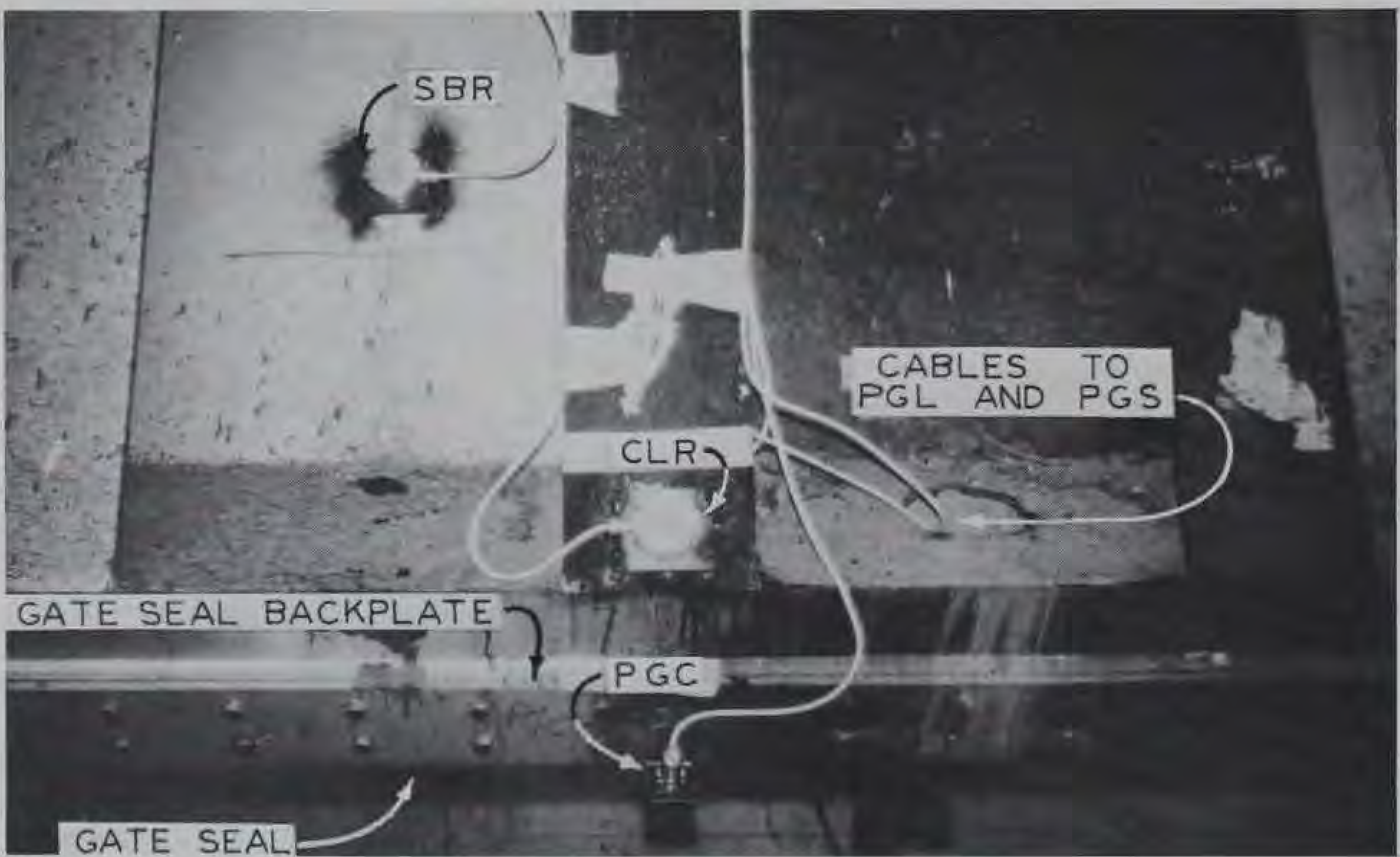

Figure 3. Transducers mounted near the lip of gate 3 (looking upstream)

Gate Vibrations

7. Fourteen ±5 g accelerometers were mounted on gate 3 as shown

Figure 4. Triaxial accelerometer pod (looking upstream)

in Plate 2 for determining gate component vibrations. Five of these transducers (LTT, CTR, SBR, SMR, and RTT) were also used at identical locations for tests of gate 11. Mounting plates for the accelerometers were prefabricated and welded to the gates at the locations shown in Plate 2. Figure 4 shows the triaxial accelerometer pod (CMP, CMR, CMT) that was mounted on the inside surface of the upstream flange, middle girder, gate 3. This transducer assembly responded to radial, transverse, and peripheral gate accelerations.

Other Measurements

8. Headwater and tailwater elevations and water and air temperatures were obtained from recorders located in the powerhouse control room. Gate openings were read directly from indicators at each gate. Discharge was determined from discharge rating curves which included compensation for reduction due to tailwater submergence.

Recording Equipment

9. The transducer cables passed from the back side of the gate

vertically upward to the top of the dam and thence to the recording shed located on the west end of the dam (Plate 1 and Figure 5). The 8- by 16-ft shed was constructed by the U. S. Army Engineer District, Nashville, and secured in place.

10. The recording equipment included (a) WES-fabricated Model 01 amplifiers to condition the output signals, (b) a Sangamo model Sabre 3,

Figure 5. Gate 3 transducer cables and recording shed

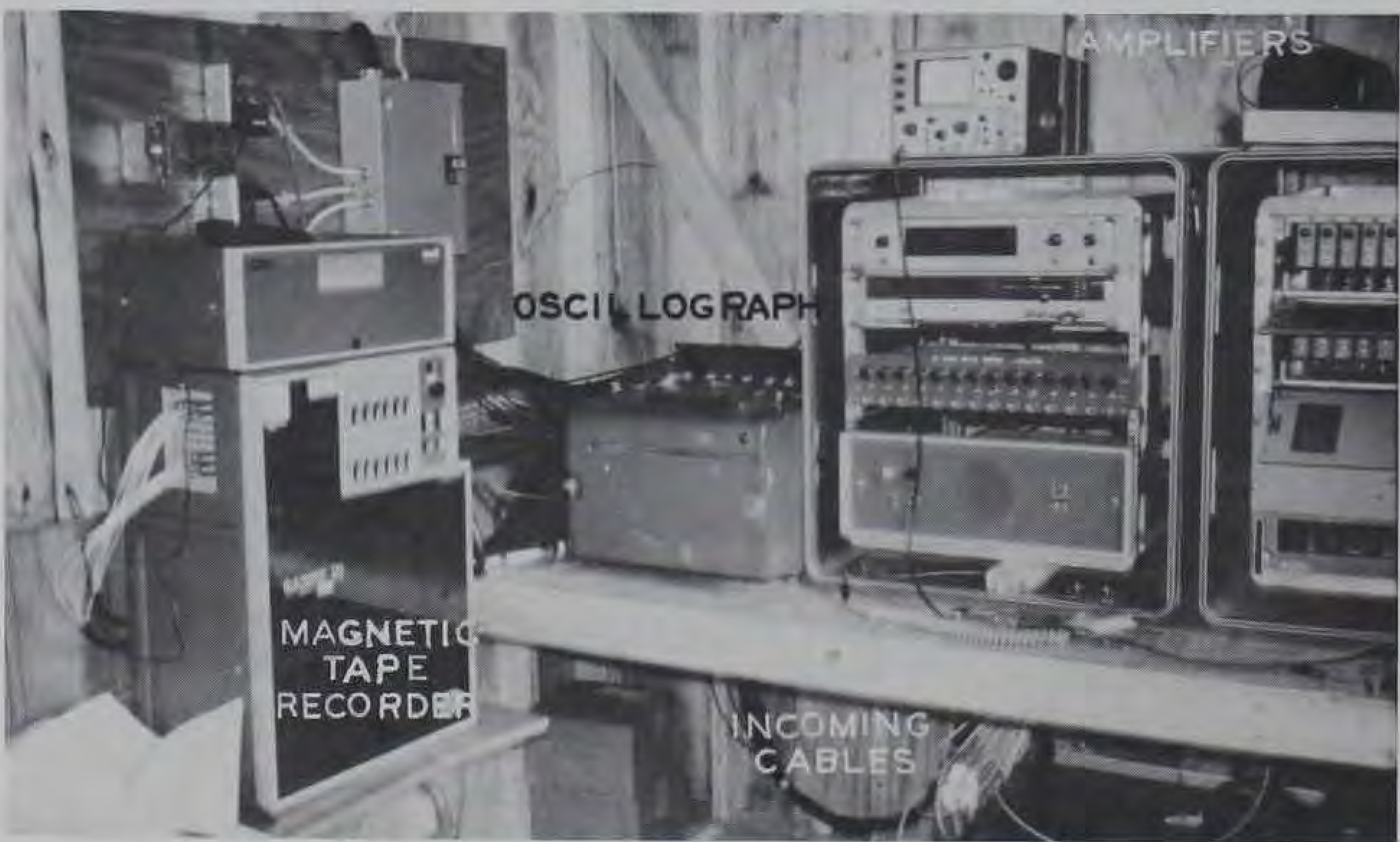

Figure 6. Recording equipment

32-channel, frequency modulated, magnetic-tape recorder (the Barkley data were recorded at 10 ips with a frequency response capability up to 10 kHz), and (c) a CEC model 1-119, 12-in. chart, oscillograph capable of reproducing 36 channels of data at a paper speed from 0.25 ips to 160 ips at a frequency response up to 2500 Hz. (Chart speeds used during the gate tests were 0.5 and 4.0 ips.) Figure 6 shows the equipment set up inside the recording shed.

Test Procedures

11. The tests, conducted in March of 1978, were recorded on magnetic tape for 7 min. During each individual test, a portion of the taped data was transferred to the oscillogram to confirm that the data were being recorded and to make a visual check and initial computation of the results.

12. Test procedures were generally the same for both gates 3 and 11, with and without the seal, and consisted of the following:

a. Record test number, date, time, and conditions.

b. Record step calibrations.

c. Raise gate to test position; allow flow to stabilize.

d. Record data on tape and oscillogram at speeds given in paragraph 10.

e. Record upper pool and tailwater elevations, air and water temperatures, and other test conditions.*

f. Record step calibrations.

13. Voice comments on the tapes and notes on the oscillograms were continuously made for later reference. Amplification gain changes (and corresponding calibrations) to improve the recorded signals were made as required during the test periods.

14. During the testing period, the Nashville District requested the additional gate 11 tests for comparison with the gate 3 results. The distance from the recording shed to gate 11 exceeded the existing

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* Test conditions are listed in Table 2.

transducer cable lengths. Since five accelerometers only would be used at gate 11 (paragraph 7) their cable lengths were increased by splicing on the pressure transducer cables which were no longer needed.

15. Cutting the pressure transducer cables would preclude their scheduled posttest laboratory calibration. For this reason they were given a check calibration by lowering them to known depths at the test site prior to cutting. The four pressure transducers were lowered to depths of 3 and 6 ft and the resulting trace shift was recorded for comparison with the step calibrations referenced in paragraph 12. Figure 7 presents the shift for transducer PGS at a depth of 6 ft. It differs from the laboratory calibrations by about 4.5 percent.

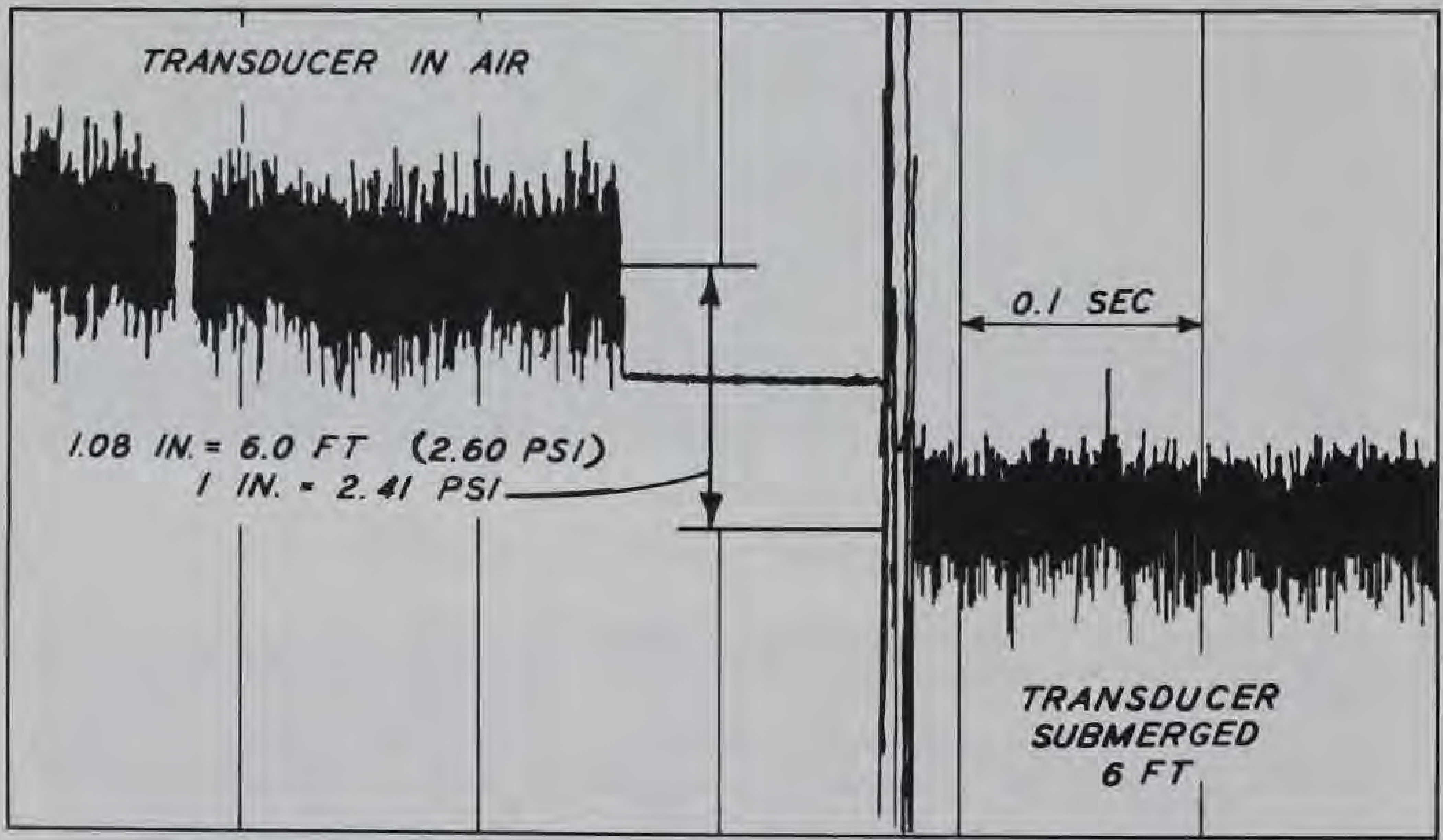

Figure 7. Field calibration of pressure transducer PGS

16. The lip seal was removed from gates 3 and 11 for tests 18, 19, and 25 (no-seal tests). This was accomplished by removing the gate seal backplate (Figure 3) while moving across the gate bay on a small barge as shown in Figure 8.

17. During the gate 3 tests (seal in place), a vertical support between the upper and middle left struts was observed vibrating rather violently. In order to record this action, accelerometer LMT was removed from the middle left strut and placed on this member. It was then

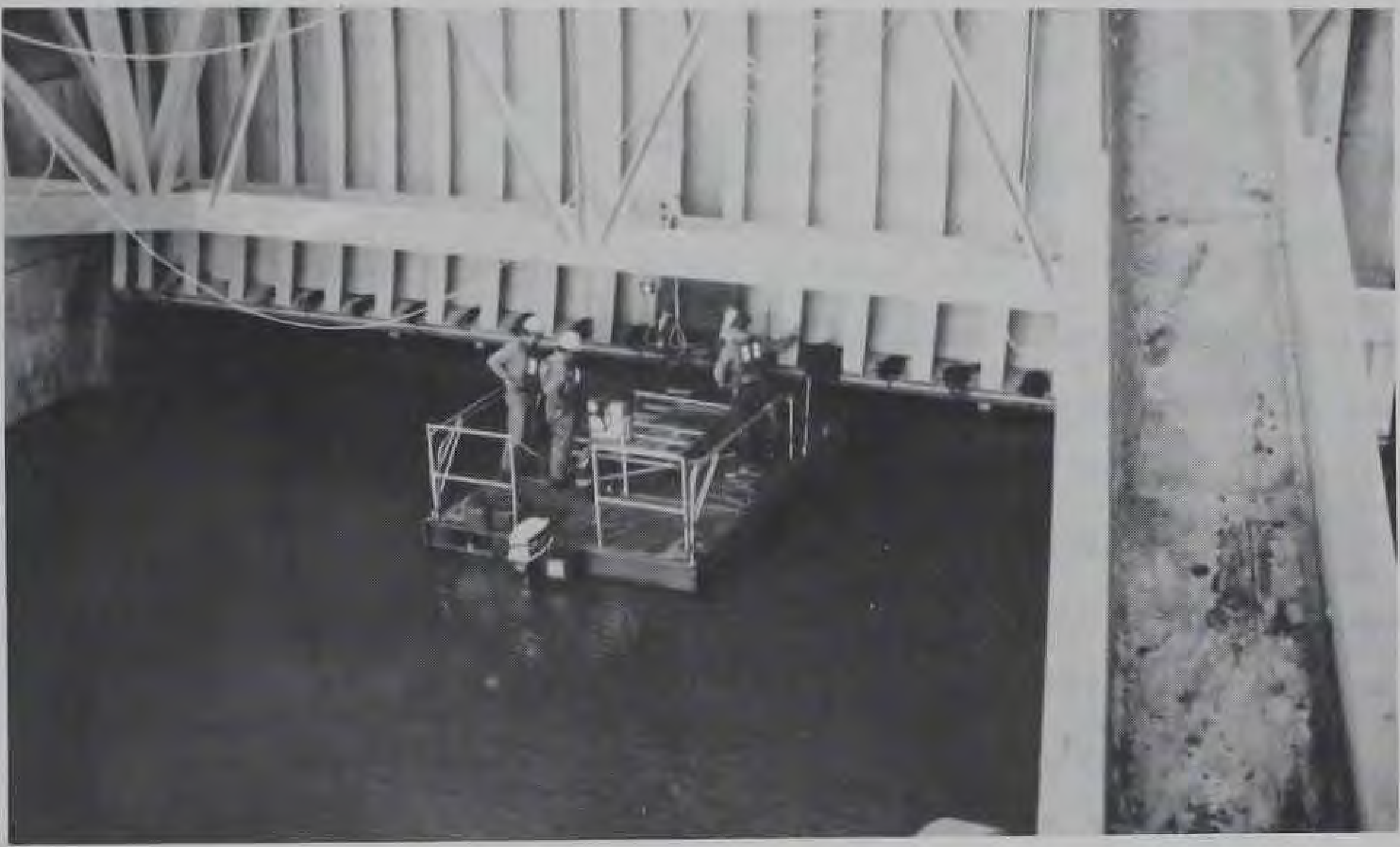

Figure 8. Removing gate 3 seal (looking upstream)

designated transducer LMTV (Table 1 and Plate 2) and left on the vertical member for the remaining gate 3 tests. To determine the natural frequency of this member, a "ring" test was conducted by tapping it with the plastic handle of a screwdriver (Figure 9) and recording the results for subsequent computations.

Figure 9. Support member LMTV "ring" test

PART III: TEST RESULTS AND ANALYSIS

General

18. The Barkley Dam tainter gates vibrate when discharging under certain lip submergence conditions caused by high tailwater.[1] Field observations and data analysis indicate that this submergence has two major effects on the gates. During submergence the upper streamlines of the flow are apparently altered so that this portion of the flow intermittently strikes the gate lip seal causing a continuous shifting of the flow control point and creating pressure fluctuations. A second effect is apparently due to the depth of tailwater submergence, i.e., as the back pressure on the lip increases with submergence the vibration intensity decreases.

Theoretical Streamlines

19. Theoretical streamlines for flow under the tainter gates at Barkley Dam were developed from procedures given in a report in preparation.[2] The report is concerned with flow conditions of a jet discharging from an orifice or an infinitely wide slot into a free stream environment and adaptable to conditions below a large tainter gate.

20. Conditions existing in a slot are shown in Figure 10a where b/B is the aperture-to-conduit ratio (also known as the height ratio) and β is the angle of deflection. These conditions were adapted to accommodate flow under a tainter gate as shown in Figure 10b by letting $b/2$ represent the gate opening and $B/2$ the difference between the upper pool and spillway crest elevations. The angle of deflection, β, for the tainter gate was determined from geometry and entered into the analysis to determine the contraction coefficient, C_c. Using the angle of deflection, contraction coefficient, and height ratio as input, the computer program (described in the referenced report) was used to plot the free streamline profiles.

21. The Barkley gate configuration and test gate openings were

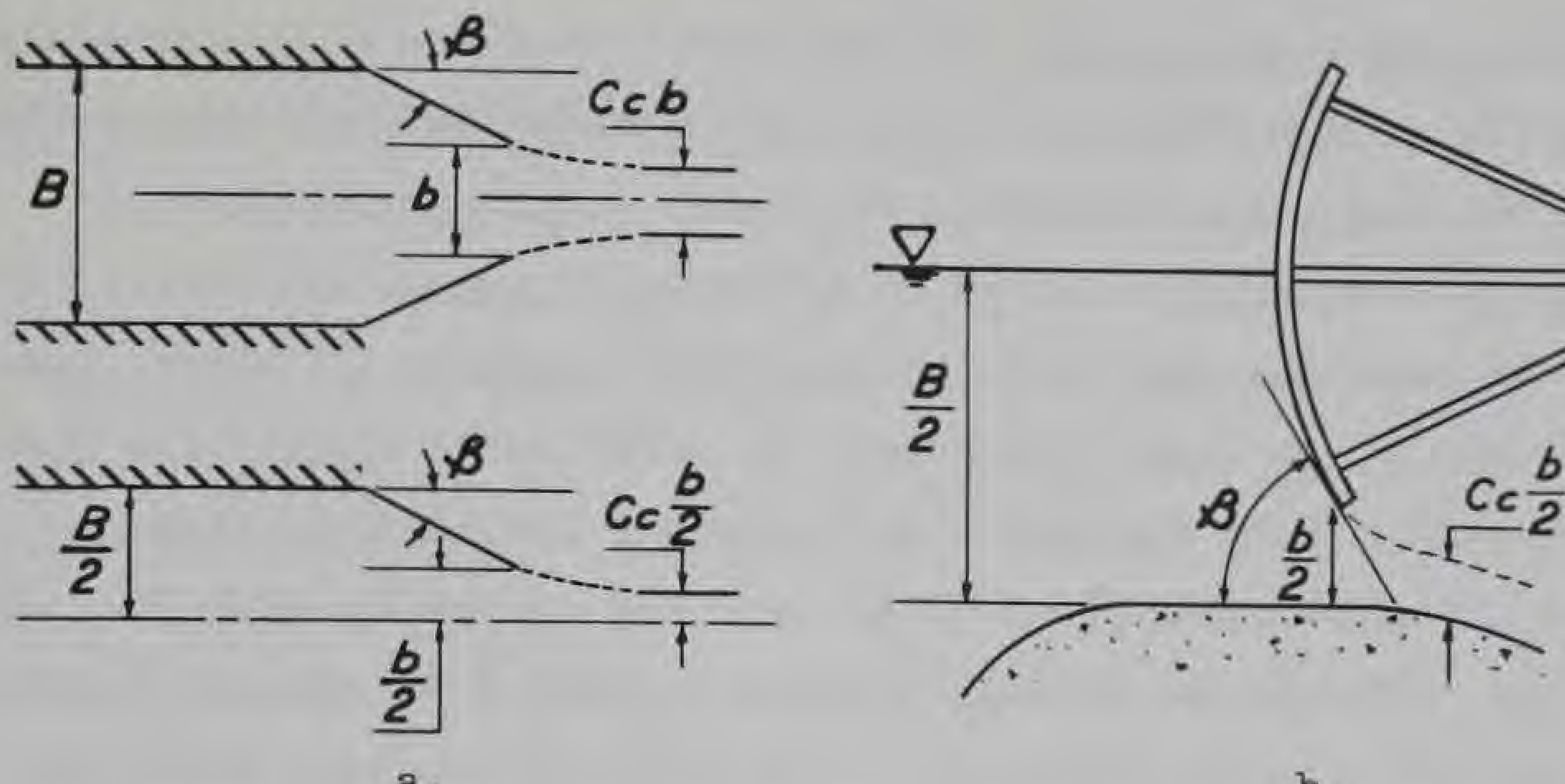

Figure 10. Conduit and gate flow configurations

applied to the analysis. The resulting plots for openings of 3.6, 4.2, and 8.6 ft are shown in Plate 3. In all three cases the flow springs free of the gate seal for these unsubmerged conditions.

Streamline Alteration

22. To determine the degree of adverse effect (vibrations) caused by the gate lip seal, tests were made with and without the seal in place. Table 3 presents a comparison listing of three identical test sets for all transducers with and without the lip seal. In the last column of each of the three series a seal/no seal ratio is listed.

23. In all but two cases, removal of the seal decreased the vibrations. Excluding these two exceptions the ratio varied from a low of 0.04 (CBR, 3.6-ft gate opening) to a maximum of 74.0 (SBR, 4.2-ft gate opening). The mean ratio value is 15.0. This excludes the high ratio for the vertical support LMTV which will be discussed subsequently.

24. The effect of seal removal is further illustrated by results from the time series analysis of the magnetic tape data. Plate 4 presents a comparison of accelerations for identical conditions except for seal removal. These data are from transducer CMP which was mounted in the gate center near the skin plate (Plate 2) and responded to movement tangent to the skin plate thereby representing gate movement in the

vertical plane. The probability density plots of Plate 5 indicate that the probability of a particular acceleration occurring is considerably higher with the seal than without. For example, the probability of experiencing an acceleration of ± 0.02 g's with the seal in place is about 5 percent. Without the seal this level of acceleration is almost nonexistent. Finally, in Plate 6 the test 10 (with seal) cumulative distribution function (CDF) indicates a 95 percent probability of an acceleration of approximately ± 0.12 g's or less occurring with the seal in place. The CDF for the no seal condition shows a 95 percent probability of ± 0.004 g's or less occurring. Thus the seal/no seal ratio for the 95 percent probable acceleration is 30.0.

Submergence Effect

25. Table 3 and Plate 7 show that vibration displacements recorded at gate 11 (tests 24 and 25) are higher in all cases than the corresponding transducer recordings for gate 3. Table 2 indicates that head differential is almost identical for all tests. Gate 3 openings, however, are about half those of gate 11, creating a gate 3 to gate 11 tailwater gate lip submergence ratio of about 2.5 to 1. It would then ppear that gate lip submergence and vibration intensity are related.

26. Data taken from the transducers common to both gates were used to compute a best-fit line relating vibration displacement and lip submergence. The average slope of this line was found to be -2.6×10^{-3} (Figure 11). This implies that for each foot of increased submergence, gate displacement (pk-pk) decreases 2.6×10^{-3} ft or 0.031 in. Though the relation is not actually linear, it is felt that the graph provides a rough approximation of the submergence-displacement relation at Barkley Dam.

27. Information from the U. S. Army Engineer District, Little Rock, gate vibration study[3] generally supports the submergence-vibration theory although there is considerable overlap of the data. This information presented for Lock and Dam 6 on the Arkansas River is summarized as follows:

Vibration Level	Range of Tailwater Lip Submergence, ft
Minor	19.5-5.0
Moderate	15.0-5.0
Severe	12.0-4.0

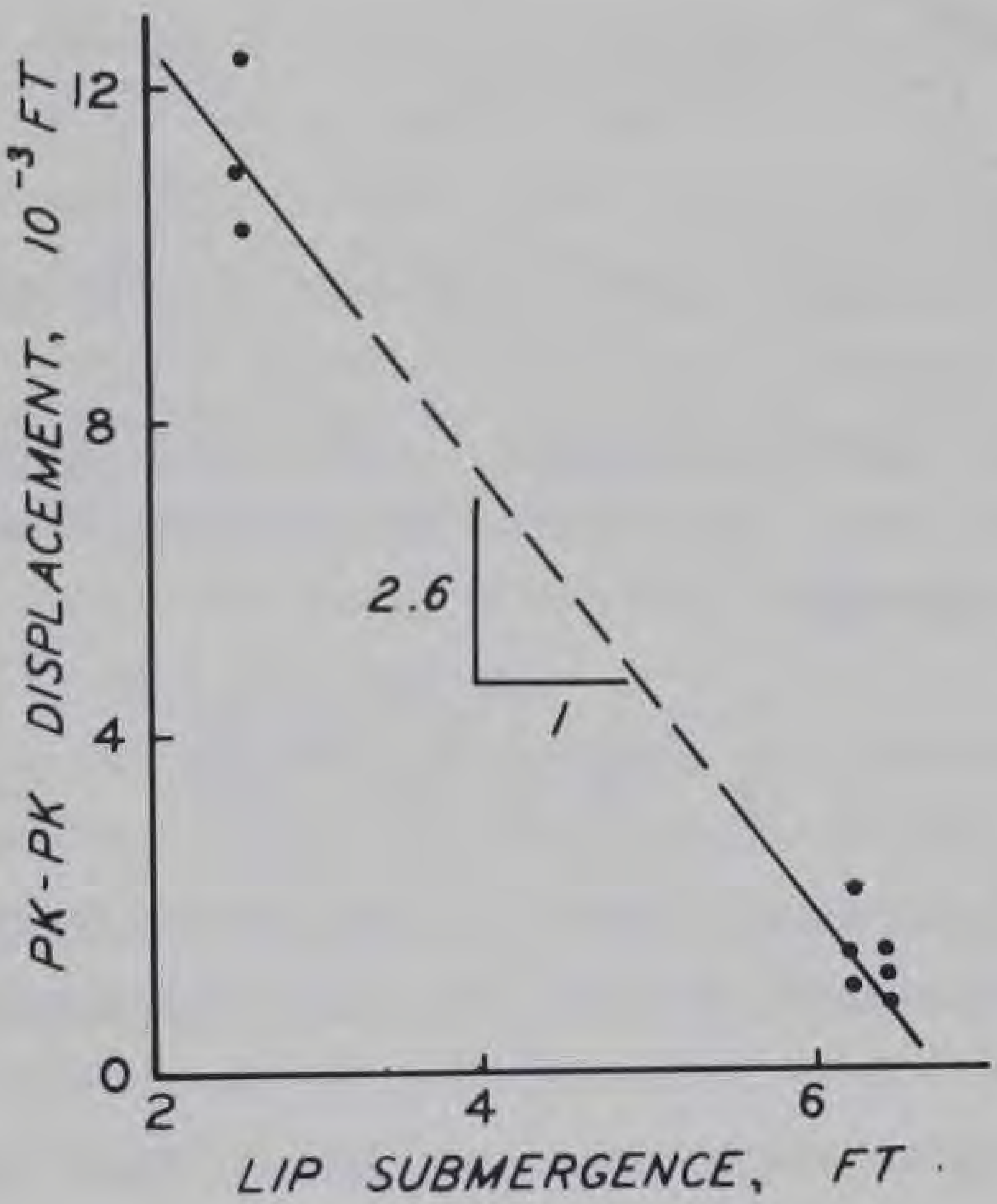

Figure 11. Displacement versus lip submergence

Frequencies

28. An estimated natural gate frequency was calculated to compare with the frequencies recorded in the test series. From this it could be determined if, under test conditions, the gates vibrated at or near their natural frequency. To make this calculation the gate configuration was converted from a complicated arrangement of metal to a simple spring mass system as shown in Figure 12. The impingement point of the

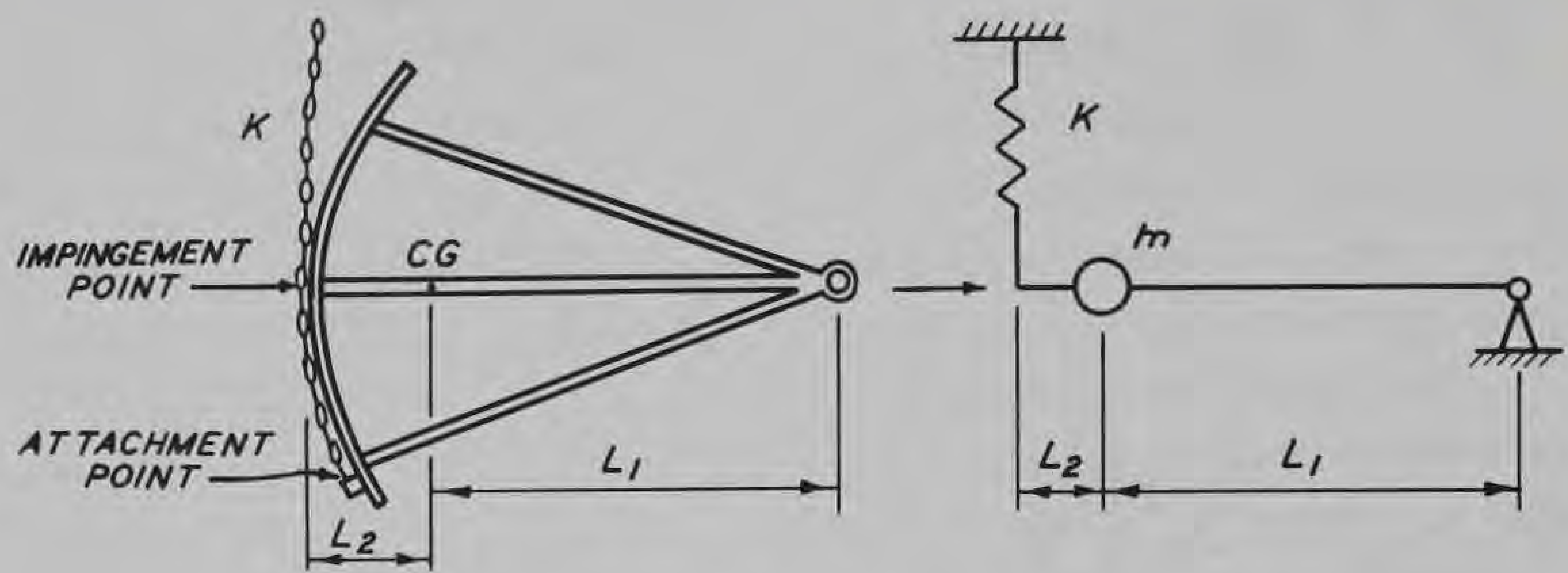

Figure 12. Mass-spring simulation of Barkley gates

chain with the skin plate was assumed to represent the attachment point of the chain to the gate. The natural frequency of the gate was calculated from the equation:

$$f_n = \frac{1}{2\pi} \left(\frac{L_1 + L_2}{L_1}\right)\sqrt{\frac{K}{m}} \qquad (1)$$

and found to be approximately 5 Hz. If the length of chain is assumed to extend to the attachment point on the gate, the calculated frequency is about 4 Hz.

29. The transducer CMP whose location is shown in Plate 2 and defined in Table 1 measured acceleration tangent to the skin plate. Results from this transducer, as stated previously, represent the vibrations of the gate system in the vertical plane. A Fast Fourier Transform (FFT) of the magnetic tape data of the tests was accomplished to compare predominant test frequencies with the gate's natural frequency. Plate 8 presents the FFT's for transducer CMP during tests 9 and 10 which were made with the lip seal in place. The FFT's of CMP for tests 18 and 19 (no seal) are shown in Plate 9. All four tests were conducted with gate 3.

30. In all four plots of these two plates, prominent frequencies appear as isolated spikes. The more prominent of these occur during tests 9 and 10 in which the seal was in place. In both of these tests

the prominent frequencies were about 29 and 44 Hz, the former corresponding closely to the gate lip pressure fluctuations which will be discussed in a subsequent section (paragraph 40).

Strouhal Number

31. The Strouhal number is the proportionality constant between the predominate frequency of vortex shedding and an appropriate length parameter divided by the free stream velocity.[4]

> The unsymmetrical vortex formation behind the component in question gives rise to a lateral thrust or lift with a frequency f . If the component is not rigidly supported, an oscillatory motion normal to the free stream velocity will develop, especially if the frequency or vortex formation is close to its natural frequency of vibration.[5]

Since this is a possible explanation for the Barkley Dam gate vibrations, it was deemed worthy of investigation.

32. The flow velocity at the gate lip was calculated to be 41.8 fps (using measured static (mean) pressures at the lip which were available for tests 9 and 10, and data from Table 2). The lip thickness (2 in.), which included the seal, was used as the length parameter (see Plate 3). This information was used to calculate the Reynolds number (R). Assuming the length dimension to represent the bottom side of a square section, Reference 4 indicated that the Strouhal number for the calculated R would be 0.12. Therefore

$$S = \frac{fL}{V} \quad \text{or} \quad f = \frac{SV}{L} = \frac{(0.12)(41.8)}{(2/12)} = 30.0 \text{ cps}$$

where

S = Strouhal number

f = lateral thrust frequency

L = length parameter (lip thickness)

V = velocity

Although this shedding frequency is much higher than the calculated natural frequency of the gate, it compares closely with the values given in paragraphs 30, 35, 37, and 40 and Plate 8.

Other Gate Members

33. During some of the tests visible vibration of gate support members was noted; an example is the vertical support designated LMTV (Plate 2). An accelerometer was placed on this member and its response recorded during tests 10, 18, and 19 as shown in Table 3. During test 10 a relatively high peak-to-peak displacement of 0.026 ft was recorded. For these three tests the average predominant recorded frequency was 28.6 Hz. The calculated first mode of vibration for a wide flange beam of equal area and length is 22.1 Hz.

34. A "ring" test was conducted by tapping the member LMTV with the handle of a screwdriver as shown in Figure 9. The recorded response is shown in Plate 10. Also shown in the lower left plot is the FFT of this ring test response. Note the first spike at approximately 30 Hz. The lower right plot shows the frequency of response of LMTV during test 10 (also presented in Table 3), again within the area of the calculated natural frequency of the member. Consideration should be given to some form of bracing to alter the natural frequency of this and any other observed oscillating members.

35. Another example is member LTT (left top strut member, see Plate 2). As shown in Table 3 for test 10 this member's predominant frequency of vibration is 29.3 Hz which corresponds closely to the gate lip pressure fluctuations discussed in paragraph 40.

Beat Frequency

36. When the forced frequency is close to but slightly different from the natural frequency of a component, a vibration takes place in which the amplitude builds up and then diminishes, repeating the process continuously.[6] This phenomenon is known as "beating" and was recorded at some of the Barkley gate accelerometer locations, primarily on the struts. Plate 11 presents an example of strut vibrations at transducer LMT.

37. The amplitude envelope shown in Plate 11 fluctuates at a rate

equal to the difference frequency.[7] The frequency of this periodic increase and decrease of amplitude is defined as the beat frequency. Therefore

$$f_b = f_n - f_f = \frac{1}{\tau_b} \tag{2}$$

where

f_b = beat frequency

f_n = natural frequency

f_f = forcing frequency

τ_b = beat period, time between points of equal phase

From Plate 11 τ_b was determined to be 0.33 sec so that f_b = 3.05 Hz. In other words f_n and f_f differ by this amount, being in (and out of) phase every 0.33 sec. From Equation 2 the natural frequency at the point of transducer LMT can be found to be 32.4 Hz. (The forcing frequency f_f, for transducer PGL was measured to be 29.3 Hz.)

Frequency Lock-In (Feedback Loop)

38. Locher[8] states that in order to initiate flow-induced vibrations, some kind of fluid-dynamic "feedback" is necessary. This theory is also discussed by others.[4,9,10,11]

39. A very brief description of the feedback loop, based on the references, follows:

a. A shear layer forms whenever flow separates from a boundary (as the upstream corner of the Barkley gate lips). Because the innermost portion of the layer moves much slower than the outermost portion, the layers roll up into discrete, swirling vortices (Figure 13).

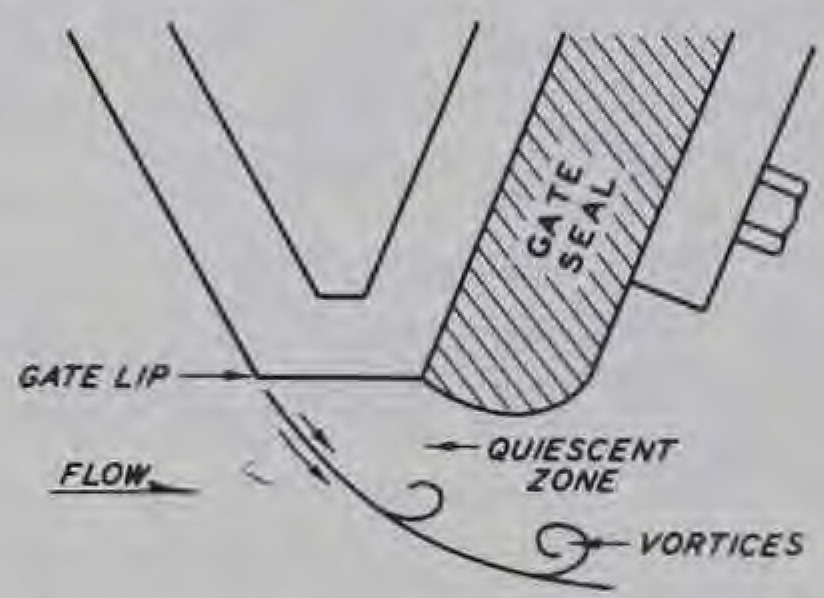

Figure 13. Submerged gate lip conditions

b. After these initial disturbances are amplified and convected downstream, they interact with the boundaries of the flow field (as, possibly, the gate seal) producing more disturbances. These, in turn, are partially transmitted back to the origin and trigger new disturbances which then proceed through the cycle. Because this is a selective amplification mechanism, the new disturbances result in fluctuations with a much narrower range of frequencies than the original perturbations. With subsequent cycles the fluctuations become more nearly periodic. Thus, interaction of the flow with its boundaries coupled with selective amplification forms what may be described as a "feedback loop." Naudascher[10] summarizes this phenomenon: "Although the fluctuating flow is the origin of the structural vibration, its pattern, periodicity, and intensity are ultimately dominated by the latter, and the vibration becomes sustained by a self-generated exciting force."

40. Plates 8 and 12 show that with the gate seal in place the gate vibrates and the pressures fluctuate at a discrete, common frequency of about 30 Hz. On the other hand, with the seal removed, Plates 9 and 12 show that the oscillations are more random and of small magnitude. A cross-spectral density calculation of transducers CMP (gate acceleration) and PGL (gate lip pressure fluctuations) was made and the plot is shown in Plate 13. The very prominent spike at 28.3 Hz implies a strong correlation at that frequency. As an additional check, short-time history segments of these two recorded signals were arbitrarily selected from test 10 (seal in place) and plotted as shown typically in Plate 14. The phase shift ϕ between the two phenomena was constant within a range of ± 5 percent for all segments evaluated.

41. These results could be evaluated as follows:

a. The occurrence of a discrete frequency correlation and constant phase with the seal in place indicates the presence of the feedback phenomenon occurring due to the wider lip boundary.

b. When the boundary width is shortened by removing the seal, feedback does not occur and the energy is transferred to turbulence leading to a predominantly periodic excitation.

PART IV: CONCLUSIONS AND RECOMMENDATIONS

Conclusions

42. The following determinations and conclusions result from field observations and analyses of the data reduction of the Barkley Dam gate vibration prototype tests.

- a. During gate lip submergence the Barkley Dam gates vibrate at certain gate openings.
- b. The degree of vibration intensity decreases with increasing gate lip submergence.
- c. On the average the severity of gate vibrations is 15 times greater with than without the lip seal.
- d. The natural frequency of the gate is in the neighborhood of 5 Hz.
- e. The predominant pressure fluctuation frequency at the gate lip is approximately 30 Hz.
- f. Some gate support members vibrate near their natural frequency at certain gate openings.
- g. The vibrations could be due to the feedback phenomenon caused by the wide lip boundary existing when the seal is in place.

Recommendations

43. It is recommended that the following structural and operational alterations be considered:

- a. Structural alterations.
  - (1) Removal of the gate seal is an obvious alteration that will reduce vibrations. This procedure is recommended by OCE,[3] "...unless water conservation requirements could not tolerate normal leakage."
  - (2) If the leakage due to the removal of all seals cannot be tolerated, consideration should be given to removing the seal from a few gates which would be the primary operating gates (for example, the middle four gates).
  - (3) Other possibilities include:
    - (a) A narrower rubber seal.

(b) Grinding the metal portion of the lip to a narrower width.

(c) Placing the rubber seal in the gate sill bearing plate.

(d) Installation of vibration absorbers.

(4) Vibrating support members should be braced or otherwise altered to change their natural frequency.

b. Operational alterations.

(1) When the tailwater elevation is only a small distance above the sill, use fewer gates at higher openings so that their lips are not submerged.

(2) When the tailwater elevation is high relative to the sill, use all gates with minimum openings to maximize the back pressure on the gate lips.

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Table 1

Barkley Dam Gate Vibrations Transducer Information

Transducer	Location on Gate	Measurement Direction	Range
	Acceleration		
CTR*	Girder flange, center top	Radial	±5g
CMR	Girder flange, center middle	Radial	↓
CMP	Girder flange, center middle	Peripheral	↓
CMT	Girder flange, center middle	Transverse	↓
SMR*	Skin plate, middle upper	Radial	↓
CBR	Girder flange, center lower	Radial	↓
SBR*	Skin plate, middle lower	Radial	↓
CLR	Rib, center bottom	Radial	↓
LTT*	Strut, left** top	Transverse	↓
RTT*	Strut, right top	Transverse	↓
LMT†	Strut, left middle	Transverse	↓
RMT	Strut, right middle	Transverse	↓
LBT	Strut, left bottom	Transverse	↓
RBT	Strut, right bottom	Transverse	↓
LMTV†	Support beam, upper left	Radial	↓
	Pressure		
PGP	Girder, center bottom	Vertical	25 psia
PGS	Skin plate, 6 in. above lip	Radial	↓
PGL	Center, lip	Vertical	↓
PGC	Center, behind seal	Vertical	↓

* Transducers used in gate 11 tests.
** Looking downstream.
† Same transducer used at both locations.

Table 2

Test Conditions, Barkley Dam Gate Vibrations - March 1978

Test No.	Gate No.	Seal/ No Seal	Date March 1978	Upper Pool El	Tail-water El	Head Diff ft	Gate Lip El	Indicated Gate Opening ft*	Actual Gate Opening ft*	Lip Sub-mergence ft	Bay Discharge cfs	Air Temp °F	Water Temp °F
9	3	Seal	21	354.3	333.7	20.60	327.20	3.60	3.08	6.5	4,446	55	51
10	3	Seal	22	354.0	334.0	20.00	327.73	4.20	3.61	5.27	5,190	56	50
18	3	No seal	22	354.2	334.1	20.10	327.73	4.20	3.61	6.37	5,190	63	51
19	3	No seal	22	354.2	334.1	20.10	327.20	3.60	3.08	6.90	4,442	62	51
24	11	Seal	24	354.5	334.3	20.20	331.69	8.60	7.57	2.61	10,622	48	52
25	11	No seal	25	354.9	334.1	20.80	331.69	8.60	7.57	2.41	10,698	41	52

* Openings which appeared to produce the most severe gate vibrations. Actual gate opening is the calculated vertical opening between the gate sill and gate lip.

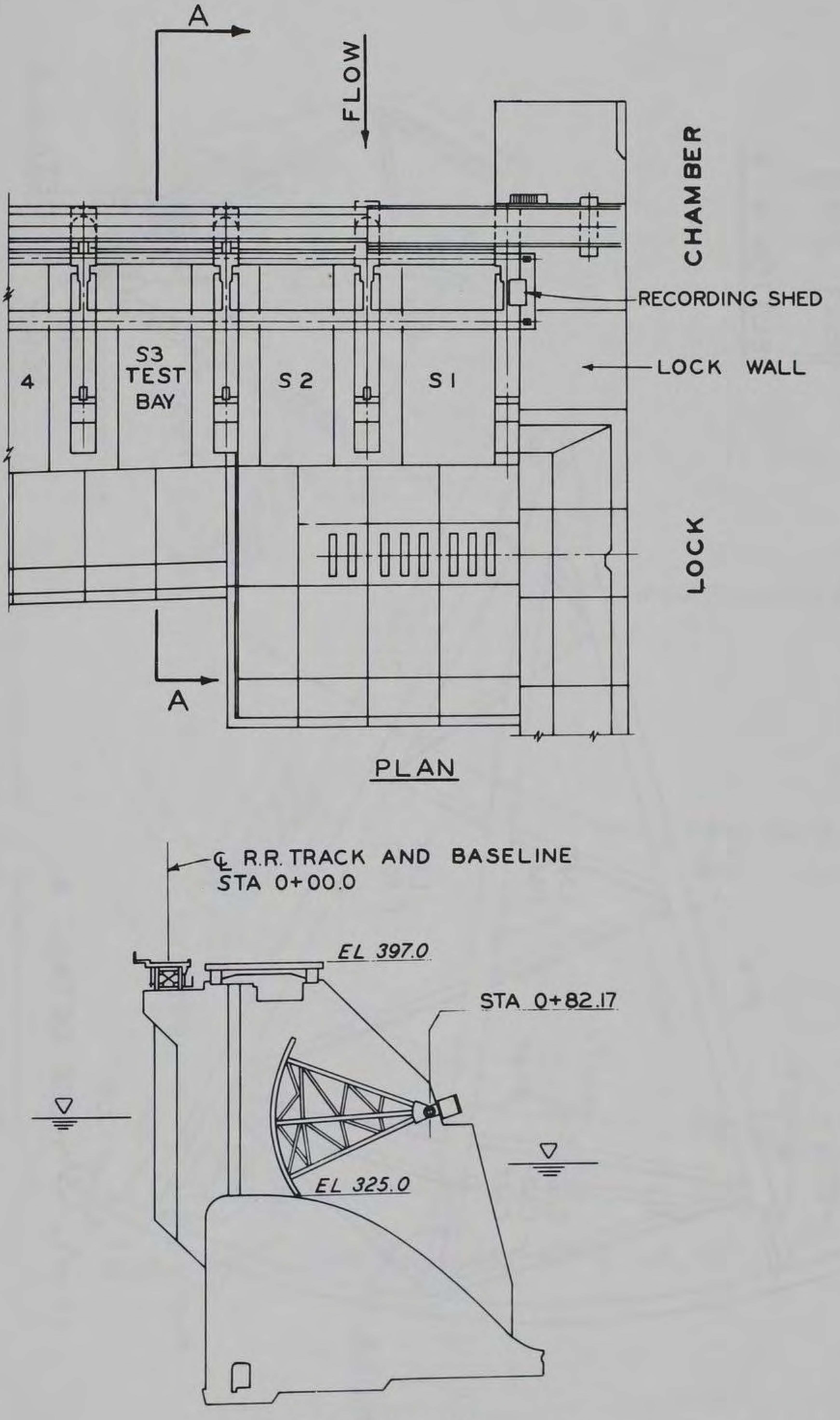
Table 3

Maximum Peak-Peak Displacements and Pressure Fluctuations

Transducer*	Test 9** Gate 3, G.O. 3.6', Seal Pk-Pk Displacement 10^{-3} ft	Pk-Pk Pressure ft-H_2O	Frequency Hz	Test 19 Gate 3, G.O. 3.6', No Seal Pk-Pk Displacement 10^{-3} ft	Pk-Pk Pressure ft-H_2O	Frequency Hz	Pk-Pk Displacement Ratio Seal / No Seal	Test 10 Gate 3, G.O. 4.2', Seal Pk-Pk Displacement 10^{-3} ft	Pk-Pk Pressure ft-H_2O	Frequency Hz	Test 18 Gate 3, G.O. 4.2', No Seal Pk-Pk Displacement 10^{-3} ft	Pk-Pk Pressure ft-H_2O	Frequency Hz	Pk-Pk Displacement Ratio Seal / No Seal
LTT	0.96	--	28.32	0.12	--	18.55	8.00	1.02	--	29.29	0.16	--	17.58	6.37
CTR	0.12	--	56.64	0.01	--	31.25	12.00	0.01	--	113.28	0.02	--	31.25	0.50
RBT	0.92	--	28.32	0.11	--	17.57	8.36	0.98	--	29.29	0.11	--	17.57	18.91
LMT	1.22	--	28.32	--	--	--	--	--	--	--	--	--	--	--
LMTV	--	--	--	0.09	--	28.32	--	25.69	--	28.32	0.09	--	29.29	285.44
RMT	1.52	--	28.32	0.09	--	16.60	16.89	1.75	--	29.29	0.12	--	16.60	14.58
SBR	1.41	--	28.32	0.00†	--	72.26	--	2.22	--	29.29	0.03	--	39.06	74.00
CBR	0.09	--	56.64	2.15	--	1.95	0.04	0.09	--	56.64	0.00†	--	208.98	--
SMR	0.15	--	112.30	0.00†	--	88.86	--	0.48	--	56.64	0.01	--	81.05	48.00
LBT	0.85	--	28.32	0.06	--	19.53	14.17	1.03	--	29.29	0.07	--	18.55	14.71
RTT	1.11	--	28.32	0.18	--	16.60	6.17	1.37	--	29.29	0.18	--	17.57	7.61
CLR	0.49	--	28.32	0.01	--	38.08	49.00	0.19	--	56.64	0.01	--	39.06	19.00
CMR	0.04	--	56.64	0.02	--	21.48	2.00	0.14	--	29.29	0.02	--	31.25	7.00
CMT	0.03	--	55.66	0.00†	--	341.80	--	0.05	--	56.64	0.00†	--	78.12	--
CMP	0.07	--	56.64	0.00†	--	117.18	--	0.08	--	56.64	0.00†	--	117.18	--
PGC	--	1.24	56.64	--	0.43	1.95	2.88	--	1.44	56.64	--	0.46	30.27	3.13
PGL	--	1.83	28.32	--	0.50	156.25	3.66	--	3.17	29.29	--	0.52	1.95	6.09
PGS	--	1.99	28.32	--	0.40	1.95	4.98	--	2.69	29.29	--	0.35	1.95	7.68
PGP	--	6.95	28.32	--	0.29	1.95	23.97	--	2.38	56.64	--	0.33	1.95	7.21

Transducer*	Test 24 Gate 11, G.O. 8.6', Seal Pk-Pk Displacement 10^{-3} ft	Pk-Pk Pressure ft-H_2O	Frequency Hz	Test 25 Gate 11, G.O. 8.6', No Seal Pk-Pk Displacement 10^{-3} ft	Pk-Pk Pressure ft-H_2O	Frequency Hz	Pk-Pk Displacement Seal / No Seal
LTT	10.40	--	16.60	0.55	--	17.57	18.91
CTR	3.17	--	16.60	0.10	--	24.41	31.70
SBR	11.10	--	16.60	0.00†	--	214.84	--
SMR	4.26	--	16.60	0.00†	--	198.24	--
RTT	12.46	--	16.60	0.55	--	17.57	22.65

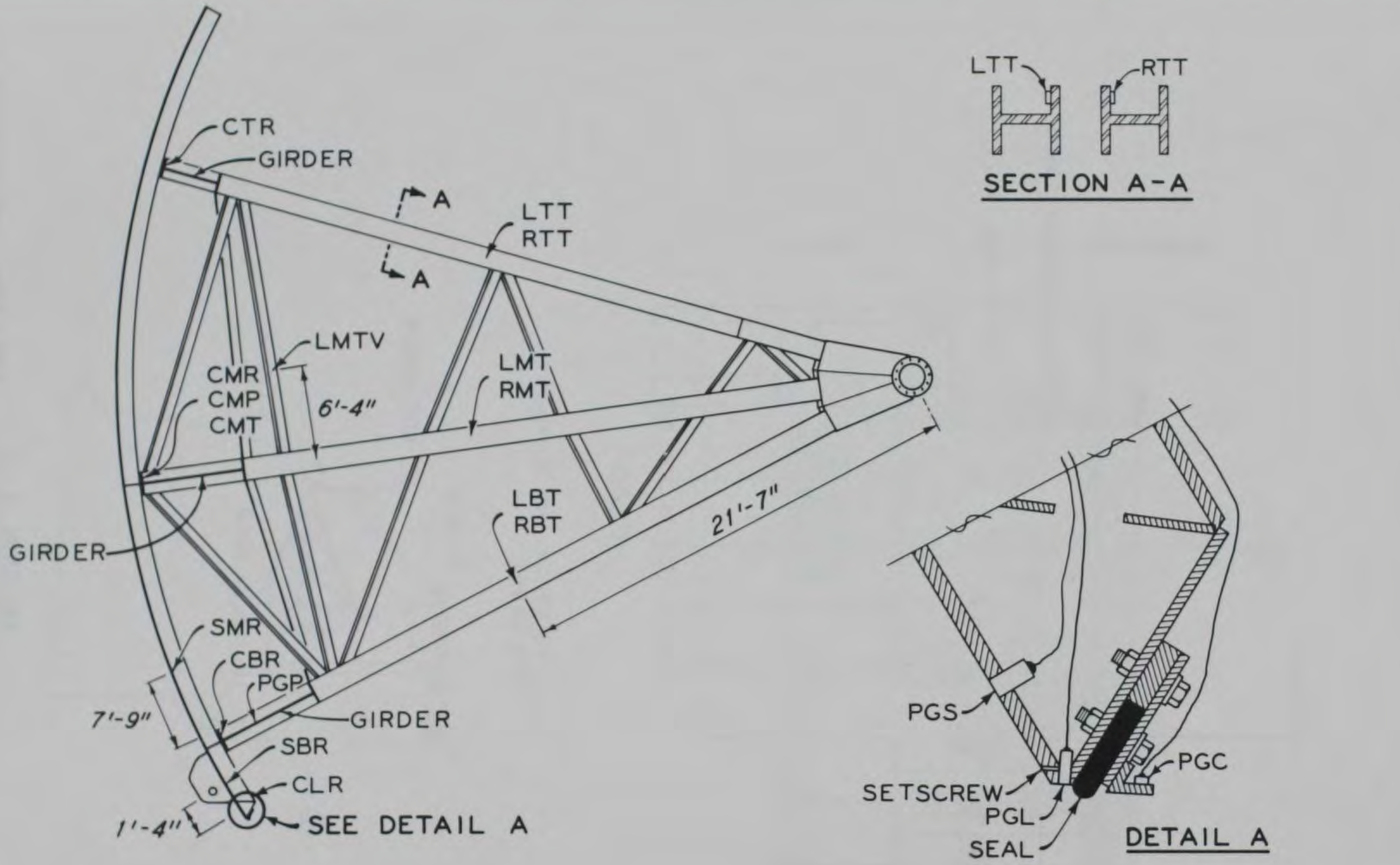
* Transducer coding defined in Table 2 and Plate 2.
** Test conditions listed in Table 1.
† Value less than 0.01 ft (10^3).



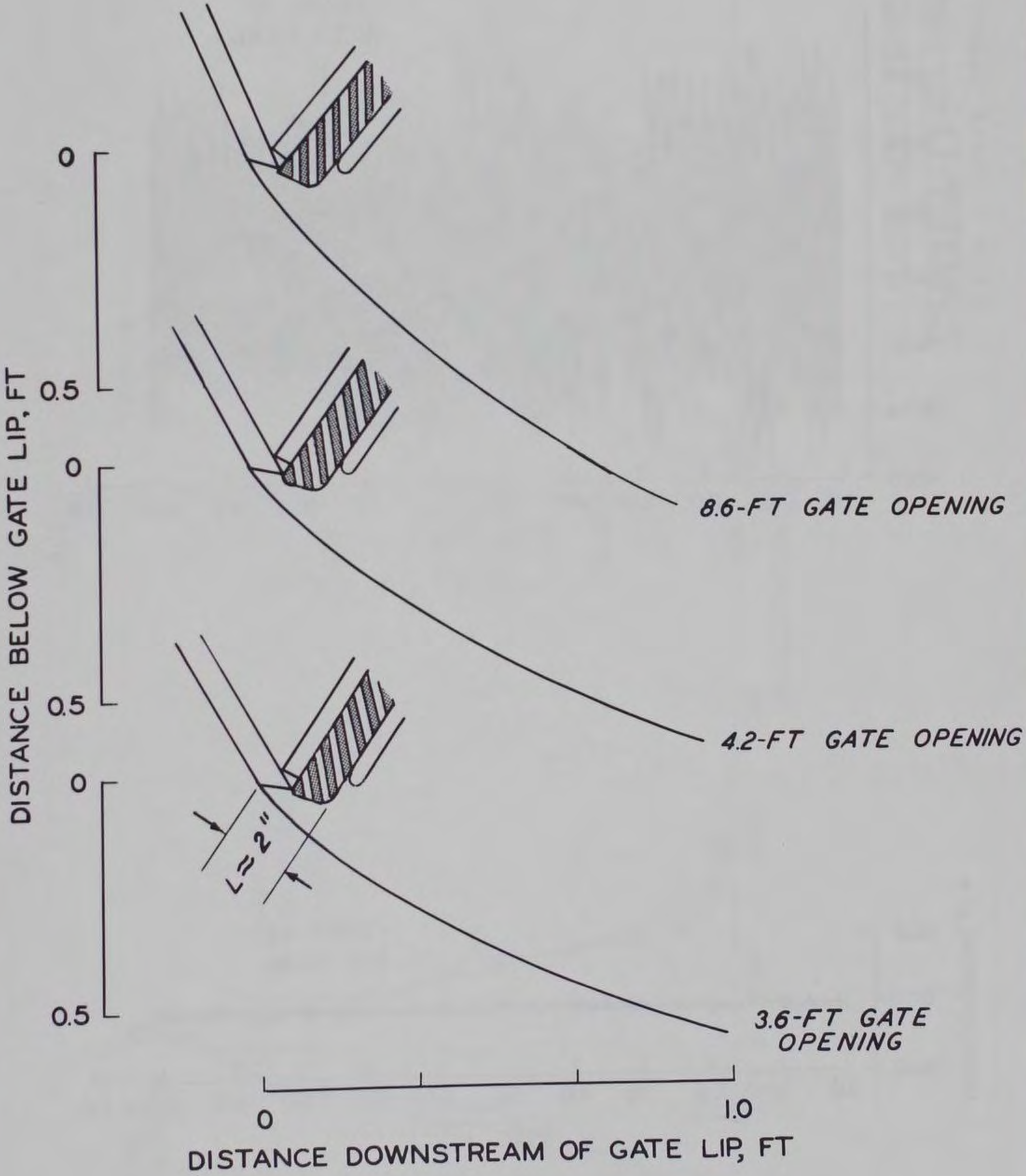
SPILLWAY AND GATE PLAN
AND SECTION

PLATE 1

PLATE 2



INSTRUMENTATION LOCATIONS
GATE 3



STREAMLINE FOR
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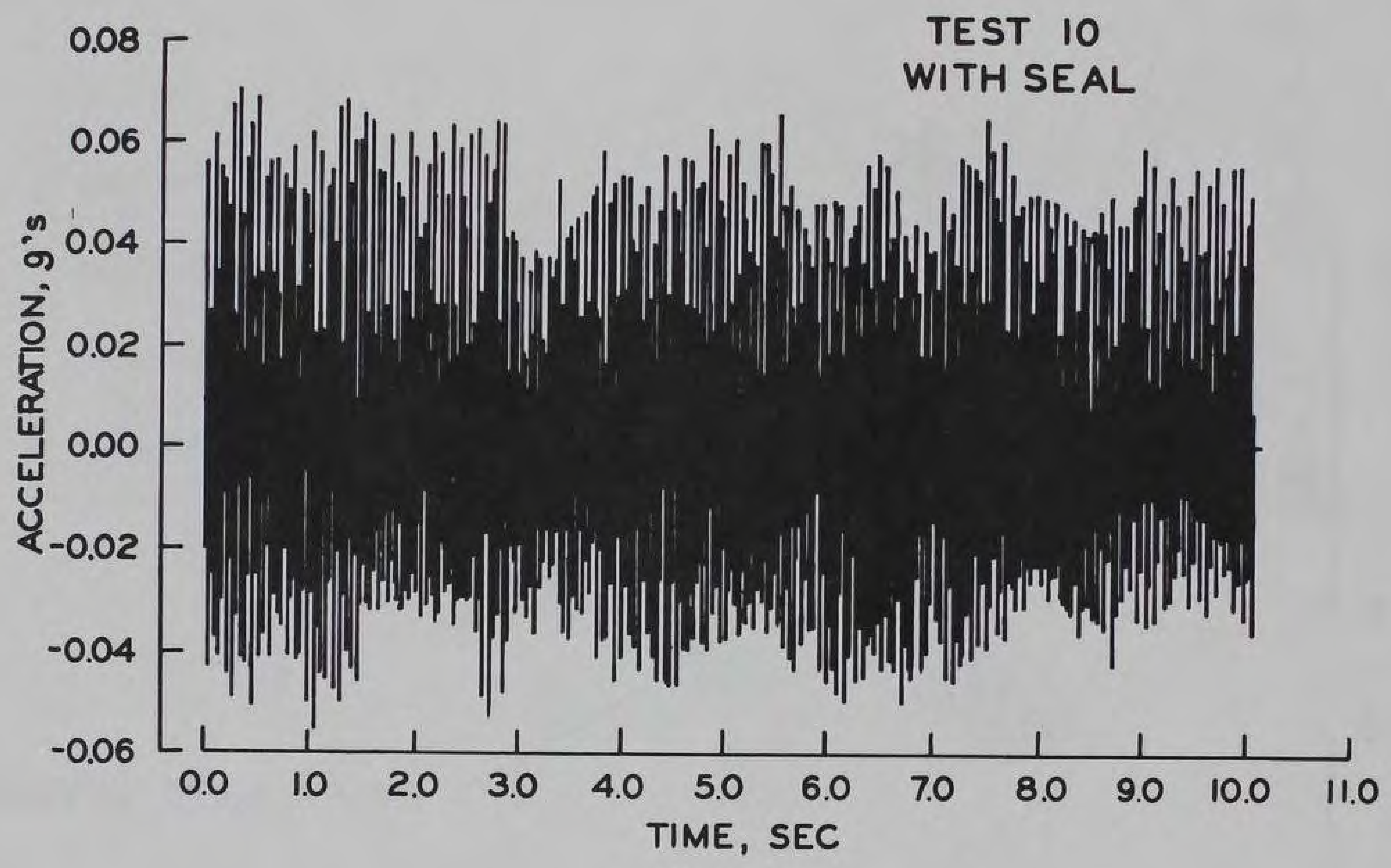
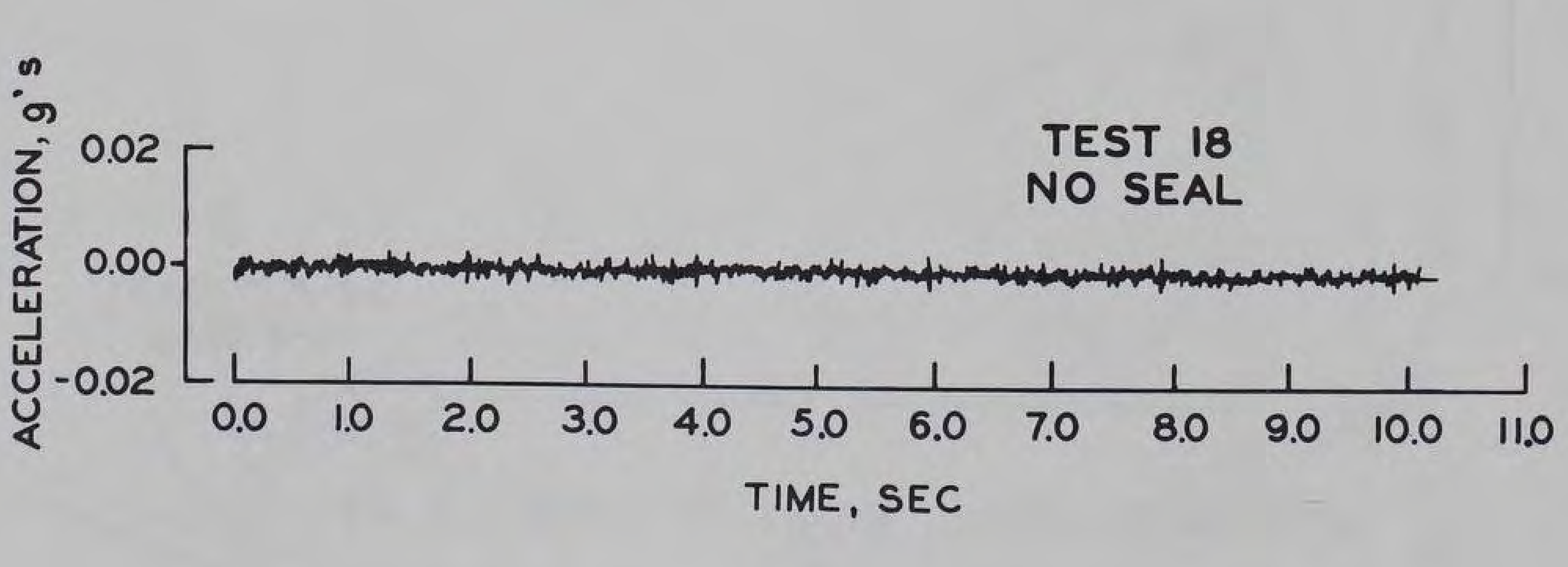
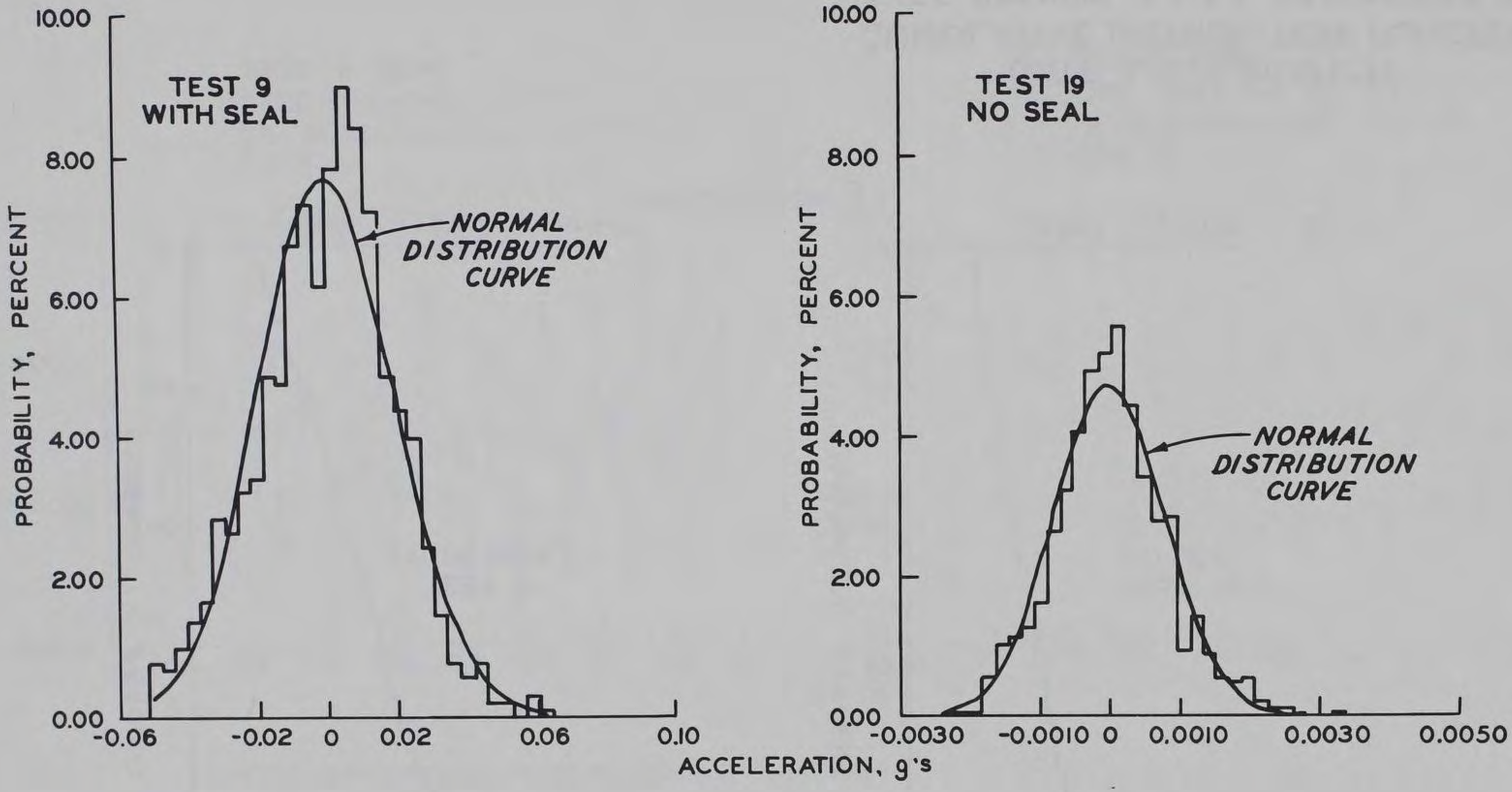




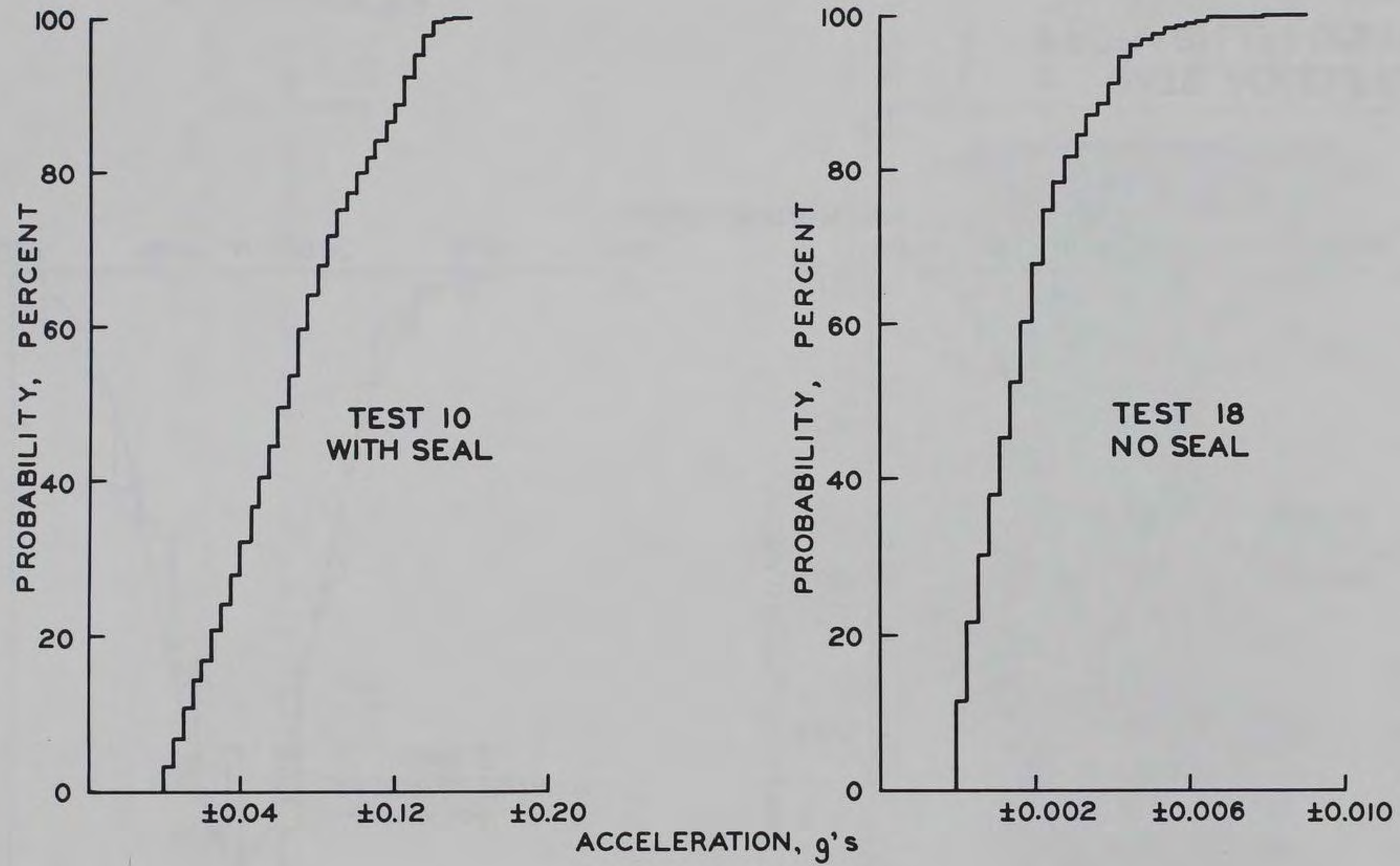
GATE ACCELERATION INTENSITY

TRANSDUCER CMP

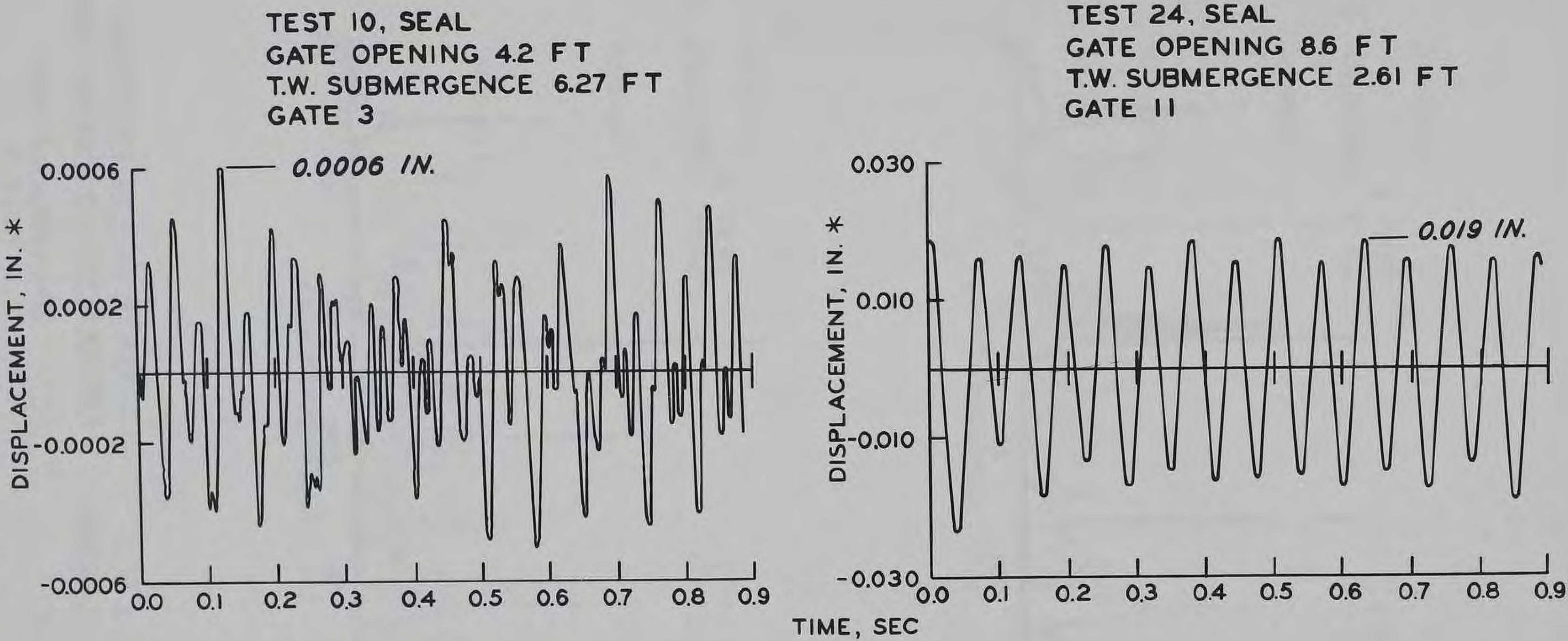
GATE 3, GATE OPENING 4.2 FT



GATE ACCELERATION
PROBABILITY DISTRIBUTION
GATE 3, GATE OPENING 3.6 FT

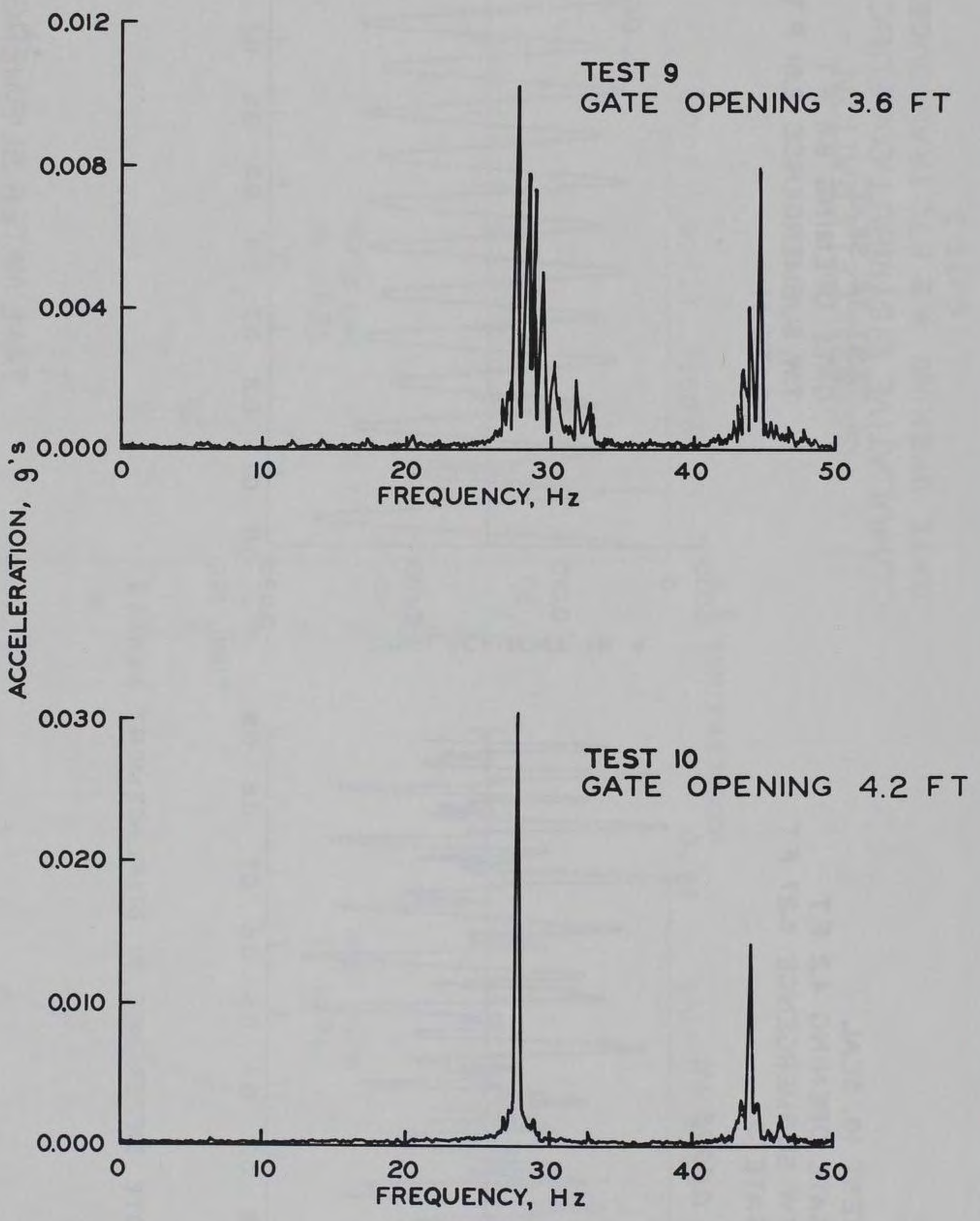


GATE ACCELERATION
CUMULATIVE DISTRIBUTION FUNCTION
GATE OPENING 4.2 FT, TRANSDUCER CMP
GATE 3



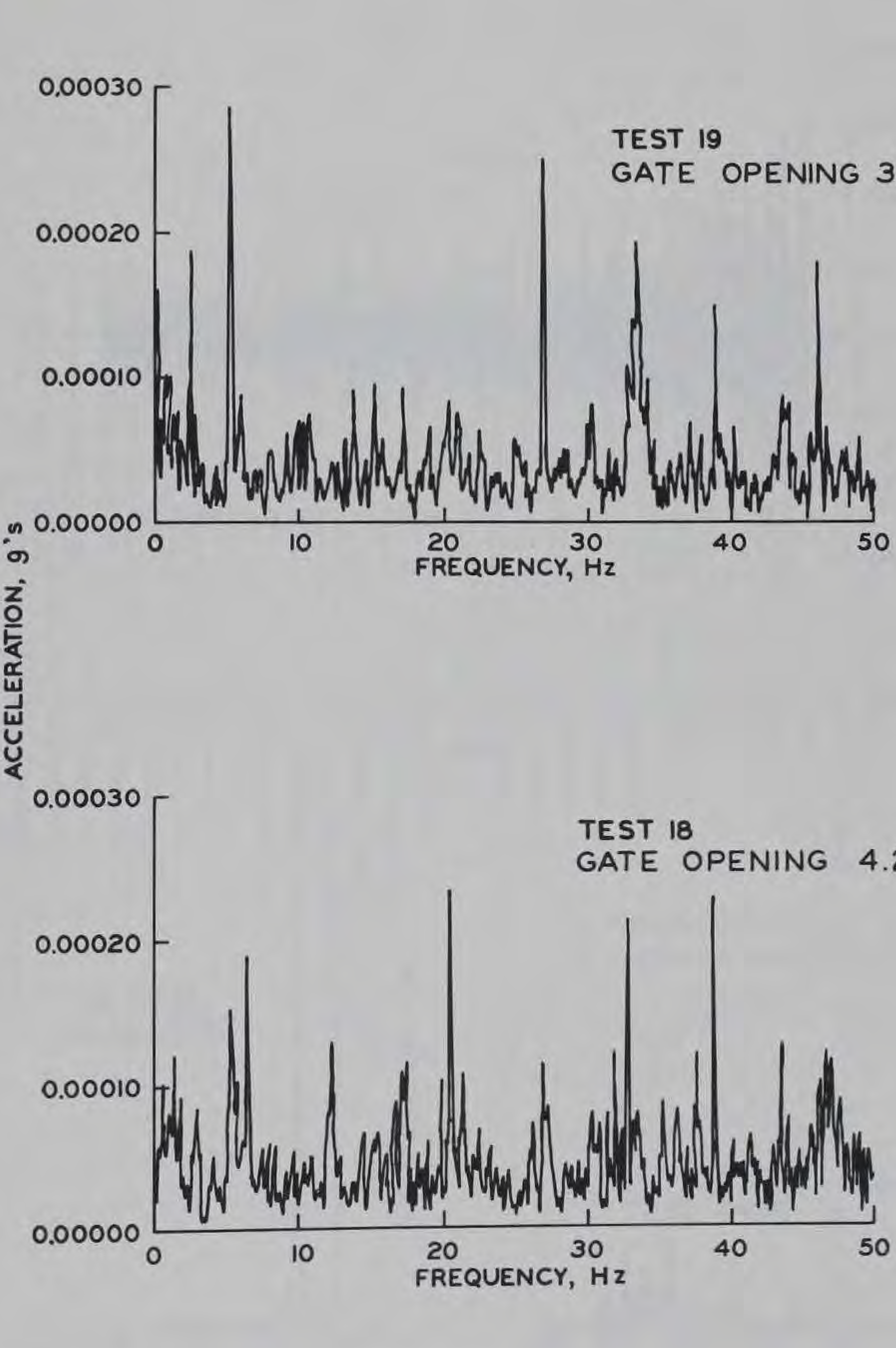
* NOTE DIFFERENCE IN DISPLACEMENT SCALES

TAILWATER SUBMERGENCE DISPLACEMENT COMPARISON
TRANSDUCER CTR



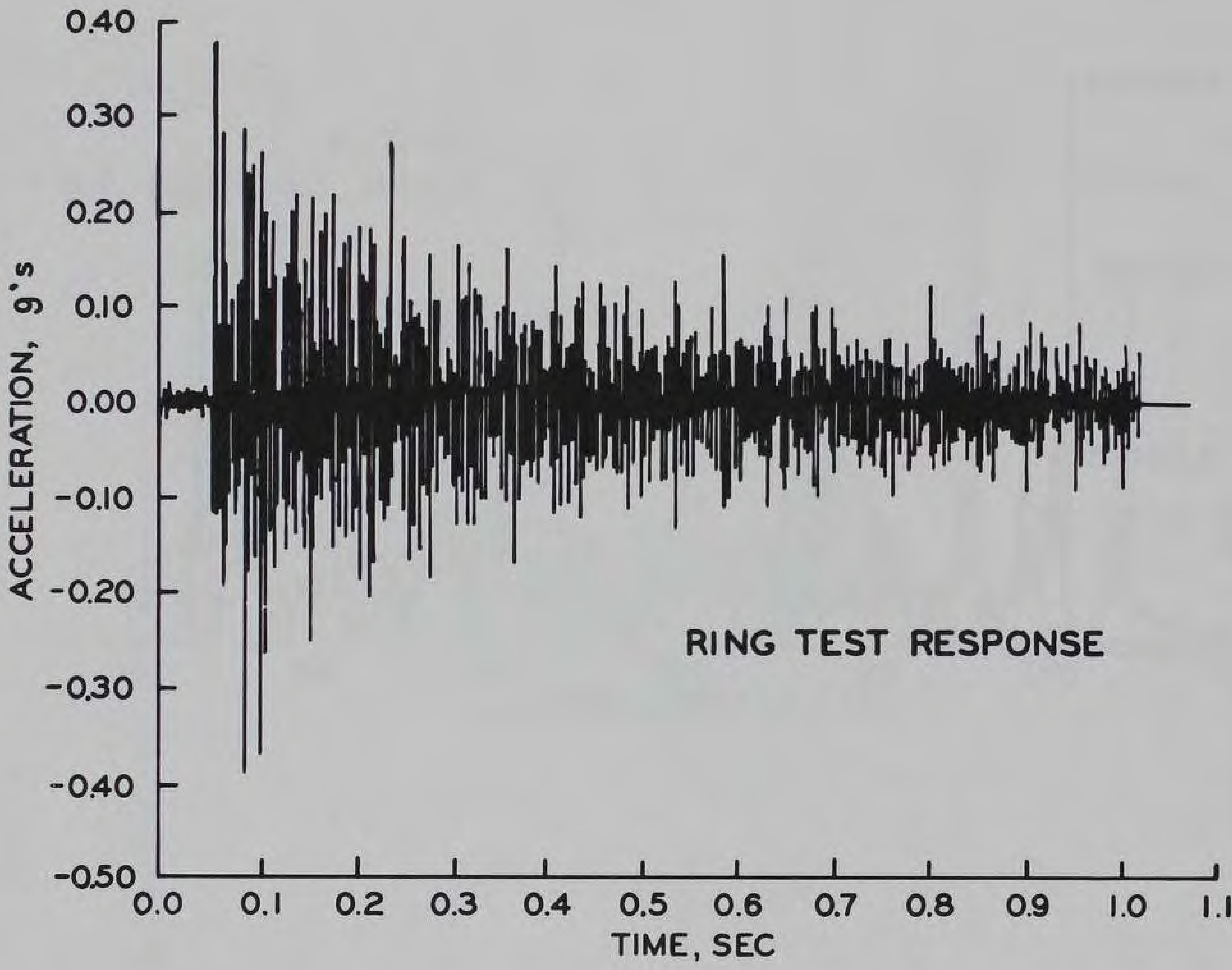
GATE ACCELERATION
FREQUENCIES (WITH SEAL)

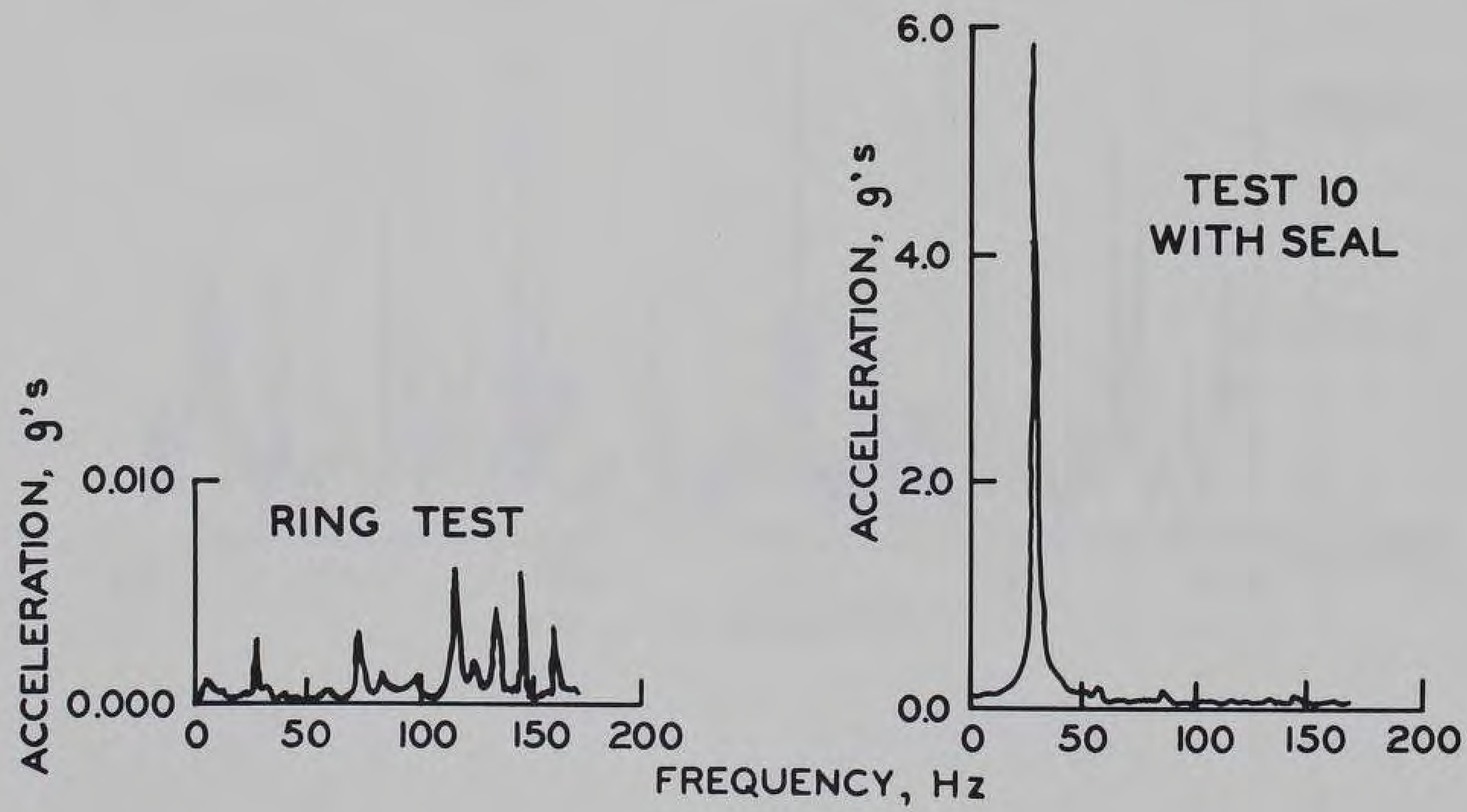
TRANSDUCER CMP
GATE 3



GATE ACCELERATION
FREQUENCIES (NO SEAL)

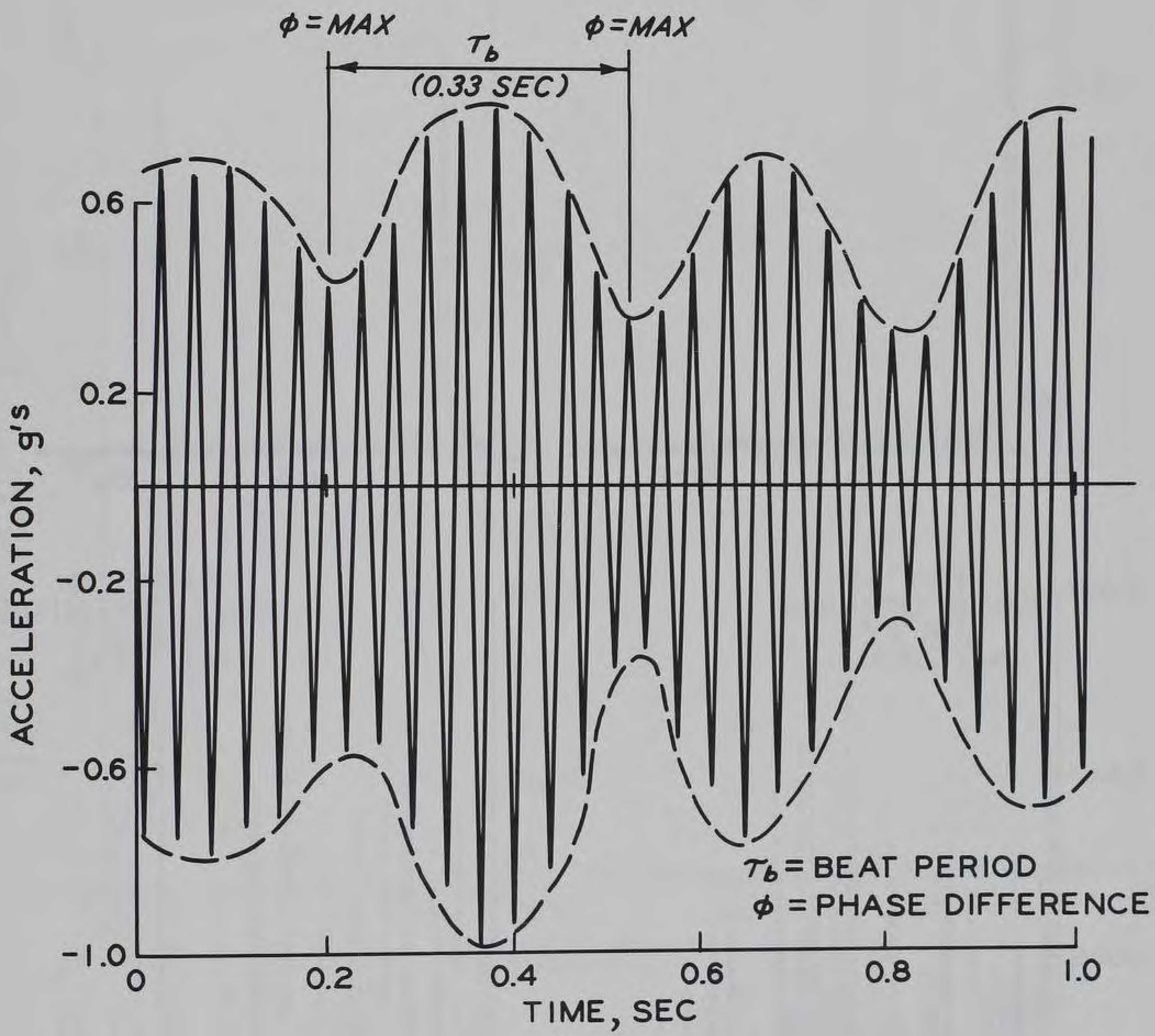
TRANSDUCER CMP
GATE 3





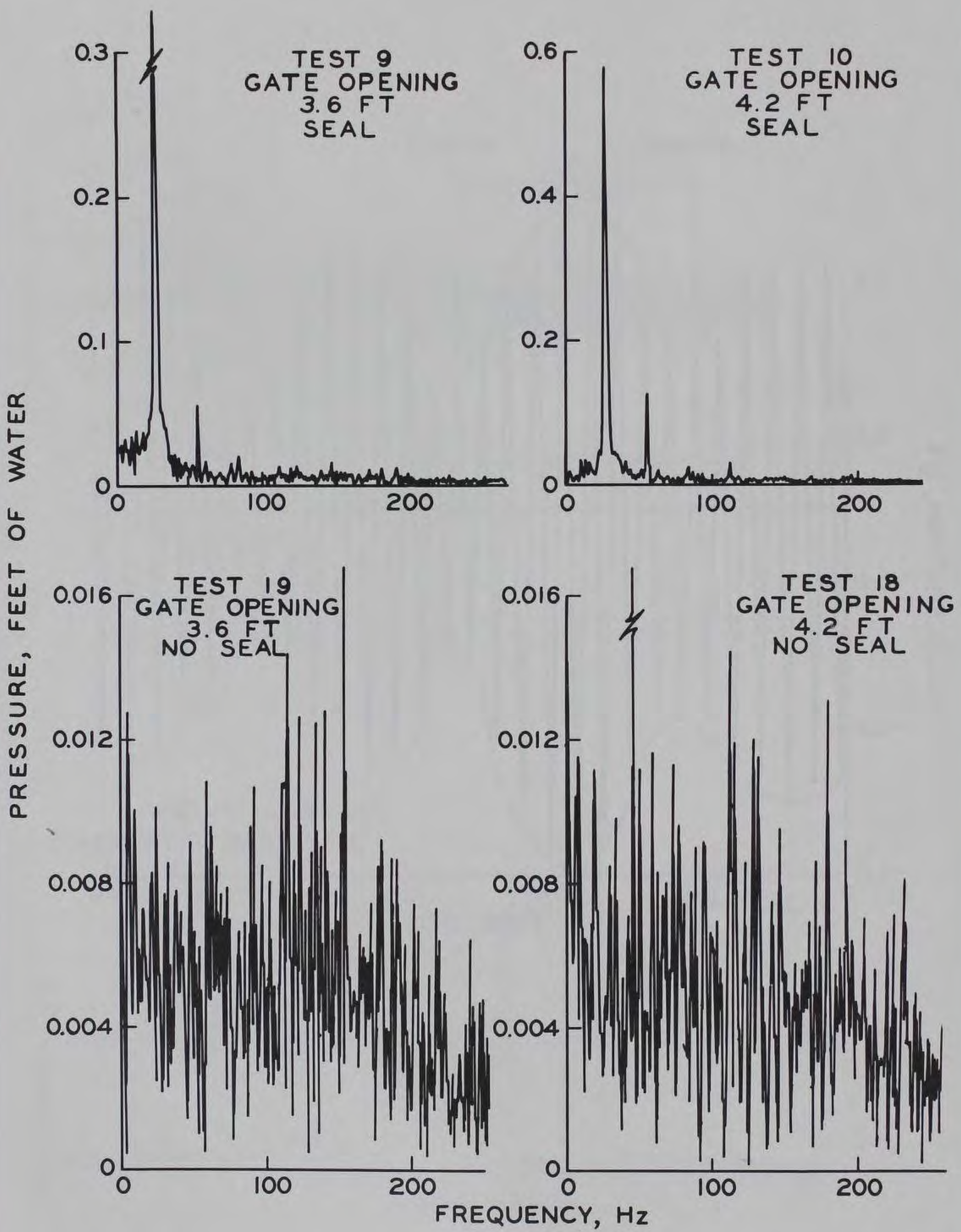
SUPPORT MEMBER LMTV RESPONSE

GATE 3



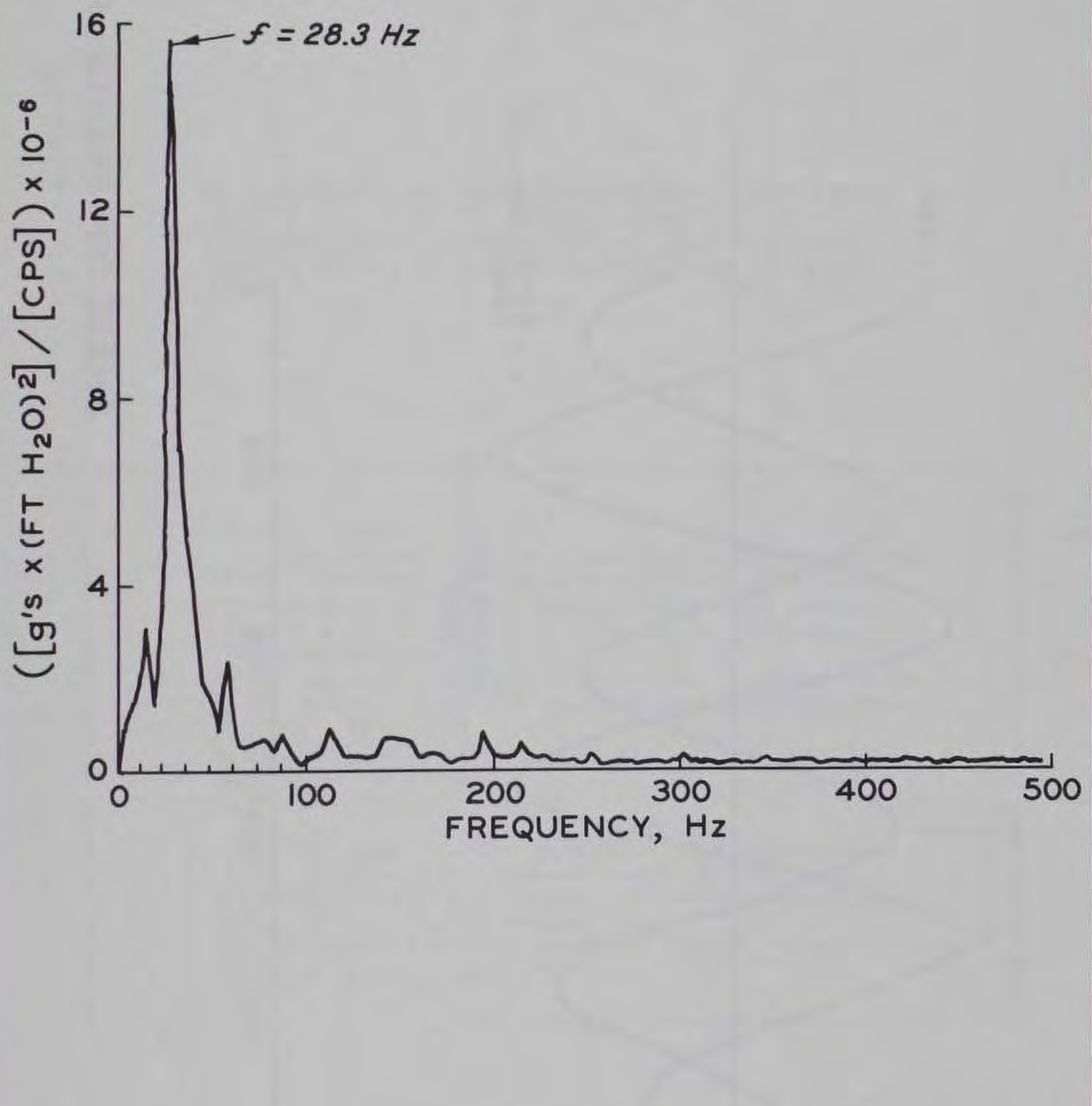
ACCELERATION BEAT FREQUENCY

TEST 8, GATE 3, GATE OPEN 4.2 FT
TRANSDUCER LMT



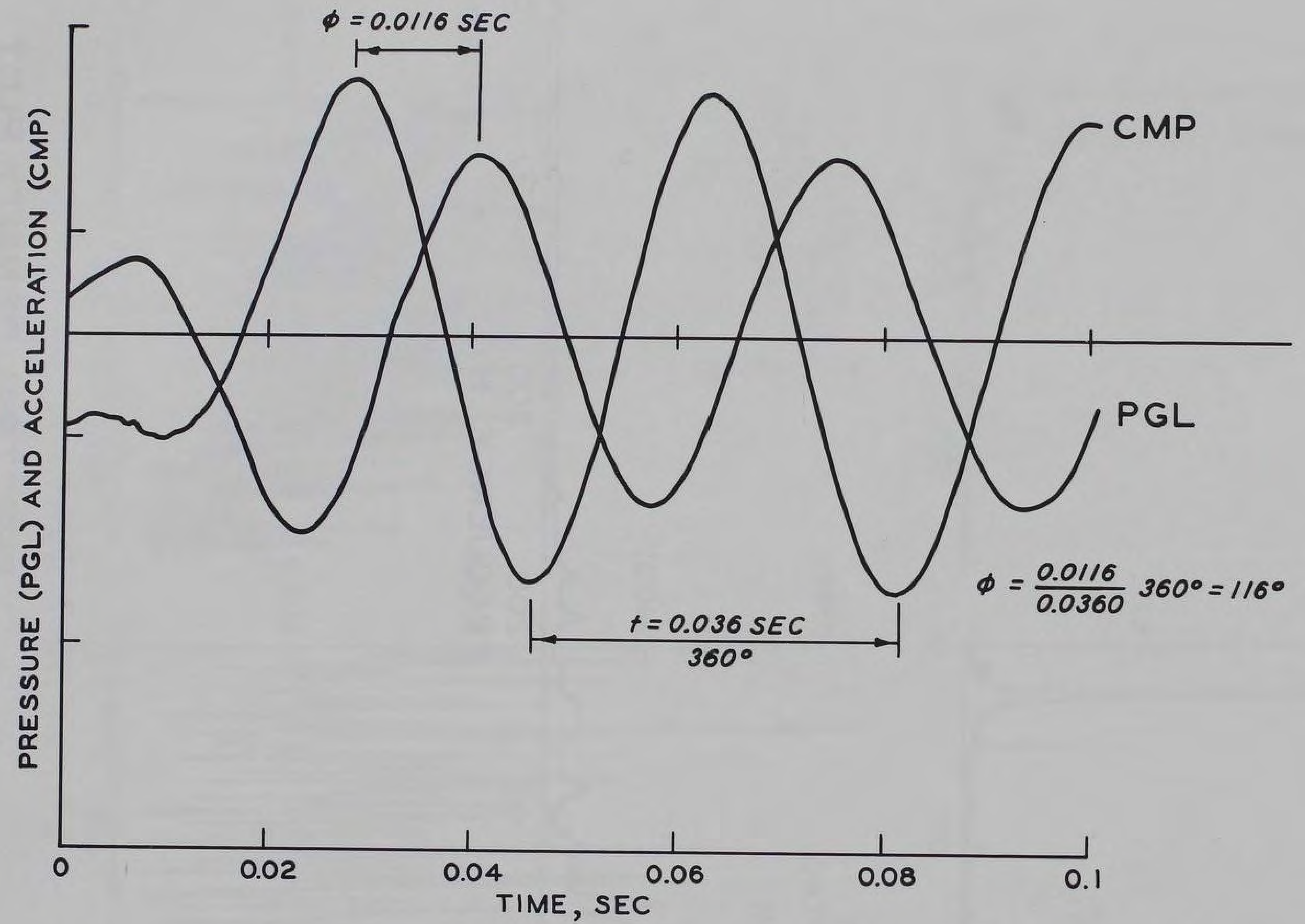
GATE LIP PRESSURE FLUCTUATION FREQUENCIES

TRANSDUCER PGL, GATE 3



SPECTRAL DENSITY PLOT

TRANSDUCERS CMP AND PGL
TEST 10, GATE 3, GATE OPEN 4.2 FT
(SEAL IN PLACE)



PHASE DIFFERENCE: PGL-CMP

TEST 10