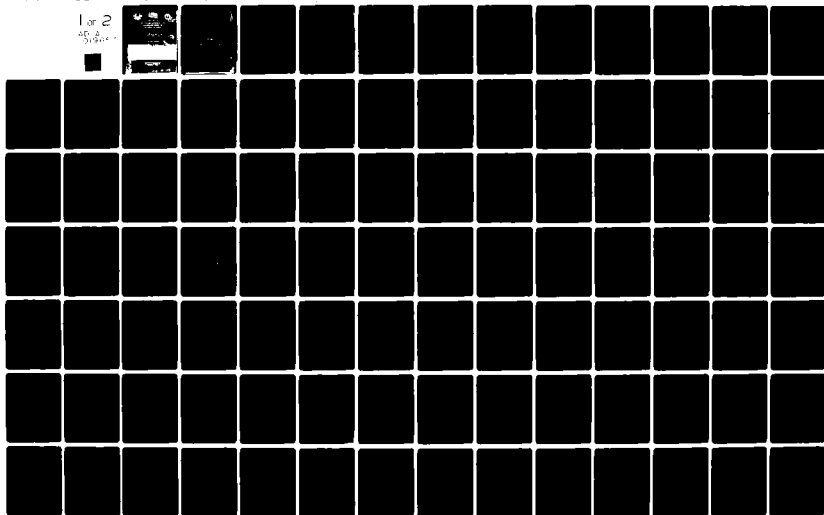


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20. ABSTRACT (Continued).

with numerical models that generated tsunamis and propagated them across the deep-ocean and nearshore region. The combined effects of the astronomical tides and tsunamis were incorporated in the analysis. Numerical simulations of the 1964 Alaskan tsunami in southern California were performed and comparisons with historical tide gage recordings were presented. Tsunami elevation predictions based upon the methods presented in the investigation were shown to be in good agreement with predictions based solely upon historical data of tsunami activity (at the limited number of locations in southern California with sufficient historical data to allow reasonable predictions to be made).

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PREFACE

The investigation reported herein was authorized by the Office, Chief of Engineers (OCE), U. S. Army, in a letter dated 11 July 1979 and was performed for the Federal Insurance Administration, Federal Emergency Management Agency, under Inter-Agency Agreement (IAA)-H-9-79, Project Order No. 20. Project coordinator was Mr. Jerome Peterson, OCE.

The investigation was conducted from July 1979 to May 1980 by personnel of the Hydraulics Laboratory, U. S. Army Engineer Waterways Experiment Station (WES), under the direction of Mr. H. B. Simmons, Chief of the Hydraulics Laboratory, and Dr. R. W. Whalin, Chief of the Wave Dynamics Division. Dr. J. R. Houston, Research Hydraulic Engineer, conducted the study and prepared this report. Mrs. L. Chou made computer plots and aided in the computer computations.

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

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TYPE 19 FLOOD INSURANCE STUDY: TSUNAMI PREDICTIONS
FOR SOUTHERN CALIFORNIA

PART I: INTRODUCTION

Background

1. Of all water waves that occur in nature, one of the most destructive is the tsunami. The term "tsunami," originating from the Japanese words "tsu" (harbor) and "nami" (wave), is used to describe sea waves of seismic origin. Tectonic earthquakes, i.e., earthquakes that cause a deformation of the seabed, appear to be the principal seismic mechanism responsible for the generation of tsunamis. Coastal and submarine landslides and volcanic eruptions also have triggered tsunamis.

2. Tsunamis are principally generated by undersea earthquakes of magnitudes greater than 6.5 on the Richter scale with focal depths less than 30 miles.* They are very long-period waves (5 min to several hours) of low height (a few feet or less) when traversing water of oceanic depth. Consequently, they are not discernible in the deep ocean and go unnoticed by ships. Tsunamis travel at the shallow-water wave celerity equal to the square root of acceleration due to gravity times water depth even in the deepest oceans because of their very long wavelengths. This speed of propagation can be in excess of 500 mph in the deep ocean.

3. When tsunamis approach a coastal region where the water depth decreases rapidly, wave refraction, shoaling, and bay or harbor resonance may result in significantly increased wave heights. The great periods and wavelengths of tsunamis preclude their dissipating energy as a breaking surf; instead, they are apt to appear as rapidly rising water levels and only occasionally as bores.

4. Over 500 tsunamis have been reported within recorded history. Virtually all of these tsunamis have occurred in the Pacific Basin. This

* Multiply miles by 1.609344 to convert to kilometres.

is because most tsunamis are associated with earthquakes, and most seismic activity beneath the oceans is concentrated in the narrow fault zones adjacent to the great oceanic trench systems which are predominantly confined to the Pacific Ocean.

5. The loss of life and destruction of property due to tsunamis have been immense. The Great Hoei Tokaido-Nankaido tsunami of Japan killed 30,000 people in 1707. In 1868, the Great Peru tsunami caused 25,000 deaths and carried the frigate U.S.S. Waterlee 1,300 ft inland. The Great Meiji Sanriku tsunami of 1896 killed 27,122 persons in Japan and washed away over 10,000 houses.

6. In recent times, three tsunamis have caused major destruction in areas of the United States. The Great Aleutian tsunami of 1946 killed 173 persons in Hawaii, where heights as great as 55 ft were recorded. The 1960 Chilean tsunami killed 330 people in Chile, 61 in Hawaii, and 199 in distant Japan. The most recent major tsunami to affect the United States, the 1964 Alaskan tsunami, killed 107 people in Alaska, 4 in Oregon, and 11 in Crescent City, California, and caused over 100 million dollars in damage on the west coast of North America.

Purpose of Study

7. The purpose of this study was to establish 100- and 500-yr tsunami elevations in southern California produced by distantly generated tsunamis. This study is an update of a previous study that predicted 100- and 500-yr tsunami elevations in southern California (Houston and Garcia 1974). Whereas the previous study by Houston and Garcia (1974) used simple analytical solutions to propagate tsunamis over the nearshore region and to statistically combine tsunamic and astronomical tides, this study used complex numerical solutions for nearshore propagation and for superposition of tsunamis and tides. Two other reports (Garcia and Houston 1975 and Houston and Garcia 1978) established tsunami elevations for the west coast of the continental United States excluding Southern California. The 100- and 500-yr tsunami elevations are required by the Federal Insurance Administration (FIA) of the Federal Emergency Management Agency (FEMA) for use in flood insurance rate calculations.

PART II: NUMERICAL MODELS

Background

8. Unlike other areas of the Pacific Ocean such as the Hawaiian Islands, southern California lacks sufficient data to allow reasonable tsunami elevation predictions based upon local historical records of tsunami activity. Virtually all of southern California is completely without data of tsunami occurrence, even data for the prominent 1960 and 1964 tsunamis. Only a handful of locations have historical data for tsunamis other than the 1960 and 1964 tsunamis. However, the FIA requires information on tsunami elevations for all of southern California, even for the many locations that have no known historical data of tsunami activity and for coastal areas that are currently not developed (since these areas may be developed in the future).

9. The lack of historical data of tsunami activity in southern California necessitates the use of numerical models to predict tsunami elevations. The Aleutian-Alaskan area and the west coast of South America were found by Houston and Garcia (1974) to be the tsunamigenic regions of concern to southern California. Both regions have sufficient data on the generation of major tsunamis to allow a statistical investigation of tsunami generation. A numerical model employing a fairly coarse grid to cover a large section of the Pacific Ocean was used to generate representative tsunamis and propagate them across the deep ocean. A second numerical model employing a fine grid was used to propagate tsunamis from the deep ocean over the continental slope and shelf to shore. Previous studies by Houston and Garcia (1974) and Garcia and Houston (1975) used analytical methods to solve one-dimensional linear equations that described the transformation of tsunamis as they propagated from deep water to shore. Houston and Garcia (1978) used a two-dimensional numerical model. In this study a two-dimensional model is used for nearshore propagation that is similar to the model used by Houston and Garcia (1978) but allows a numerical grid with a varying spatial grid cell size.

10. There has been disagreement among tsunami researchers concerning the equations that govern tsunami generation, deep-ocean propagation, and nearshore propagation. The significance of frequency dispersion and nonlinear advection on tsunami propagation has been determined only in recent years. Using the nonlinear and dispersive Korteweg-deVries equation, Hammack and Segur (1978) concluded that "if the length of the initial wave is approximately 100 miles, the lead wave is described by a linear nondispersive model from source region until shoaling occurs near the shoreline." This conclusion also applies to leading waves that have reflected off land areas and traveled to a distant location. Thus two or three of the initial waves may be governed by linear nondispersive equations. Similarly, in studying tsunami propagation from the deep ocean to the nearshore region, Goring (1978) concluded that "... because of the small relative height of tsunamis and their large lengths relative to the lengths of the continental slope, the propagation of tsunamis from the deep ocean to the continental shelf-break and for some distance onto the shelf will be predicted as well by the linear nondispersive theory as by the nonlinear theories." Furthermore, Tuck (1979) found that "... linear long-wave equations are adequate to describe most of the tsunami generation, propagation and reception processes." Also, numerical studies by Hwang et al. (1972) have indicated that linear nondispersive equations govern tsunami propagation over the deep ocean. Numerical studies by Houston (1978) have shown that linear nondispersive equations govern tsunami generation, propagation over the deep ocean, and interaction with the Hawaiian Islands.

11. In this study, only large tsunamis (initial wavelengths greater than 100 miles) are considered; therefore, linear nondispersive equations are used for tsunami generation and deep-ocean propagation. The nearshore numerical model includes bottom friction and nonlinear advection terms. However, it was found by numerical experiments that these terms have no significant effect on tsunamis propagated from the deep ocean to the shoreline in the southern California region.

12. In this report, only tsunamis of distant origin (at least two or three tsunami wavelengths away from the west coast) are considered in

the analysis. Hammack (1972) has shown that near the generation area of a tsunami, details of ground motion during the earthquake and details of the permanent deformation of the sea floor influence the form of the resulting tsunami. Very little is known about the actual time-dependent ground motion during earthquakes generating major tsunamis, and small-scale details of the permanent deformation of the sea floor following earthquakes cannot be predicted in advance. Thus, accurate predictions of the properties of locally generated tsunamis are not possible at this time. However, Hammack (1972) has shown that the time-dependent ground motions and small-scale details of the permanent ground deformation produce waves which are not significant far from the source region. Thus, distantly generated tsunamis can be studied only knowing major features of the permanent ground deformation.

13. The probability is not considered great that an extremely destructive, locally generated tsunami will occur in southern California. Tsunamis are generally produced by earthquakes having fault movements that exhibit a pronounced "dip-slip," or vertical component of motion. "Strike-slip," or horizontal displacement, fault movements are inefficient generators of tsunamis. Faults in southern California characteristically exhibit strike-slip motion since the Pacific block of the earth's crust is moving horizontally relative to the North American block.

14. There have been reports of significant locally generated tsunamis in southern California. For example, a recent publication of the California Division of Mines and Geology (Weber and Kiessling 1978) mentions that Wood and Heck (1966) reported that runup heights of a tsunami generated by the 1812 Santa Barbara earthquake reached 50 ft* at Gaviota, 30-35 ft at Santa Barbara, and 15 ft or more at Ventura in southern California. However, an exhaustive study (Marine Advisors, Inc., 1965**) of this event that included an investigation of the unpublished notes of the late Professor G. D. Lauderback, University of California,

* Multiply feet by 0.3048 to convert to metres.

** Marine Advisors, Inc. 1965. "An Examination of the Evidence for the Reported Santa Barbara Coast Tsunami of December 1812" (unpublished report submitted to the Southern California Edison Company).

Berkeley (cited by Wood and Heck (1966) as a basis for their reported runup heights) has shown that the runup heights for this possible tsunami were not nearly as large as those reported. Professor Lauderback took an old report that said that the sea flowed 1/2 mile inland and transferred it to the present day topographic chart in the vicinity of Gaviota Canyon. This yielded a 50-ft level. However, the study by Marine Advisors, Inc. (1965), discovered that the old report actually referred to an estuary near Santa Barbara that is approximately at sea level. In addition, they learned that there were no reported drownings even though Indian villages were on the beach at the time and many people were there. (The mission padres kept meticulous records of Indian births, deaths, and other statistics). Other evidence indicates that there may have been a runup as great as 10 to 12 ft at Gaviota and a smaller runup at Santa Barbara (Marine Advisors, Inc., see footnote on page 7). A report of a tsunami at Santa Cruz, California, in 1840 also has been shown to be erroneous.

15. The largest authenticated locally generated tsunami in southern California was generated by the 1927 Point Arguello earthquake and produced runup elevations as great as 6 ft in the immediate vicinity. The only other reports of locally generated tsunamis in southern California were for possible tsunamis of very small heights in Santa Monica Bay (Joy 1968).

16. Thus relatively small locally generated tsunamis have been known to occur in southern California, but there are no reliable reports of major locally generated tsunamis. There could be a few locations in southern California (e.g. Gaviota) for which locally generated tsunamis are more significant than distantly generated tsunamis because the elevations produced by distantly generated tsunamis are small. However, the frequency of occurrence of locally generated tsunamis in southern California is not known and predictions of locally generated tsunami elevations are beyond the scope of this report.

17. The finite-difference numerical model used to simulate the generation of tsunamis in the Alaskan region and their propagation across the deep ocean was originally developed by Hwang et al. (1972), and

described in detail in an earlier report (Houston and Garcia 1974). A numerical model developed at WES (Garcia 1976) that used a more efficient solution scheme (explicit) than the Hwang et al. (1972) model (implicit-explicit scheme) was used to simulate the generation of tsunamis in the Peru-Chile region and their propagation across the deep ocean. This model was needed as a result of the extremely large grids (approximately 100,000 grid cells) used to propagate tsunamis over the great distance from Peru-Chile to southern California. In this study, the model employed $1/5^\circ$ by $1/3^\circ$ spherical coordinate grids to solve the linearized long-wave equations. Such coarse grids adequately resolve the very long tsunami wavelengths in the deep ocean. The grids covered very large sections of the Pacific Ocean including either Alaska and the west coast of the United States or South America and the west coast of the United States. The boundary condition on the solid boundaries (land) of the grids was that the component of the velocity normal to the boundary equaled zero. On open boundaries (ocean), a first-order approximation of total transmission was made.

18. The deep-ocean finite-difference model solved an initial value problem starting with an uplift deformation of the water surface identical with the major features of the permanent deformation (permanent in the sense that the time scale associated with it is much longer than the period of the tsunami) of the sea floor following the seismic disturbance. The transient movements within the time-history of the ground motion were neglected because Hammack (1972) has further shown that the initial deformation of the water surface will closely approximate major features of the permanent deformation of the ocean floor, provided these features have characteristic lengths that are at least four times as great as the water depth. The neglect of smaller features is unimportant because such small-scale details produce waves that are negligible in the far field.

Nearshore Numerical Model

19. The nearshore finite-difference numerical model used in this study is described in detail by Butler (1978). The model solves the

classical shallow-water wave equations that govern tsunami propagation in the nearshore region. A highly efficient implicit solution scheme that employs a centered, alternating-direction procedure is used.

20. The nearshore propagation numerical model employed in this study uses a smoothly varying grid that allows cells to be small in shallow water and larger in deeper water. A piecewise reversible transformation (analogous to that used by Wanstrath (1976)) is used independently in the x- and y-directions to map the grid into a uniform grid used in computational space. The coordinate transformation has the form

$$x = p + q\alpha^r$$

where p , q , and r are arbitrary constants and the transformation is applied piecewise for each axis. The transformation is such that there is a regular grid in computational space and all derivatives in computational space are centered. Many stability problems commonly occurring in variable grid schemes are eliminated using this transformation since the real space grid is smoothly varying with the variation and its first derivative being continuous. The variable grid allows accurate resolution of the tsunami wave form as it enters shallow water and its wavelength decreases.

21. The nearshore numerical model used as input the time-history calculated by the generation and deep-ocean propagation numerical model. A tsunami was generated in the Aleutian-Alaskan area or the west coast of South America and propagated across the deep ocean to a 500-m depth off the west coast of the United States. Wave forms calculated at this depth by the deep-ocean numerical model were recorded all along the west coast. These wave forms then were used as input to the nearshore numerical model, which propagated the tsunamis from the 500-m depths across the continental slope and shelf to shore.

22. The nearshore numerical grid covered an area approximately 280 miles by 142 miles. It extended from Point Conception, California, to Ensenada, Mexico. The grid was oriented approximately parallel to the 500-m contour, since refraction would have bent the wave fronts to such

an orientation before they reached the 500-m contour. Grid cells in water depths less than 500-m were slightly less than 1 mile on a side.

Verification

23. The numerical models used in this report were verified by numerical simulations of the 1964 Alaskan tsunami. This was the only large tsunami for which reliable information exists concerning source characteristics. The initial condition used in the generation and deep-ocean propagation numerical model was that the uplift of the ocean's surface in the source region was identical with the permanent deformation of the ocean bottom following the earthquake. The permanent deformation of the ocean's bottom as a function of spatial location was taken from Plafker (1964). The generation and deep-ocean propagation numerical model was used to propagate the 1964 Alaskan tsunami to a water depth of approximately 500 m off the coast of southern California. The nearshore numerical model then was used to propagate the tsunami to shore.

24. There were seven tide gages in operation along the coast of southern California from Point Conception to San Diego. Figures 1-7 show comparisons between recordings of the 1964 Alaskan tsunami by these tide gages and wave forms calculated using the generation and deep-ocean propagation and the nearshore numerical models to propagate the 1964 tsunami from Alaska to southern California. The comparisons extend over a period of 1.5 to 2.0 hr. This time period was selected since numerical models that generate tsunamis and propagate them across the deep ocean to distant locations will provide good values only for the first 1.5 to 2.0 hr (Houston 1978).

25. The numerical model calculations agree remarkably well with the tide gage recordings shown in Figures 1-7, considering the fact that the uplift used to generate the 1964 tsunami is only approximately known. In addition, tide gages do not record tsunamis without distortion of amplitude, period, and phase. Even so, the amplitudes, periods, and phases of the calculated and recorded wave forms shown in Figures 1-7 are in good general agreement. The greatest amplitude difference is for the second

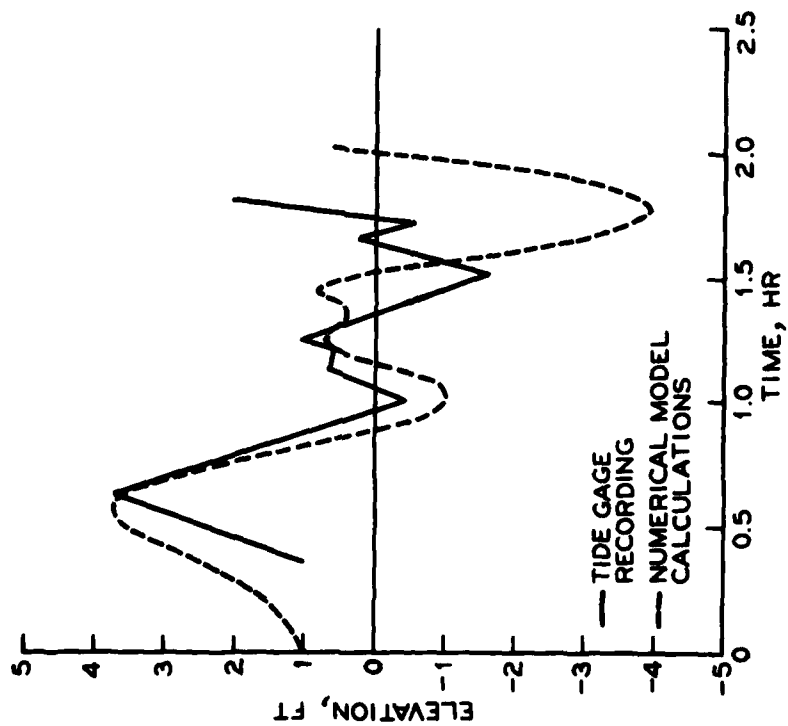


Figure 1. 1964 tsunami at Rincon Island,
California

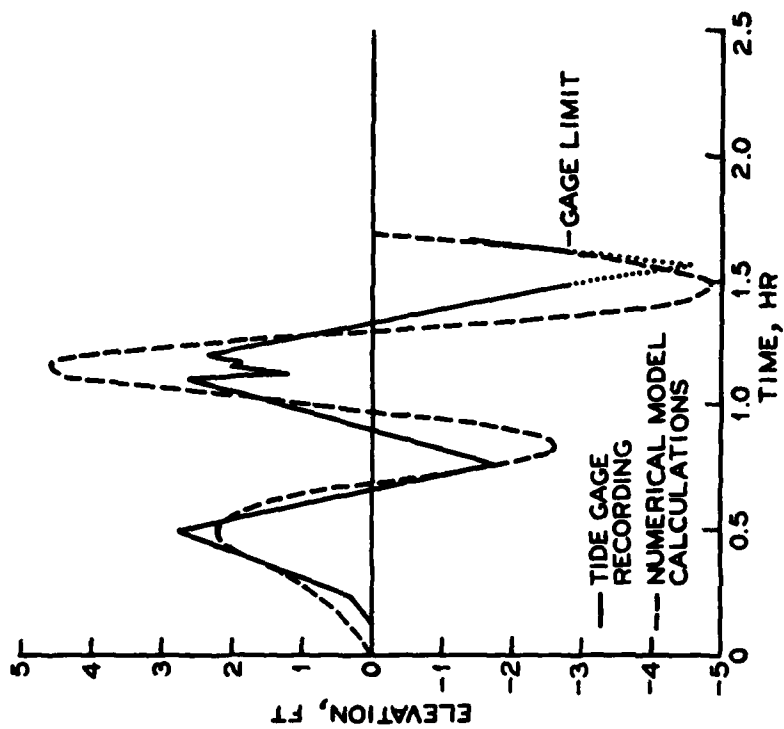


Figure 2. 1964 tsunami at Santa Monica,
California

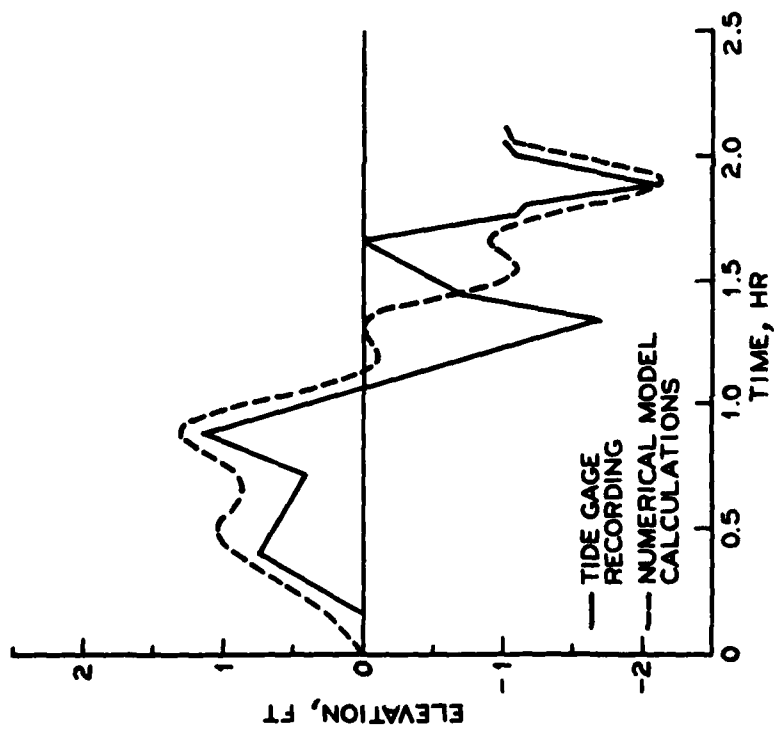


Figure 3. 1964 tsunami at Los Angeles
(Berth 60), California

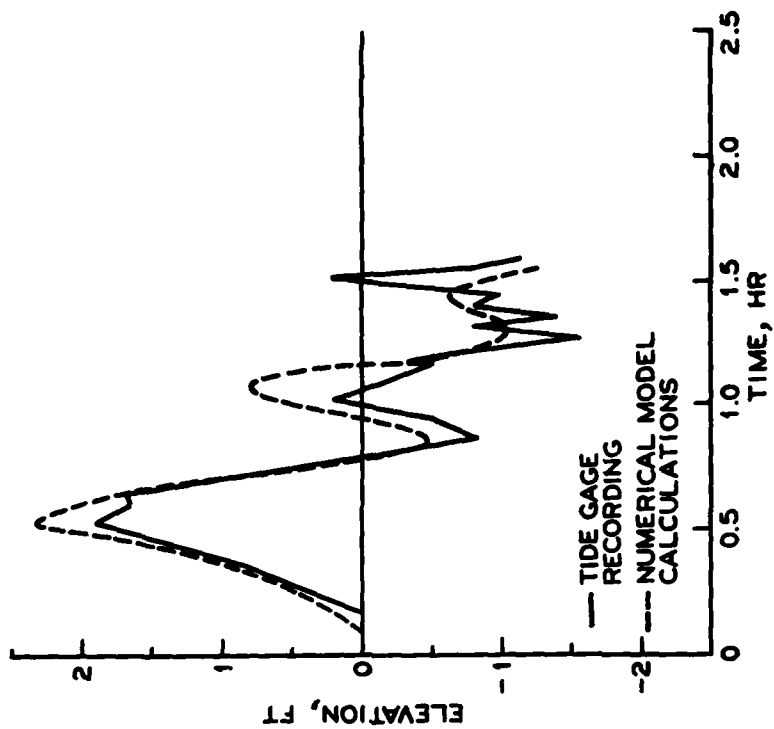


Figure 4. 1964 tsunami at Alamitos Bay,
California

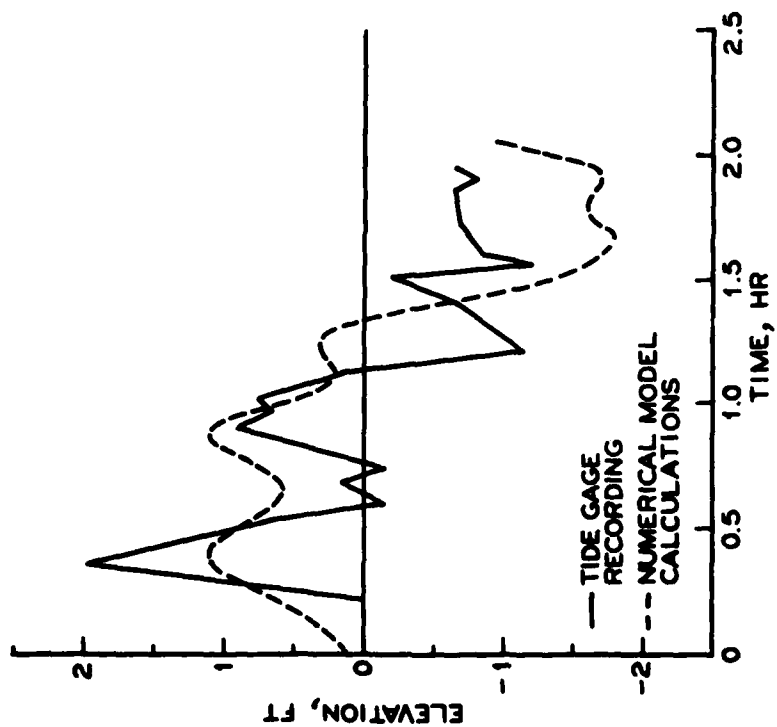


Figure 5. 1964 tsunami at La Jolla, California

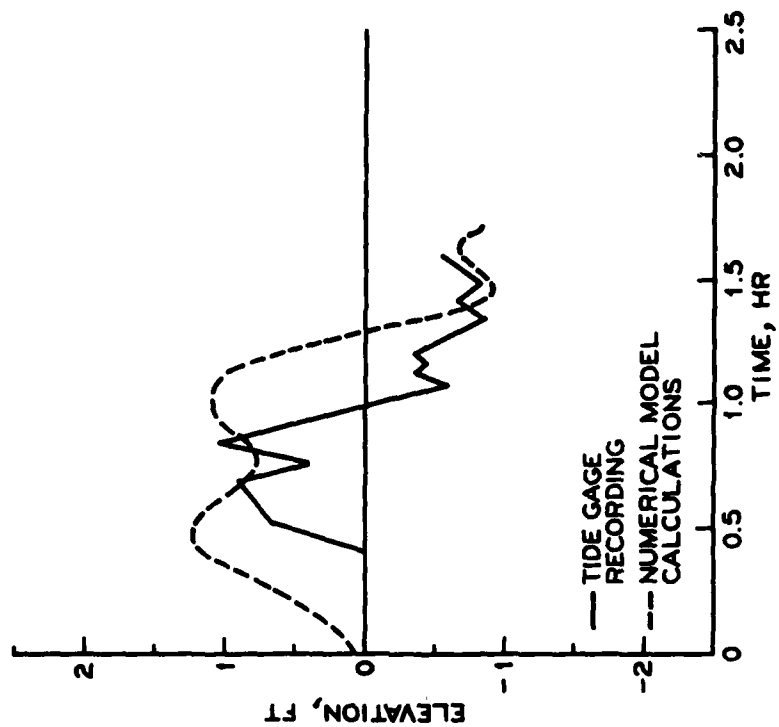


Figure 6. 1964 tsunami at San Diego, California

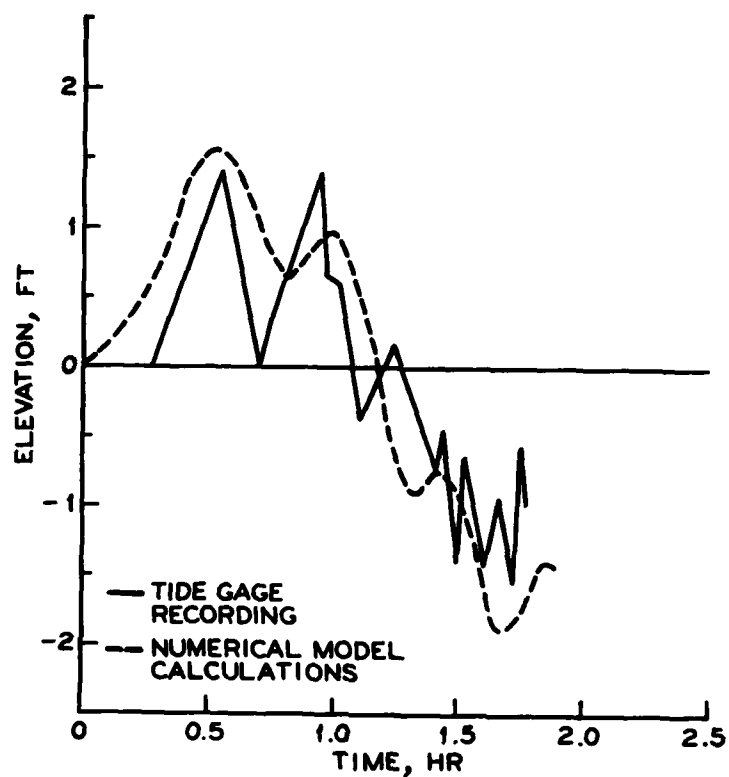


Figure 7. 1964 tsunami at
Newport Bay, California

wave crest at Santa Monica, California, shown in Figure 2. However, the tide gage may have had response problems while recording this wave crest since the recording appears to be truncated and there are unusual high frequency oscillations in this truncated region of the wave form.

PART III: METHODOLOGY FOR ELEVATION PREDICTIONS

Tsunami Occurrence Probabilities

26. Historical data on tsunami generation must be the basis for an analysis that considers the probability of tsunami generation in the two tsunamigenic areas in the Pacific Ocean of concern to southern California--the Aleutian and Peru-Chile Trench areas. A satisfactory correlation between earthquake magnitude and tsunami intensity has never been demonstrated. Not all large earthquakes occurring in the ocean even generate noticeable tsunamis. Furthermore, earthquake parameters of importance to tsunami generation, such as focal depth and vertical ground motion, have only been measured for earthquakes occurring in recent years. Therefore, data on earthquake occurrence cannot be used to determine occurrence probabilities of tsunamis. Historical data of tsunami occurrence in generation regions must be used to determine these probabilities.

27. In South America, a wealth of information exists concerning tsunami occurrence. Reliable data (grouped in intensity increments of 0.5) exist for tsunamis with intensity greater than or equal to 0 for a 169-yr period and greater than or equal to 2.5 for a 417-yr period. The intensity scale used was a modification (by S. L. Soloviev of the Soviet Union) of the standard Imamura-Iida tsunami intensity scale. Intensity is defined as

$$i = \log_2 \left(\sqrt{2H_{\text{avg}}} \right)$$

This definition in terms of an average runup (in metres) over a coast instead of a maximum runup elevation at a single location (used for the standard Imamura-Iida scale) tends to eliminate a spurious intensity magnitude caused by often observed anomalous responses (due, for example, to local resonances) of single isolated locations.

28. Using the most recent and complete catalog of tsunami occurrence in the Pacific Ocean (Soloviev and Go 1969), a relation between

tsunami intensity and frequency of occurrence was determined for the tsunami-generating trench running the length of the Peru-Chile coast. Tsunamis with intensity greater than or equal to 0 were considered. It was assumed that the logarithm of the tsunami frequency of occurrence was linearly related to the tsunami intensity. Earthquake magnitude and frequency of occurrence have been similarly related by Gutenberg and Richter (1965) and used extensively in earthquake predictions. Soloviev (1970) has shown a similar relation between tsunami intensity and frequency of generation for moderate to large tsunamis throughout the Pacific Ocean. Furthermore, Wiegel (1965) found the same type of relation between tsunami occurrence and runup levels for historical tsunamis at Hilo, Hawaii; San Francisco, California; and Crescent City, California; and Adams (1970) for tsunamis at Kahuku Point, Oahu. A recent study by Rascon and Villarreal (1975) revealed this same relation for historical tsunamis on the west coast of Mexico (data from 1732) and on the Pacific west coast of North America, excluding Mexico.

29. Letting $n(i)$ equal the probability of a tsunami with an intensity i being generated during any given year and using statistics for the entire trench along the Peru-Chile coast, a least-squares analysis resulted in the following expression:

$$n(i) = 0.074e^{-0.63i} \quad (1)$$

30. In using statistics for the entire trench area along the Peru-Chile coast, it was assumed that the probability of tsunami occurrence was uniform along the trench. This is a standard assumption for earthquake frequency analysis (Gutenberg and Richter 1965). The tectonic justification of this assumption lies in the fact that a single sialic block or plate of the earth's crust or lithosphere is dipping into the Peru-Chile Trench (Wilson 1969). It can be reasonably expected that the movement of this single plate is similar along its entire length.

31. In the Aleutian Trench area, only large tsunamis occurring in relatively recent years (since 1788) have been recorded due to the

isolation of the area. Assuming an exponential coefficient of -0.71 for this trench area (determined by Soloviev 1970) as a mean value for areas of the Pacific with the most data on tsunamis and using only the reliable data for large tsunamis (intensity greater than or equal to 3.5), the following relation was determined by a least-squares analysis:

$$n(i) = 0.113e^{-0.71i} \quad (2)$$

Again, the probability of tsunami occurrence was assumed to be uniform along the trench.

Use of Numerical Models

32. To relate the probability distribution of tsunami intensities to source characteristics, it was assumed that the ratio of the source uplift heights producing two tsunamis of different intensities (as defined in the previous section) is equal to the ratio of the average runup heights produced on the coasts near these tsunami sources. This ratio is equal to $2(i_1 - i_2)$ for two tsunamis with intensities i_1 and i_2 .

33. If H_a is the wave height emitted in the direction parallel to the major axis of length a by a tsunami source with an elliptical shape (large tsunamis have historically had elliptically shaped uplifts) and H_b is the wave height emitted in the direction parallel to the minor generation axis of length b , then experimental research of tsunami generation has shown that $H_b/H_a \approx a/b$ (Hatori 1963). For a large tsunami, H_b can be larger than H_a by a factor of as much as 5 or 6. Thus, the orientation of the tsunami source relative to the area where elevations are to be determined is very important; that is, the elevation at a distant site due to the generation of a tsunami at one location along a trench cannot be considered as being representative of all possible placements of the tsunami source in the entire trench region. Hence, the Aleutian and Peru-Chile Trenches had to be segmented and elevations along the coast of southern California determined for

tsunami sources located at the center of each of the segments.

34. The spatial size of a tsunami source was standardized because there is not an apparent correlation between tsunami intensity and spatial size of a tsunami source. For example, the 1946 Aleutian tsunami had an uplift region of very small spatial extent, whereas the 1957 Aleutian tsunami had an uplift region that covered perhaps the greatest spatial extent of any known earthquake (Kelleher et al. 1974); yet the 1946 tsunami had the greater tsunami intensity, producing, in general, greater runup elevations in the near and distant regions.

35. The standard source employed (described in Houston and Garcia 1974), represents a large tsunami with intensity 4 on the modified Imamura-Iida scale. Certainly, tsunamis of low intensity may have smaller spatial extents; however, large tsunamis pose the greatest threat to a distant area such as southern California. These large tsunamis can be expected to have similar spatial extents, with any spatial differences being unimportant in the far field compared with the effects of source orientation and vertical uplift.

36. Figures 8 and 9 show the Aleutian Trench divided into 12 segments and the Peru-Chile Trench into 3 segments. The segments in the Aleutian Trench were approximately one-quarter the length of the major axis of the standard source, whereas the segments in the Peru-Chile Trench were approximately the length of the major axis of the standard source. The standard source was centered in each segment such that the major axis of the source was parallel to the trench axis. Uplift regions historically have had such an orientation relative to trench systems. The Aleutian Trench was segmented much finer than the Peru-Chile Trench because the Aleutian Trench is oriented relative to southern California such that elevations produced in southern California are very sensitive (Houston et al. 1975) to the location of a source along the trench. Uplifts along the Peru-Chile Trench do not radiate energy directly toward southern California regardless of their position along the trench. Therefore elevations in southern California are not very sensitive (Garcia 1976) to source location within these sections.

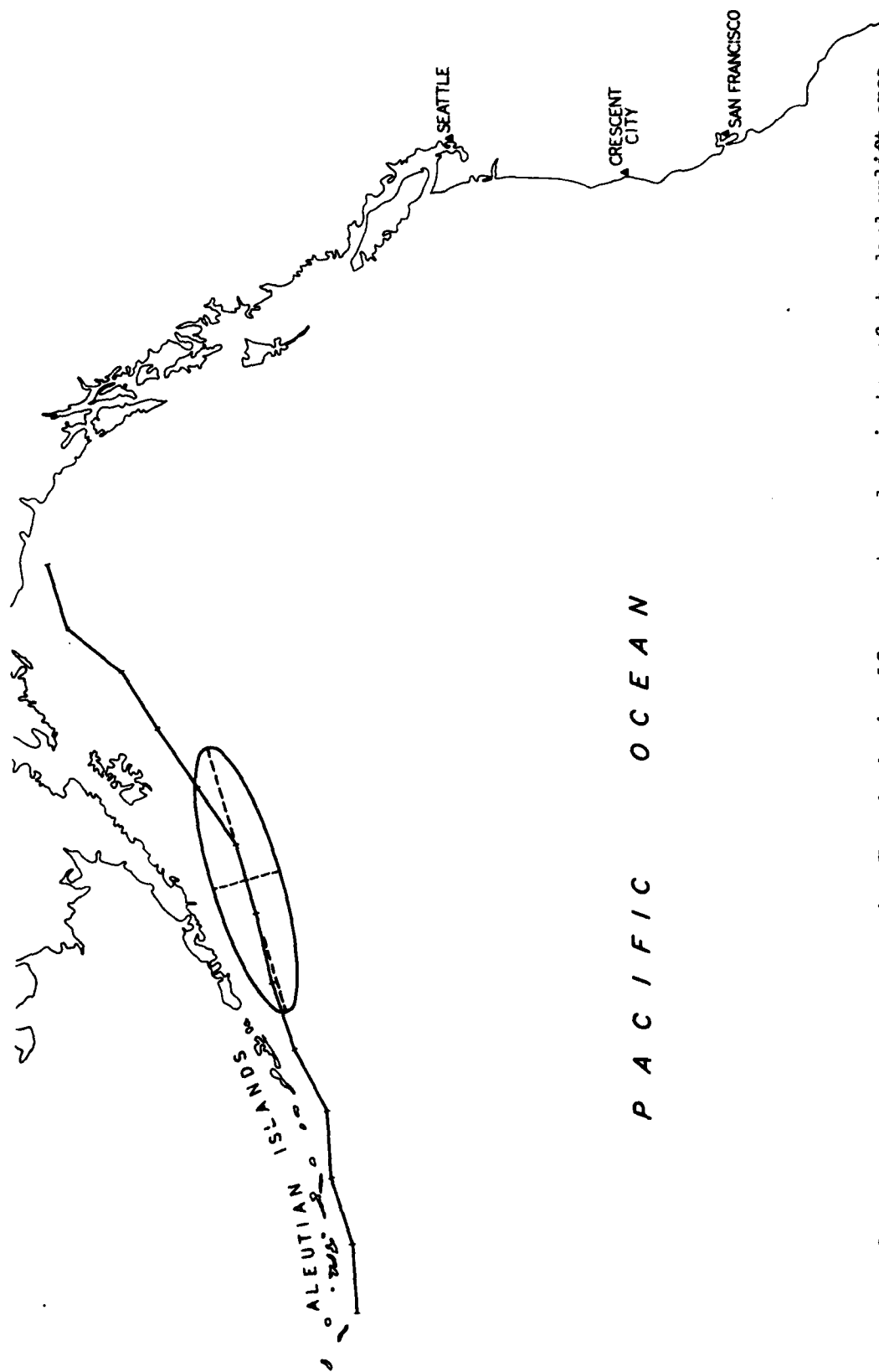


Figure 8. Idealized axis of Aleutian Trench showing 12 segments and perimeter of standard uplift area

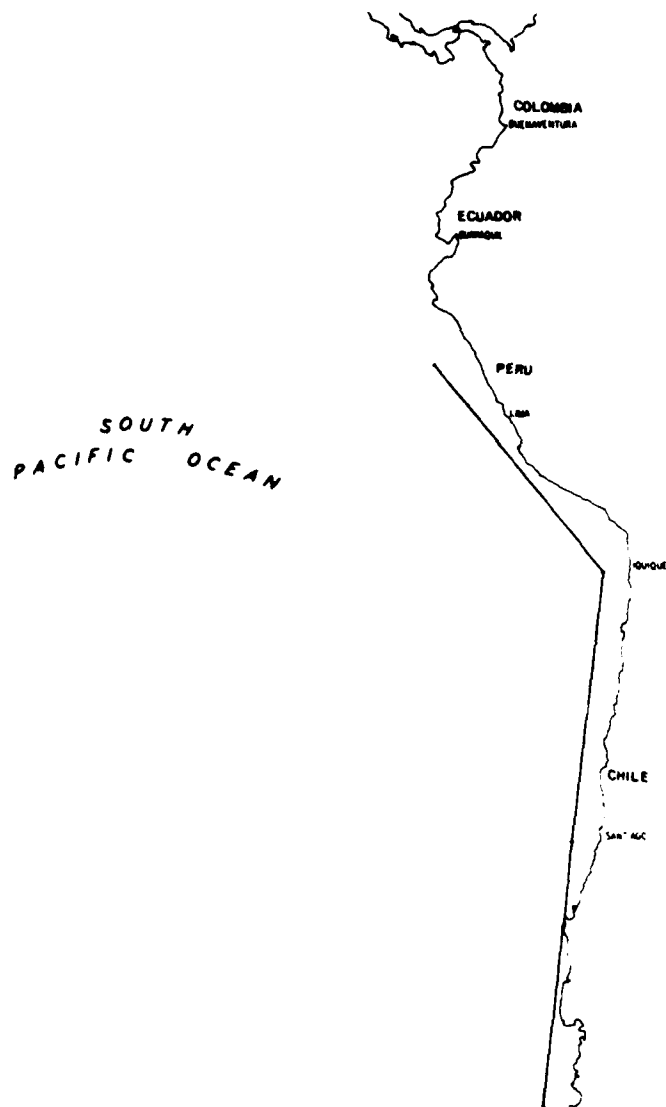


Figure 9. Idealized axis of Peru-Chile Trench showing 3 segments

37. In each of the segments of the Aleutian and Peru-Chile Trenches, tsunamis with intensities from 2.5 to 4.5 in increments of 0.5 were generated and propagated across the deep ocean using the deep-ocean numerical model discussed in an earlier section. Tsunamis with intensities less than 2.5 are too small to produce significant elevations in southern California. An upper limit of 4.5 was chosen because the largest tsunami intensity ever reported was less than 4.5 (Soloviev and Go 1969). Gutenberg and Richter (1965) indicate that there is an upper limit to the strain which can be supported by rock before fracture. Thus, earthquakes only reach certain maximum magnitudes and tsunamis can be expected to have analogous upper limits of intensity. Perkins (1972) and McGarr (1976) have demonstrated that future earthquakes cannot have seismic moments (measure of earthquake magnitude for large earthquakes) much larger than those of earthquakes that occurred in recorded history.

38. The wave forms propagated to southern California by the deep-ocean propagation numerical model were used as input to the nearshore propagation numerical model. Each wave form was propagated from a water depth of 500 m to shore using the nearshore model. Thus, at each grid location on the shoreline of the west coast, there was a group of 75 wave forms--5 wave forms (for intensities from 2.5 to 4.5 in increments of 0.5) for each segment of the Aleutian and Peru-Chile Trenches. Each of these wave forms had an associated probability equal to the probability that a certain intensity tsunami would be generated in a particular segment of a trench region.

Effect of Astronomical Tides

39. The maximum "still water" elevation produced during tsunami activity is the result of a superposition of tsunami and astronomical tide wave forms. Therefore, the statistical effect of astronomical tides on total tsunami runup must be included in the predictive scheme presented in this report. Since the wave forms calculated by the

near-shore model did not have a simple form (e.g., sinusoidal), the statistical effect of the astronomical tide on tsunami runup had to be determined through a numerical approach.

40. The wave forms calculated by the nearshore numerical model extended over a period of time of approximately 2 hr. One to three wave crests (the largest waves in the tsunami) arrived during this time. Smaller waves arriving at later times, however, have often persisted for days during historical tsunamis. An analysis of tide gage records of the 1960 and 1964 tsunamis in southern California indicated that these smaller waves have amplitudes on the average of 50 percent of the maximum wave amplitude of the tsunami; therefore a sinusoidal group of these small waves was added to each of the calculated wave forms so that the total wave form extended over a 12-hr period. These smaller waves are important for locations where tsunami waves are fairly small compared with tidal variations. At such locations, the maximum combined tsunami and astronomical elevation occurs during the maximum tidal elevation.

41. A computer program was developed to predict time-histories of the astronomical tides in southern California. The program was based upon the harmonic analysis methods used in the past by the National Ocean Survey for mechanical tide-predicting machines (Schureman 1948). Tidal constants available from the National Ocean Survey were used as input to the computer program. A year of tidal elevations was then predicted for grid locations in southern California. The year 1964 was selected because all the major tidal components for tides in southern California had a node factor of approximately 1.00 during this year, thus making it an average year. The node factor is associated with the revolution of the moon's node and has an 18.6-yr cycle. Since a tsunami can arrive at any time during this 18.6-yr period (arrival at a low of the node factor is equally likely as an arrival at a high), the statistical effect of the temporally varying node factor on the predicted runup elevations is shown to be very small in Appendix A of this report.

43. The many maximum elevations with associated probabilities were used to determine exceedance frequency distributions of combined

tsunami and astronomical tide elevations. The maximum elevations were ordered and frequencies summed, starting with the largest elevations, until a desired frequency was obtained. The elevation encountered when the summed frequency reached a desired value F was the elevation that is equaled or exceeded with an average frequency of once every $1/F$ yr. Thus, when the summed frequencies reached the value 0.01, the elevation associated with the last frequency summed was the 100-yr elevation.

PART IV: RESULTS

Explanation

44. Figures 10-23 present predicted 100- and 500-yr elevations (in feet) in southern California produced by distantly generated tsunamis. These elevations include the effects of the astronomical tide; that is, they are maximum elevations due to the superposition of tsunami and tidal wave forms (see PART III). The lower curves in Figures 10-23 represent the 100-yr elevation and the upper curves, the 500-yr elevation. A 100-yr elevation is one that is equaled or exceeded with an average frequency of once every 100 yr (i.e. 100-yr return period); a 500-yr elevation has a corresponding definition. Elevations in this report are referenced to the mean sea level (msl) datum.

45. The elevations presented in Figures 10-23 extend along more than 200 miles of coastline in southern California from Santa Barbara to San Diego. Similar elevations north and west of Santa Barbara are presented in an earlier report (Houston and Garcia 1978). Calculations were made at 240 locations (presented in Figures 24-31) along this coastline. The latitude and longitude of each of these gage locations are presented in Table 1. The elevations calculated at each gage location are connected by straight lines in Figures 10-23.

46. Plates 1-120 present exceedance distributions at all 240 gage locations. The y-axis of the plots presents tsunami frequency in events per year. Tsunami frequency is the inverse of the tsunami return period. Thus the 100-yr tsunami has a frequency of 0.01 events per year and the 500-yr tsunami a frequency of 0.002 events per year. The tsunami frequency is presented in Plates 1-120 on a logarithmic scale. Each tick mark from a frequency of 0.001 to 0.01 represents an increment of 0.001. Each tick mark from a frequency of 0.01 to 0.1 represents an increment of 0.01. Figure 32 illustrates how to determine 100- and 500-yr elevations using an exceedance frequency distribution.

47. The tsunami elevations presented in Figures 10-23 and Plates 1-120 are elevations at the shoreline. As discussed by Houston

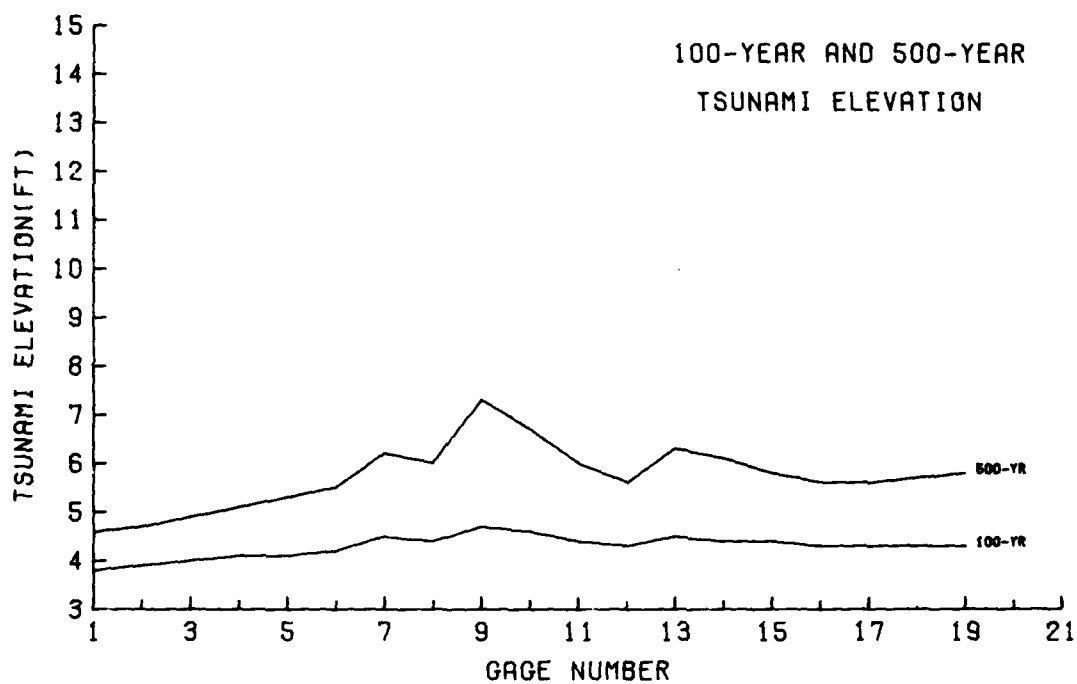


Figure 10. Gage numbers 1-19

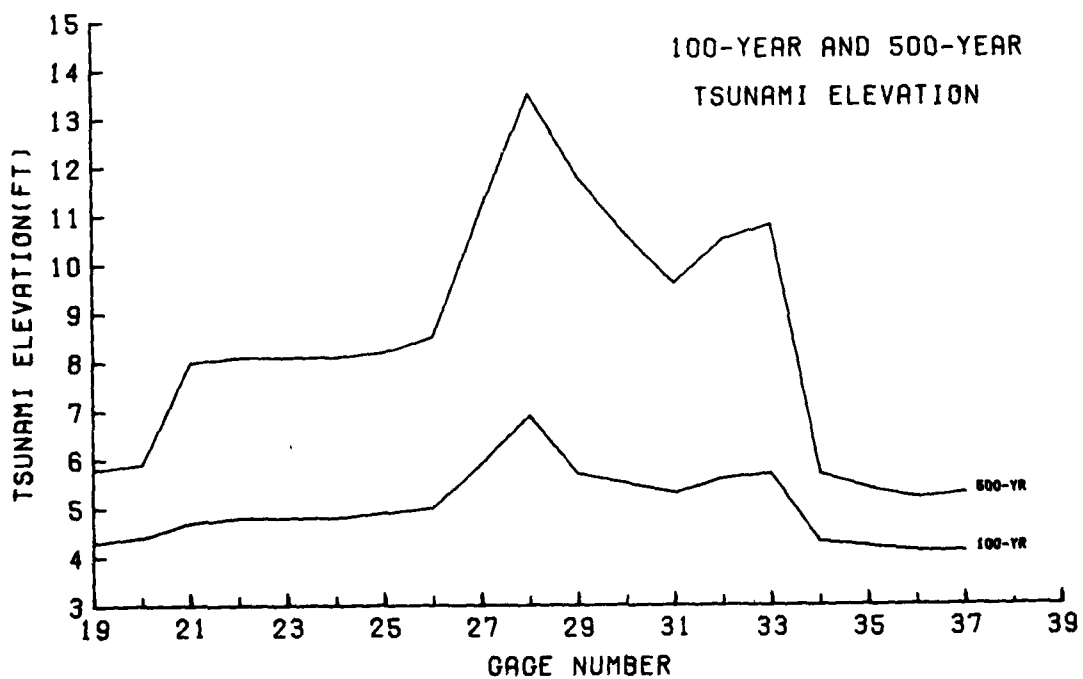


Figure 11. Gage numbers 19-37

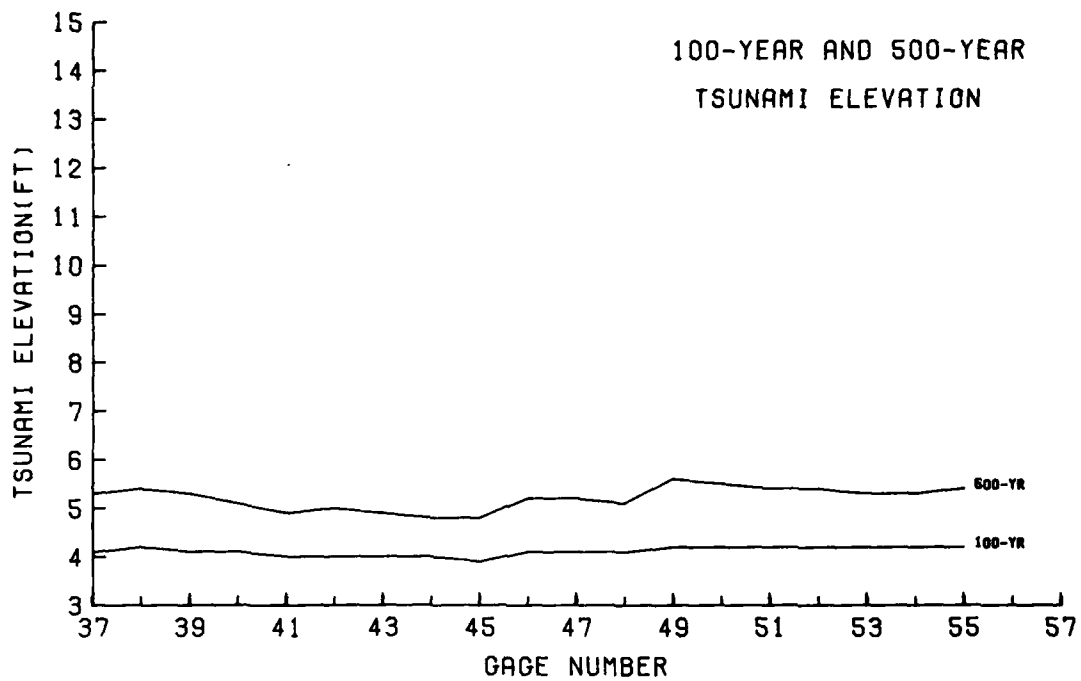


Figure 12. Gage numbers 37-55

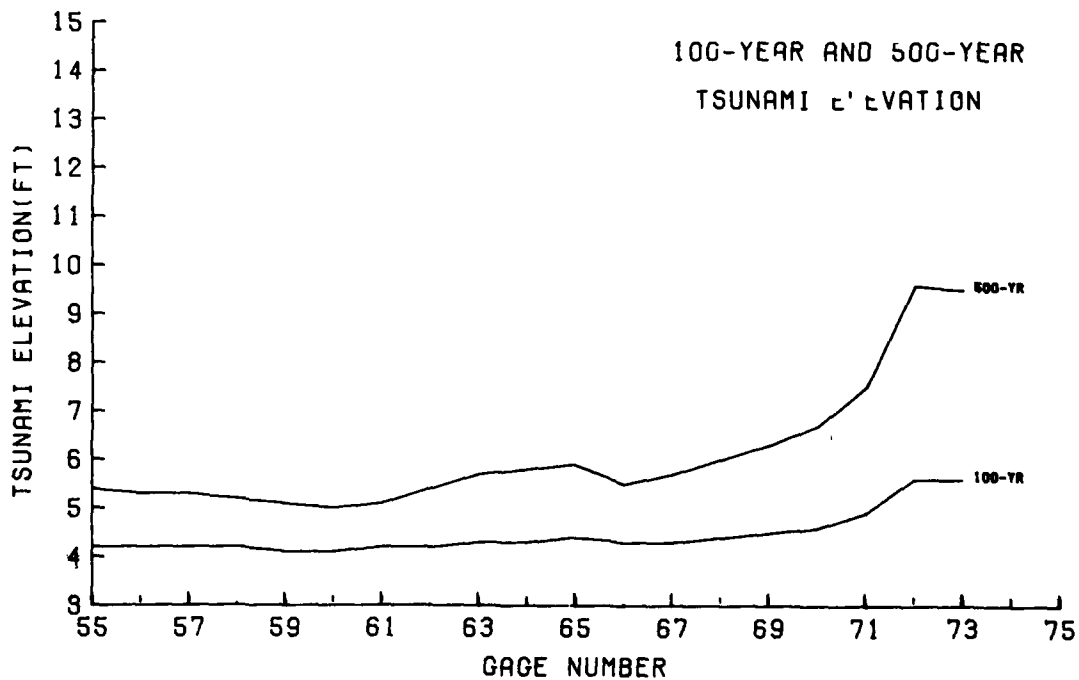


Figure 13. Gage numbers 55-73

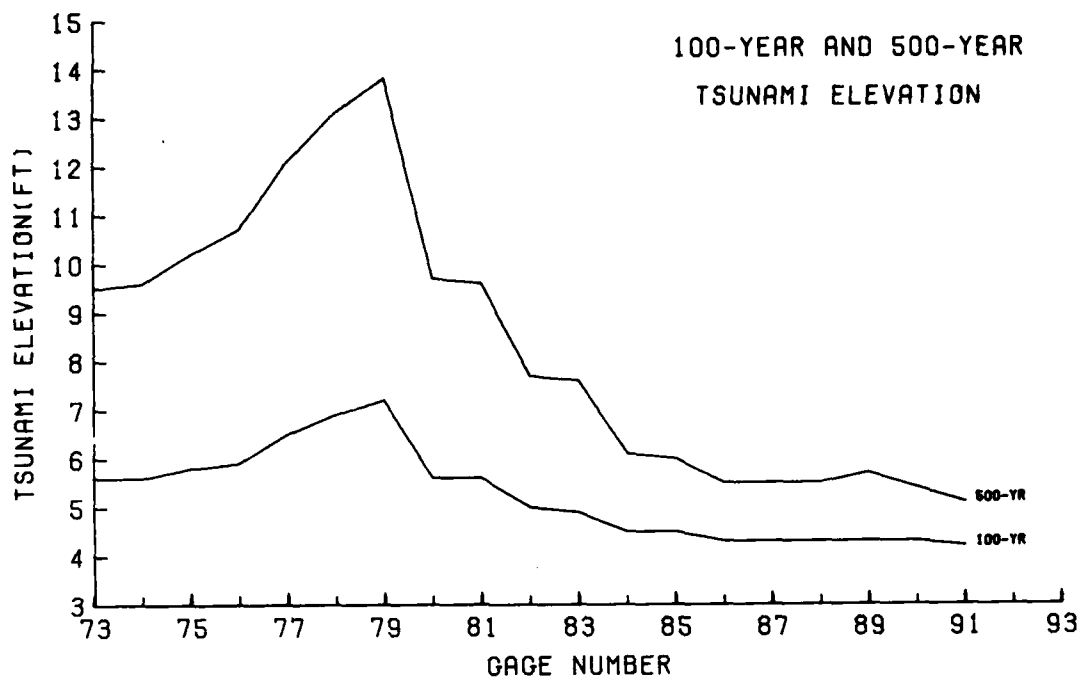


Figure 14. Gage numbers 73-91

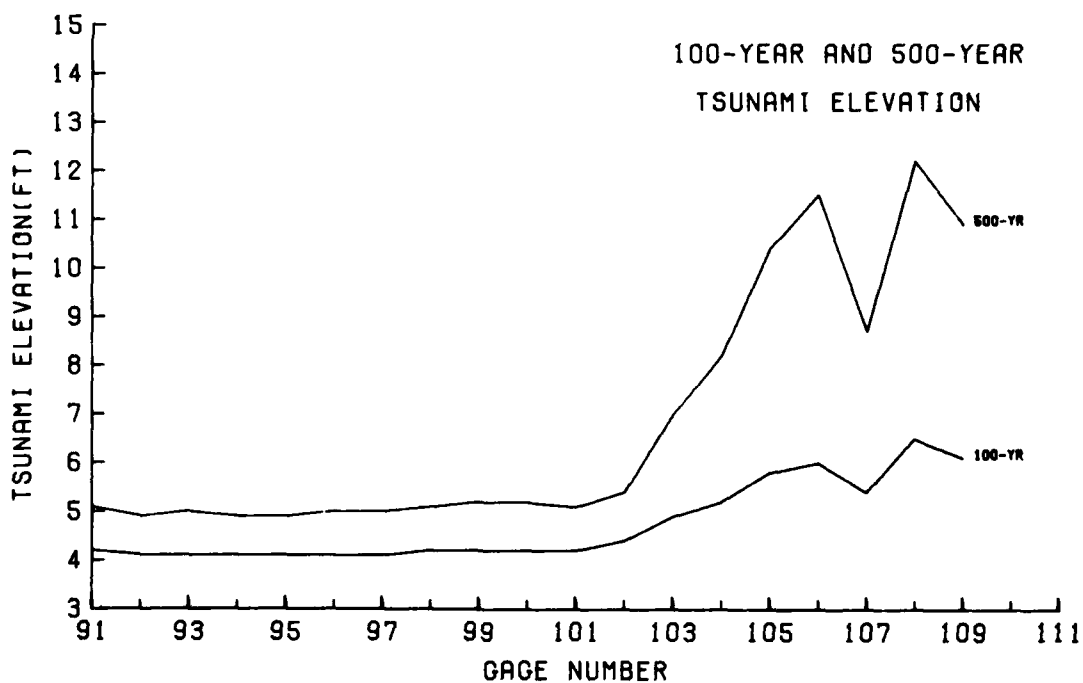


Figure 15. Gage numbers 91-109

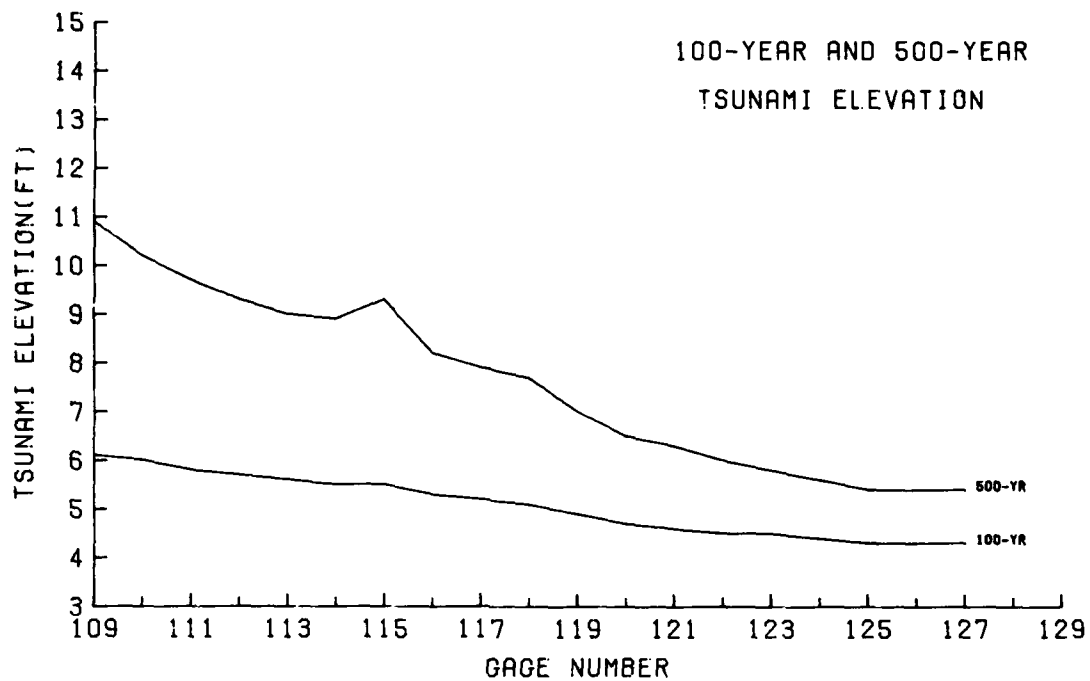


Figure 16. Gage numbers 109-127

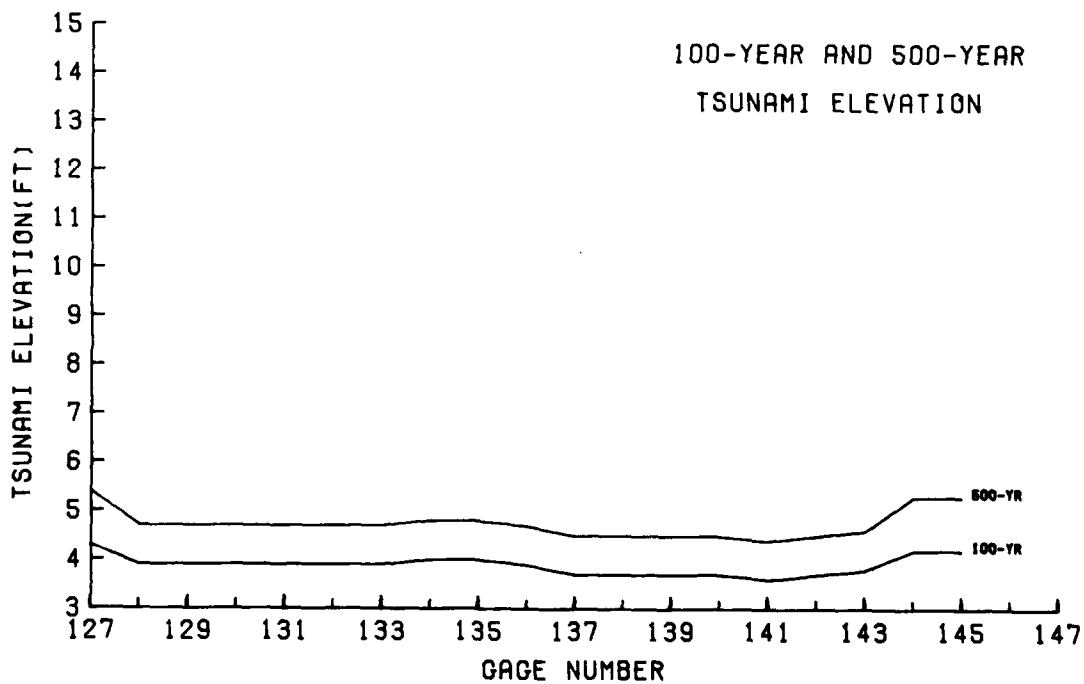


Figure 17. Gage numbers 127-145

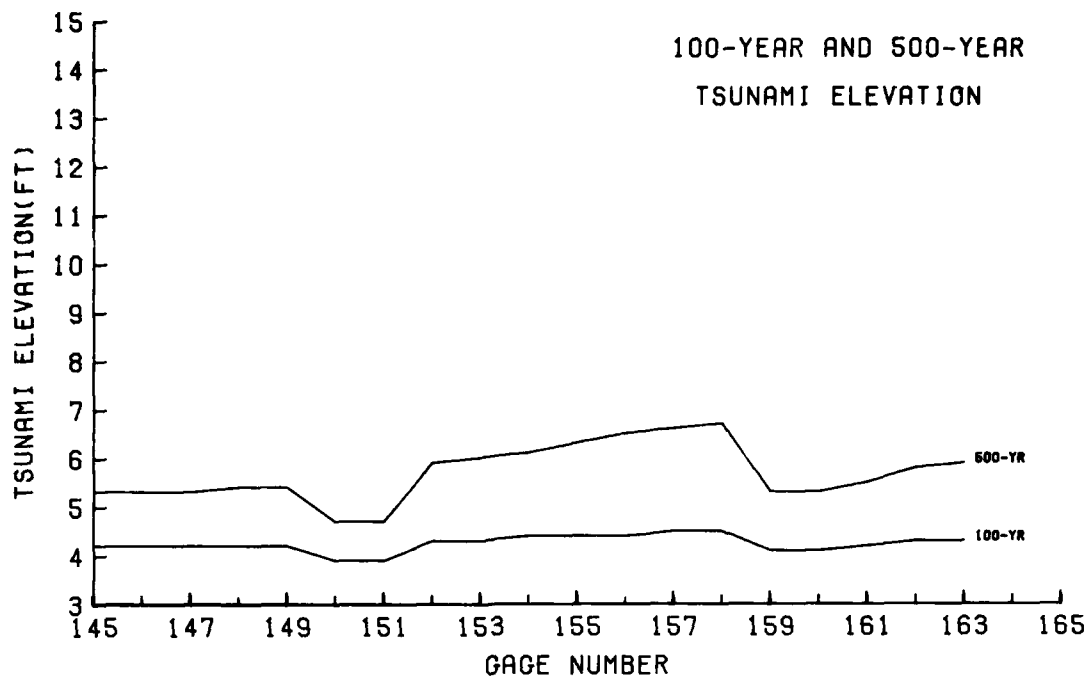


Figure 18. Gage numbers 145-163

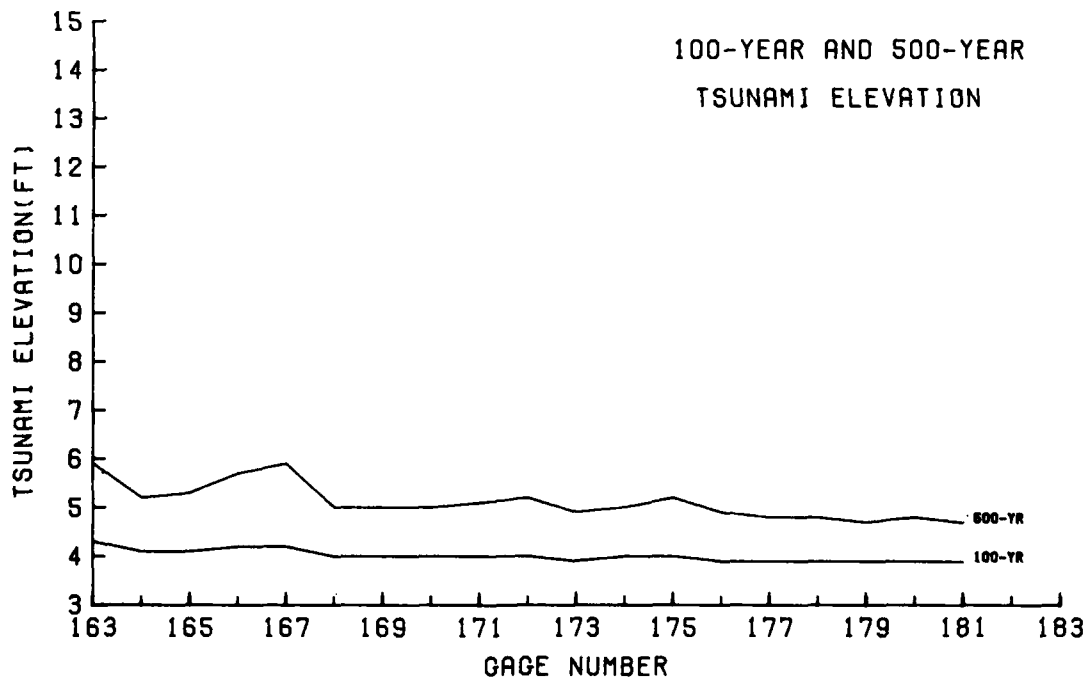


Figure 19. Gage numbers 163-181

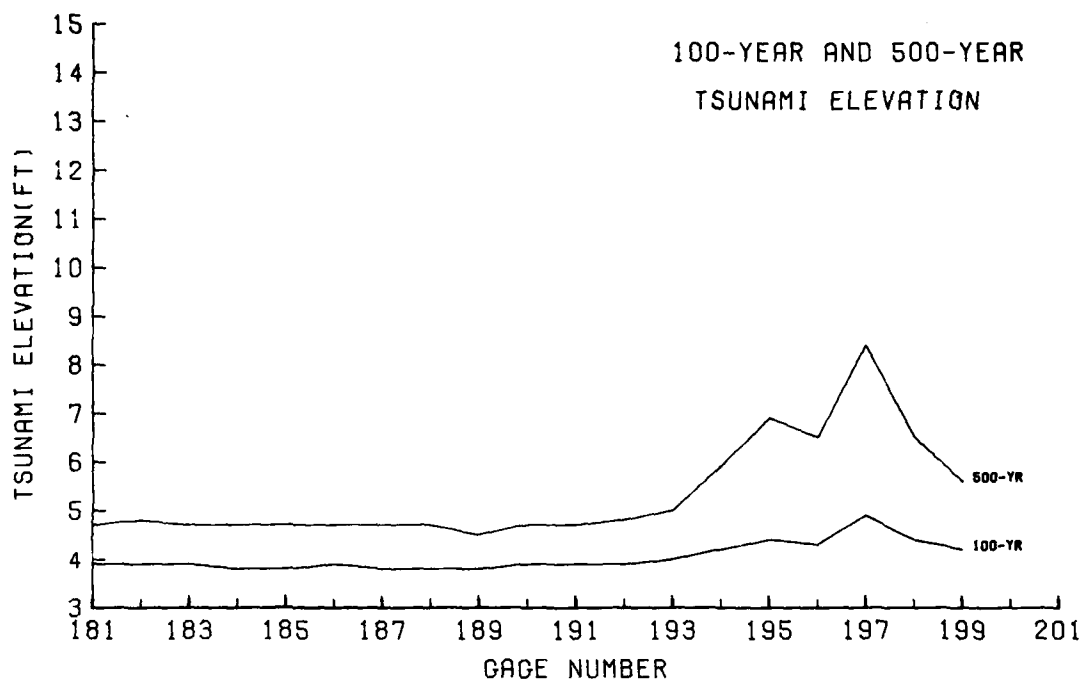


Figure 20. Gage numbers 181-199

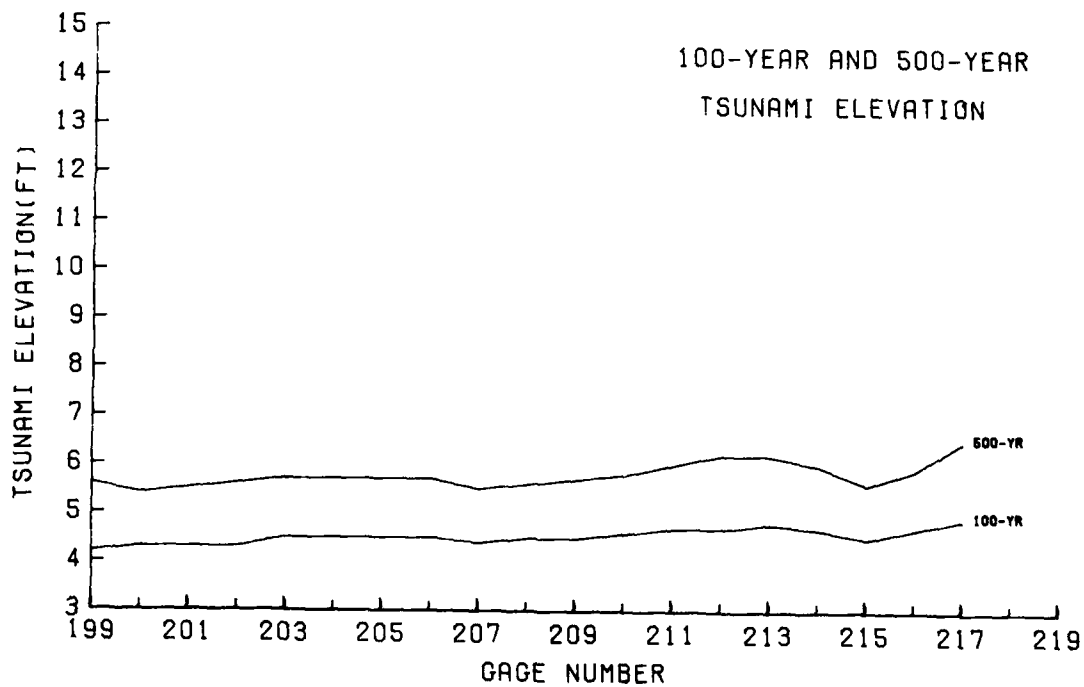


Figure 21. Gage numbers 199-217

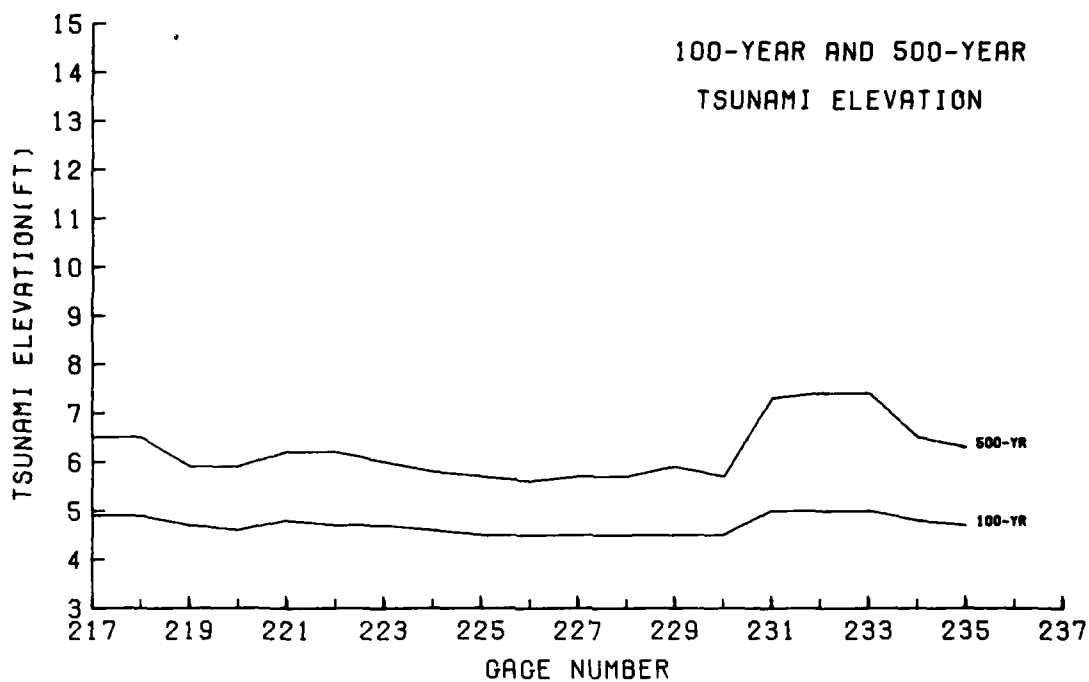


Figure 22. Gage numbers 217-235

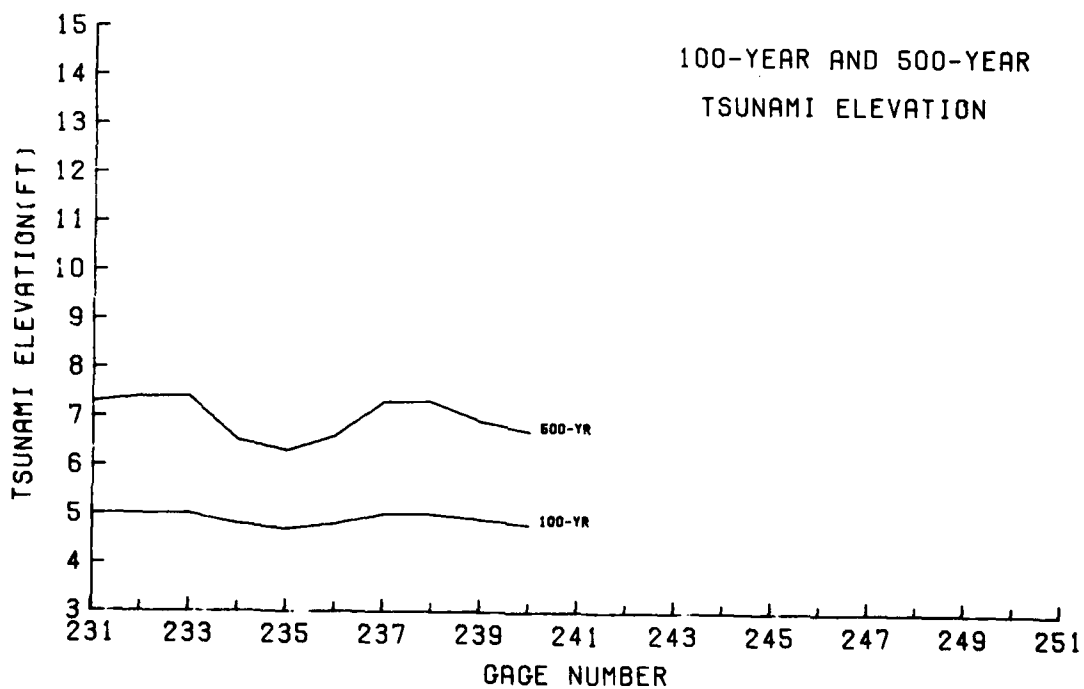


Figure 23. Gage numbers 231-240

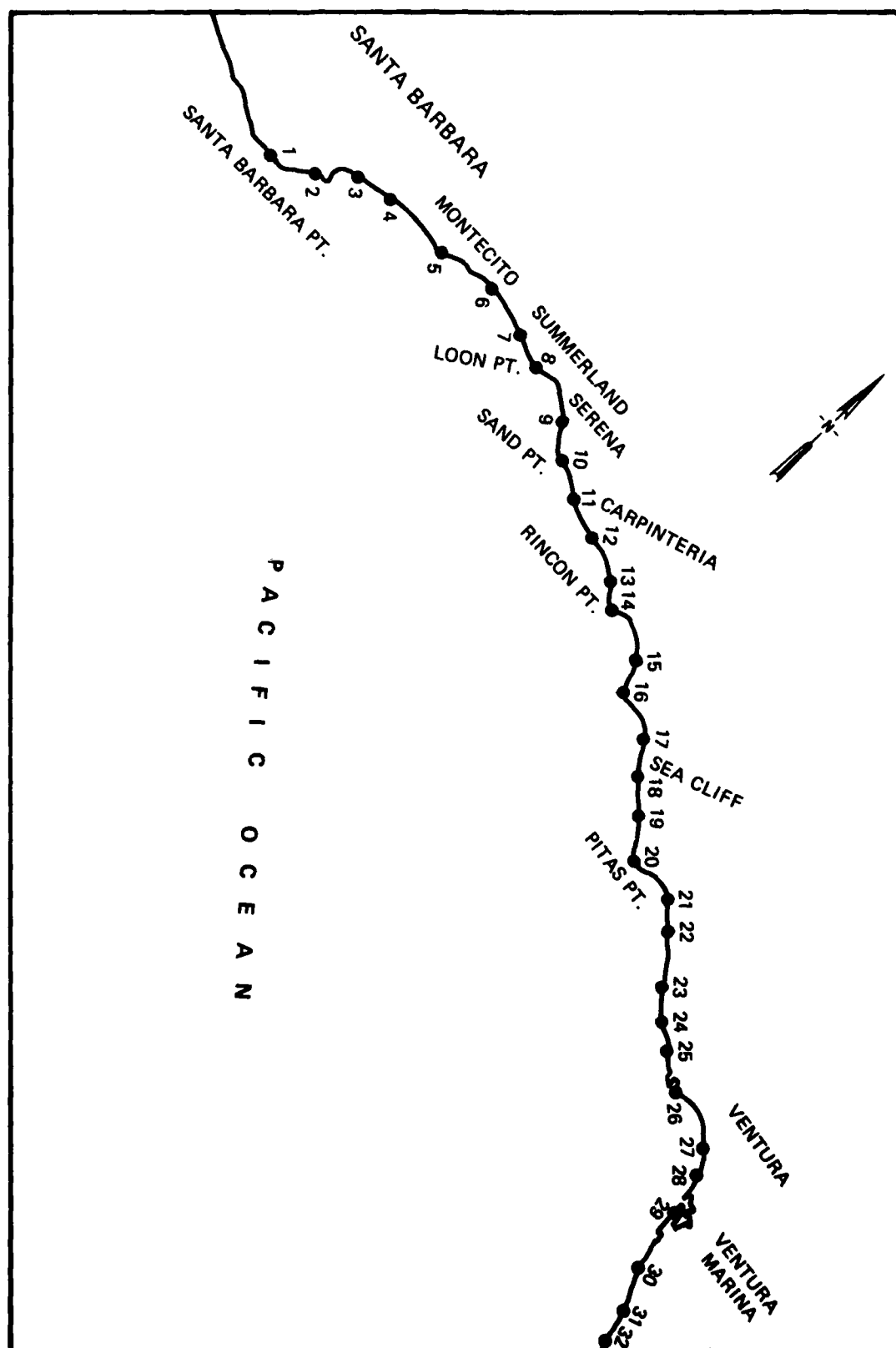


Figure 24. Gage locations 1-32

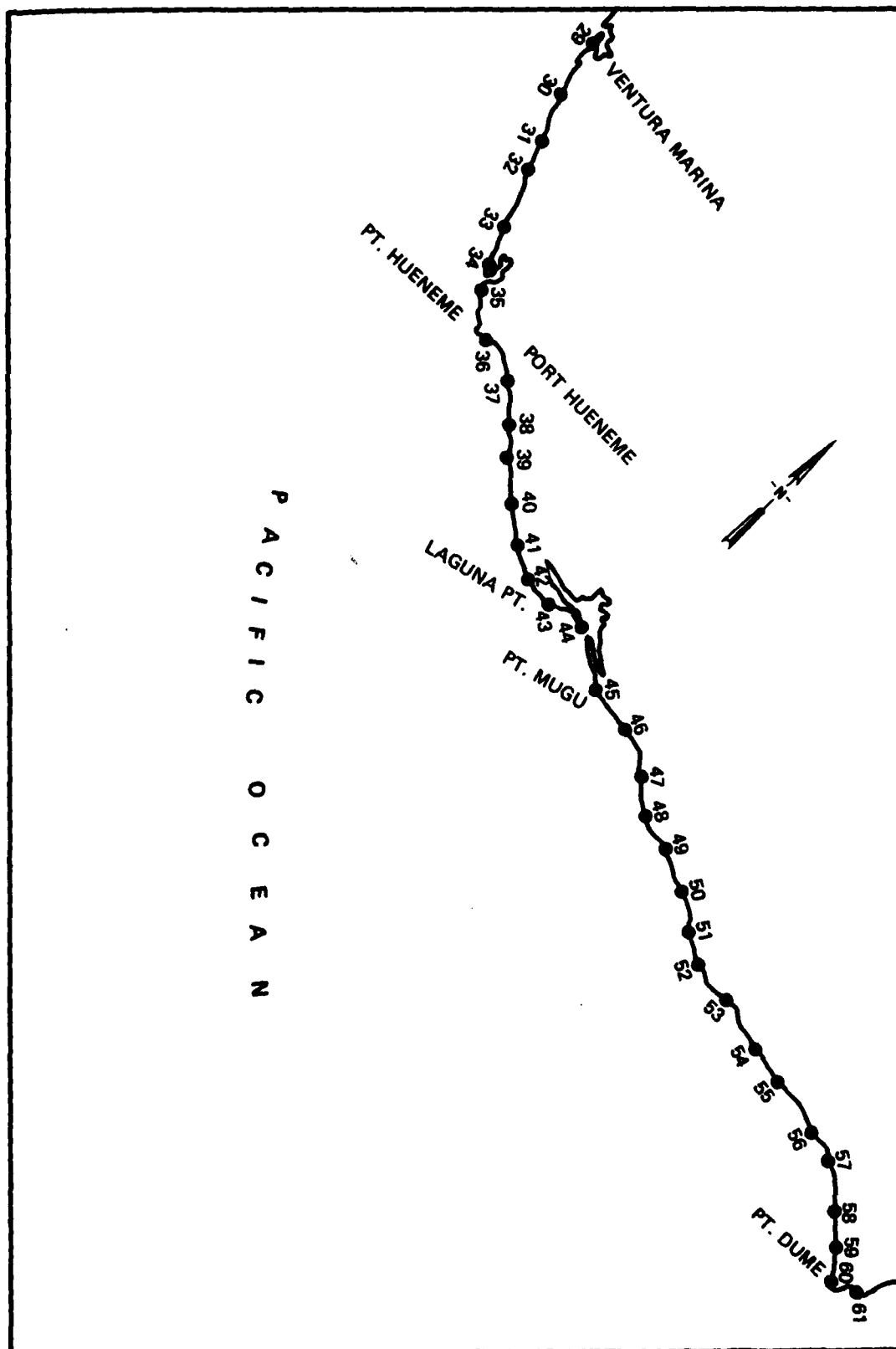


Figure 25. Gage locations 29-61

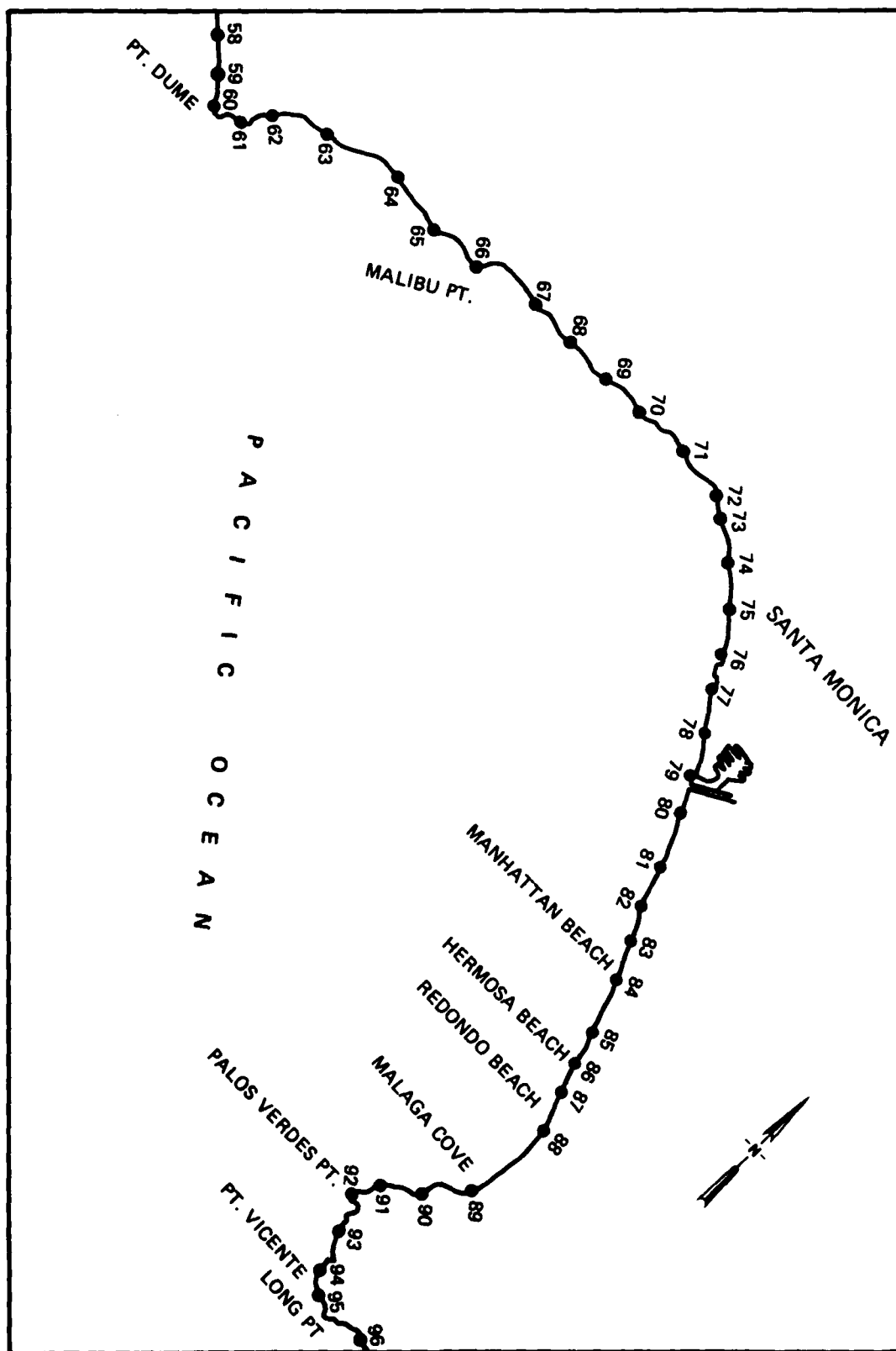


Figure 26. Gage locations 58-96

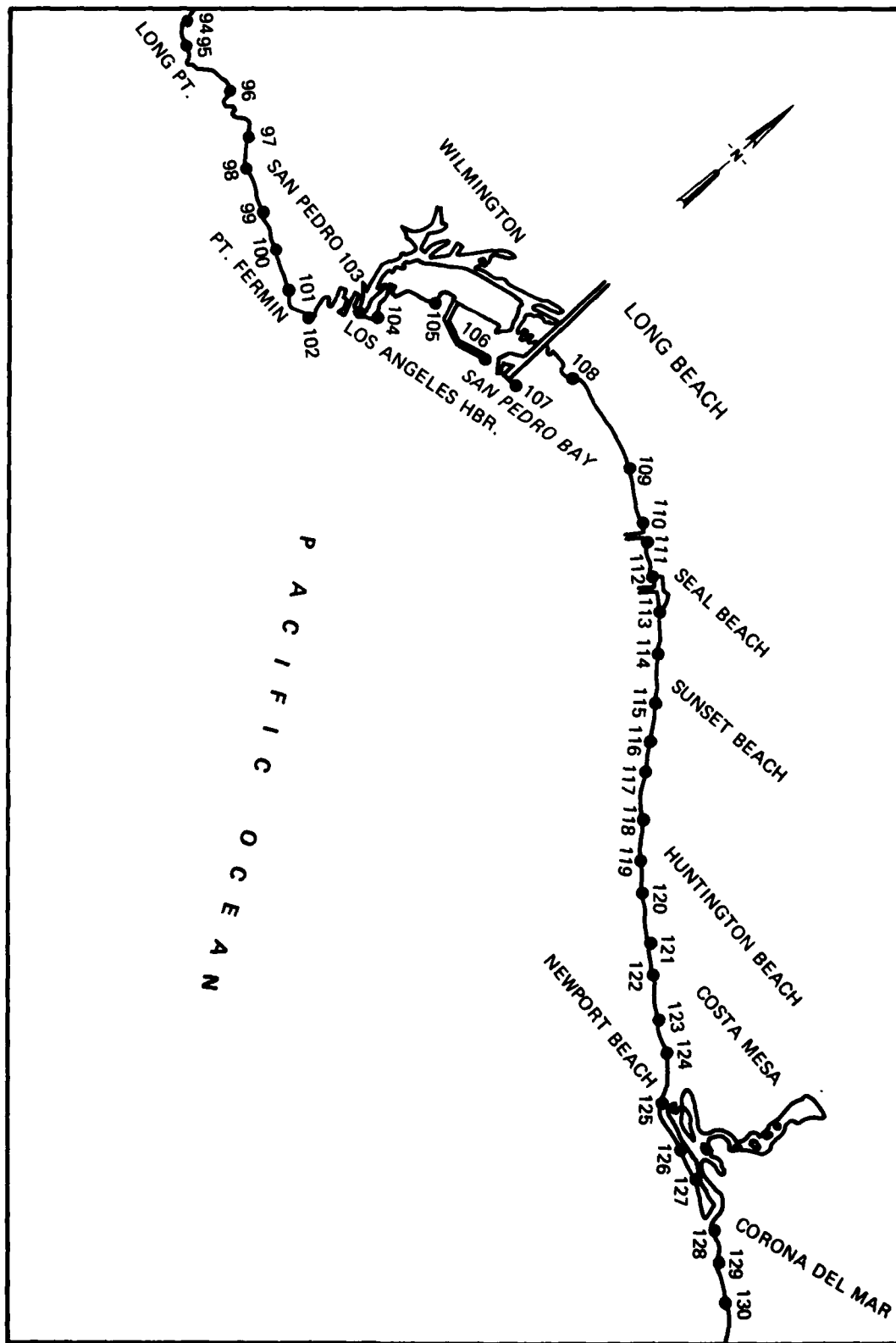


Figure 27. Gage locations 94-130

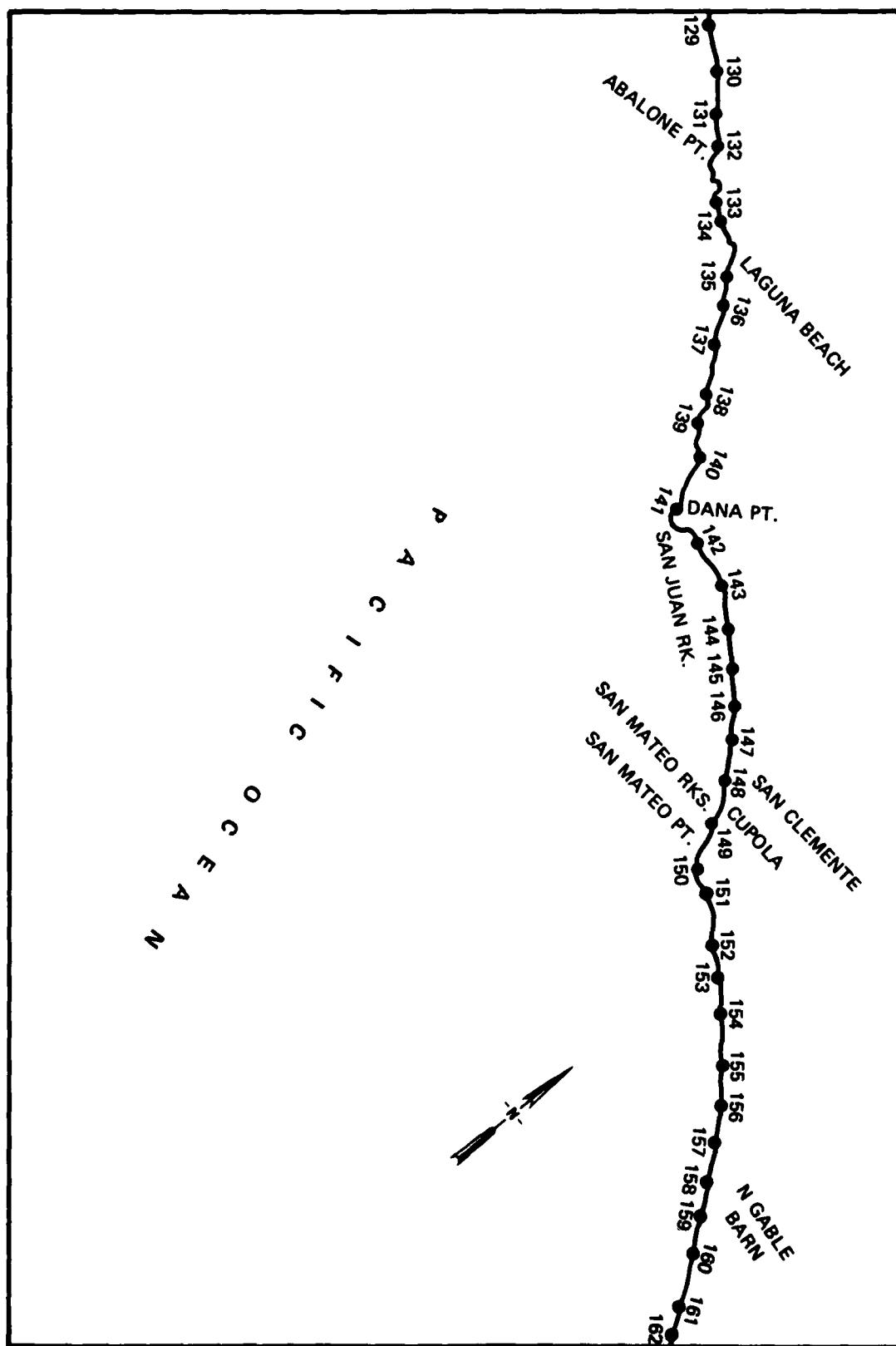


Figure 28. Gage locations 129-162

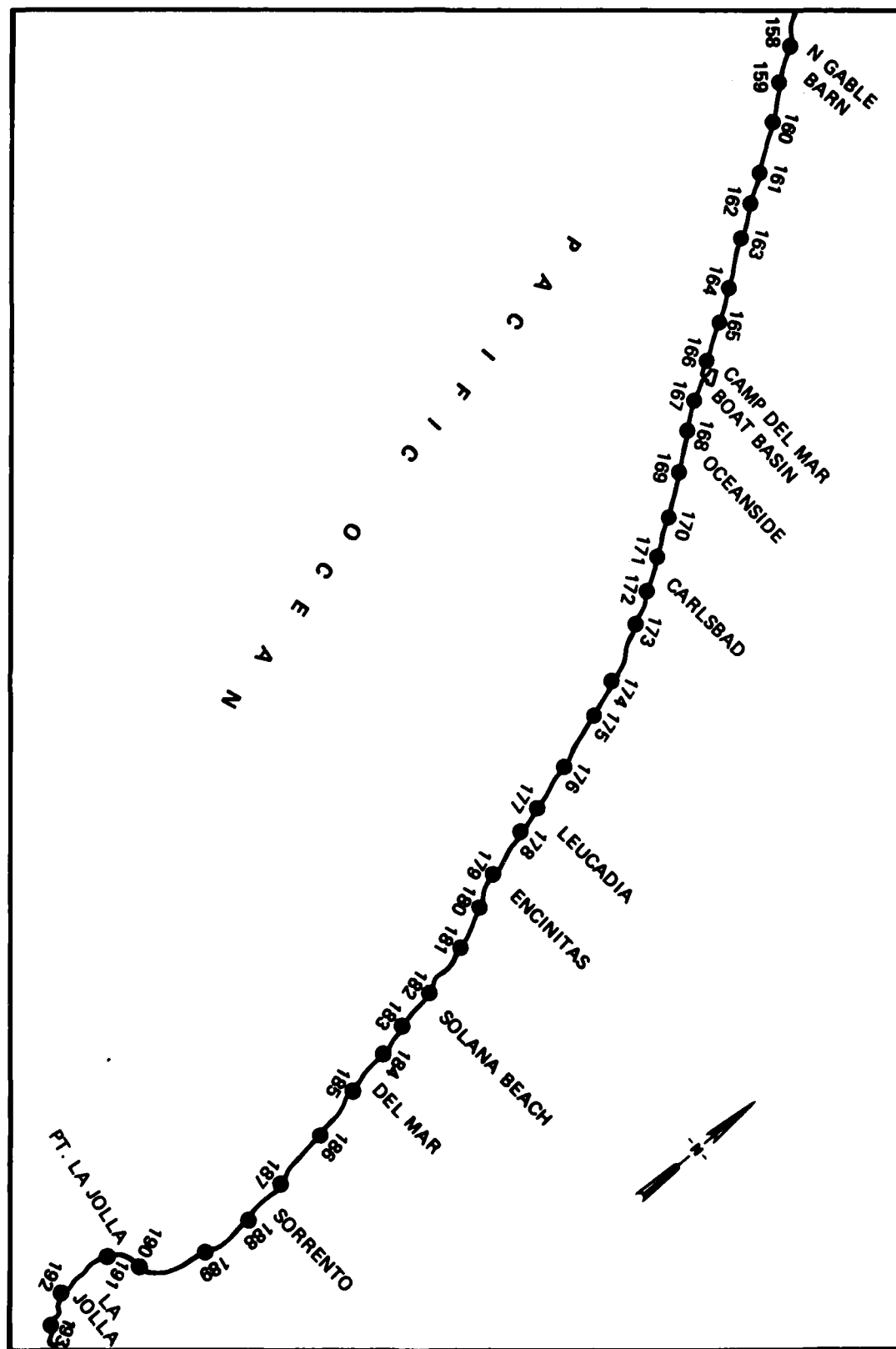


Figure 29. Gage locations 158-193

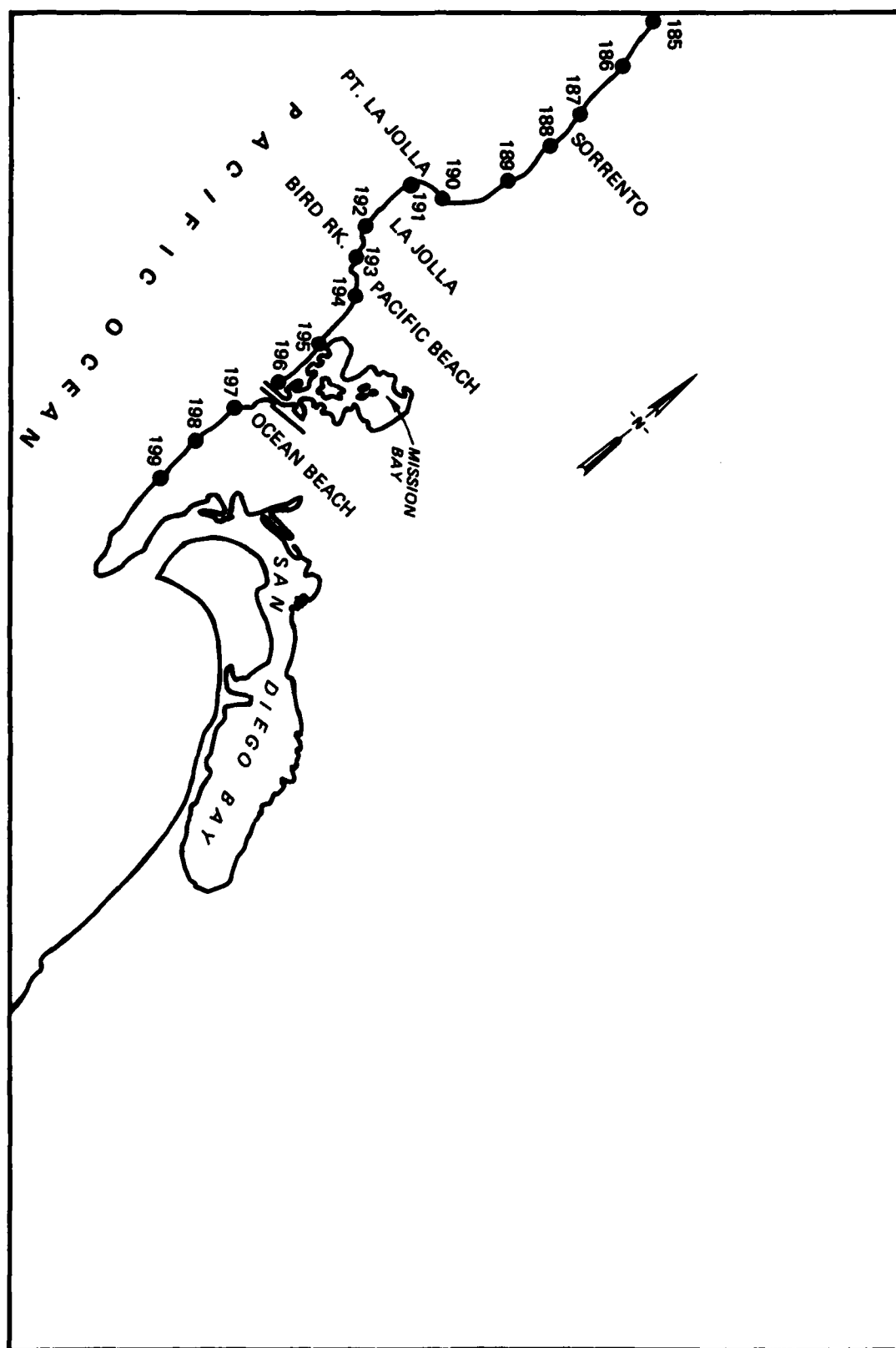


Figure 30. Gage locations 185-199

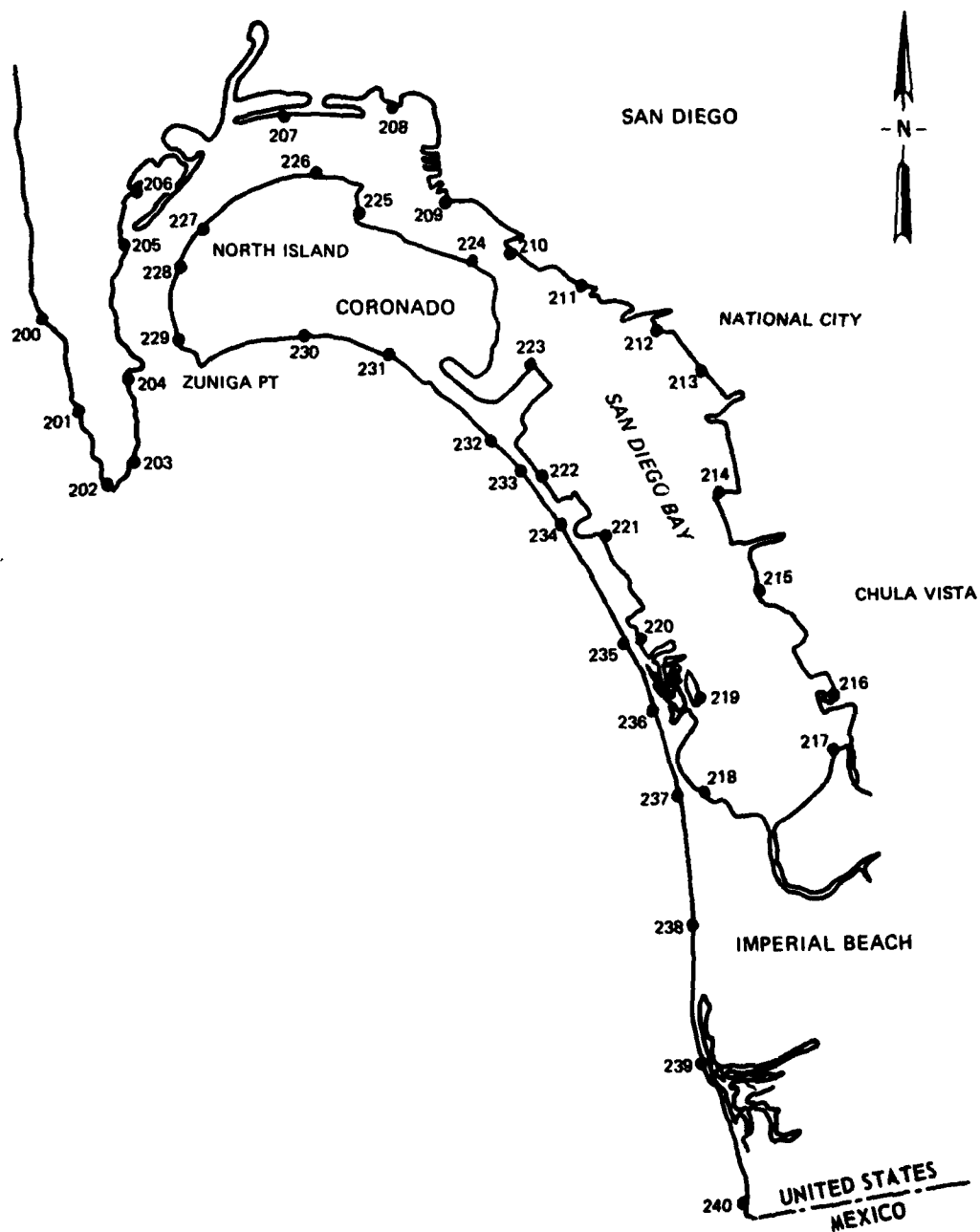
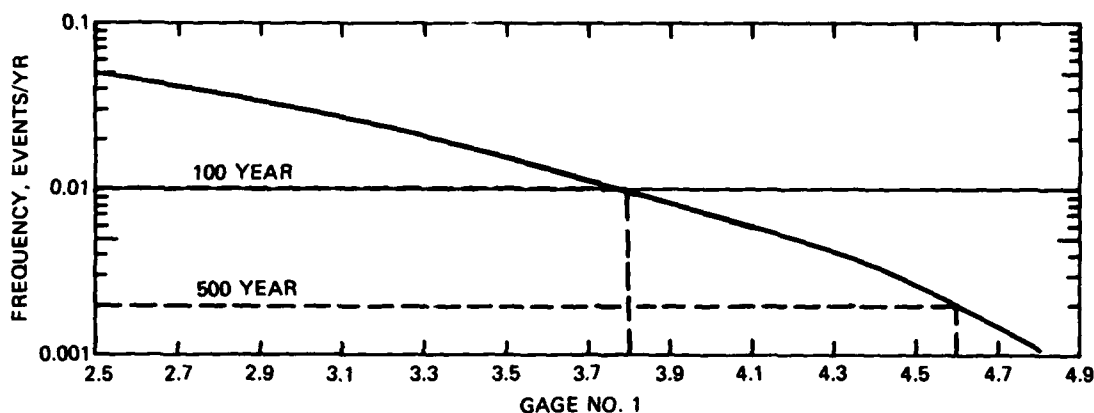


Figure 31. Gage locations 200-240



EXCEEDANCE FREQUENCY DISTRIBUTION

Figure 32. Use of frequency curves

and Garcia (1974) and Houston (1979), runup elevations should be equal to elevations at the shoreline for most locations in southern California. Thus the elevations presented in this report also can be considered to be runup elevations. However, runup elevations may not equal shoreline elevations at locations where dunes prevent flooding except through inlets or if the land is extremely flat and inland flooding is extensive. A land-flooding numerical model (e.g. model presented by Houston and Butler (1979)) can be used to determine runup for such cases.

Discussion

48. The exceedance frequencies presented in Plates 1-120 are for combined tsunami and astronomical tide elevations given the occurrence of a noticeable tsunami in southern California. It is not true that in the limit of a tsunami with an amplitude of zero, the frequency analysis presented determines the maximum possible elevation for the astronomical tide alone over a 100-yr period. It is quite possible that the 100-yr combined tsunami and astronomical tide elevation is less than the maximum possible astronomical tide elevation over a 100-yr period or even less than the maximum astronomical tide elevation that occurs during a typical year. For example, the maximum combined tsunami and astronomical tide

elevation during the last 100 yr at Rincon Island, California, probably occurred during the 1964 Alaskan tsunami (the 1960 Chilean tsunami may have been somewhat larger, but it was not recorded at Rincon Island). The maximum combined elevation was approximately 3.5 ft above msl. This elevation is greater than mean higher high water (2.8 ft) but less than the maximum astronomical tide elevation that typically occurs during the average year at Rincon Island. Thus the fact that the combined tsunami and astronomical tide elevations presented in Plates 1-120 are at some locations less than the maximum possible or even yearly tide elevations that may occur at the locations is a property of the natural phenomenon (tsunami heights are small compared with the tide, and arrival of a tsunami during the maximum astronomical tide of a year is more than a 100-yr event) and not of the methods used to calculate exceedance frequencies.

49. The logarithm of tsunami frequency is plotted versus elevation in Plates 1-120. There are sections of the exceedance frequency distribution curves that are approximately linear. This linear relationship between the logarithm of the tsunami exceedance frequency and tsunami elevations has been noted by many observers (see PART III).

50. The linear relationship between the logarithm of tsunami frequency and tsunami elevations holds only over a certain range of tsunami frequency. Cox (1964)* has shown that tsunami frequencies and elevations are linearly related for frequencies greater than approximately 0.05 to 0.1. Since earthquakes probably only reach certain maximum magnitudes, tsunamis can be expected to have similar upper limits to intensity. Thus the exceedance frequency curves must eventually approach a maximum elevation.

Comparison with Predictions Based on Local Observation

51. Virtually all of the coast of southern California lacks observations of tsunami activity. Only four locations (Alamitos Bay, Los

* Cox, D. C. 1964. "Tsunami Height-Frequency Relationship of Hilo" (unpublished paper), Hawaii Institute of Geophysics, University of Hawaii, Honolulu, Hawaii.

Angeles, Santa Monica, and San Diego) have tide gage recordings for both major tsunamis in 1960 and 1964. Since the tide gage at Alamitos Bay malfunctioned during the 1960 tsunami and there is a gap in the recording of approximately 2-1/2 hr, a reasonable determination of exceedance frequency based on observed data cannot be made at Alamitos Bay. The tide gage at Santa Monica also malfunctioned during the 1960 tsunami, but there is a good indication of a lower limit for the maximum elevation.

52. Except at San Diego (where a tide gage has operated since the midnineteenth century), recordings of tsunamis in southern California were not made prior to the twentieth century. Thus the 80-yr period of time from 1900 through 1979 will be used to estimate tsunami exceedance frequencies at Los Angeles, Santa Monica, and San Diego based upon local historical data. The 1960 and 1964 tsunamis produced the largest elevations at all three of these locations during the 80-yr period. By using data for these two tsunamis and assuming that the logarithm of the tsunami exceedance frequency is linearly related to the maximum combined tsunami and astronomical tide elevation (see PART III), the 100- and 500-yr combined tsunami and tide elevation can be estimated. This estimate is quite approximate since the time period is relatively short, there are many locations in source regions where tsunamis can be generated but were not during the time period (the numerical predictions include this effect by considering tsunamis generated all along the source regions), and the effect of tsunami arrival during various tidal stages is not accounted for in the historical data.

53. Using microfiche of tide gage recordings (from the National Oceanic and Atmospheric Administration) of the 1960 and 1964 tsunamis, the 1960 and 1964 tsunamis were found to have produced combined tsunamic and astronomical tide elevations of 4.0 ft and 2.8 ft at Los Angeles, greater than 4.6 ft (tide gage went off scale) and 3.0 ft at Santa Monica, and 3.9 ft and 3.1 ft at San Diego. The tabulation on the following page compares 100- and 500-yr elevations using these data and elevations presented in Plates 52, 38, and 113 for gage locations 104 (Los Angeles), 75 (Santa Monica), and 225 (San Diego) respectively.

<u>Location</u>	<u>Local Historical Data Predictions ft</u>		<u>Predictions Pre- sented in this Report, ft</u>	
	<u>100 yr</u>	<u>500 yr</u>	<u>100 yr</u>	<u>500 yr</u>
Los Angeles	4.4	7.2	5.2	8.2
Santa Monica	>5.2*	>8.9*	5.8	10.2
San Diego	4.2	6.0	4.6	5.7

* Lower limit since tide gage off scale during 1960 tsunami at Santa Monica.

PART V: CONCLUSIONS AND RECOMMENDATIONS

Conclusions

54. The deep-ocean and nearshore numerical models used in this report accurately simulated tsunami generation, deep-ocean and nearshore propagation, and interaction with coastlines. The nearshore numerical model was superior to the analytical techniques used for nearshore propagation in a previous study (Houston and Garcia 1974) because it was two-dimensional and handled arbitrary incident wave forms. The techniques used in this report to predict tsunami elevations provided good estimates of 100- and 500-yr tsunami elevations for southern California. Based upon the techniques presented in this report, 100- and 500-yr predictions at Los Angeles, Santa Monica, and San Diego, California, were shown to agree quite well with predictions based upon historical observations of tsunami activity at these three locations. These were the only locations in southern California which had sufficient local historical data to allow predictions based upon local observations.

Recommendations

55. The elevations predicted in this report are at the shoreline but can be assumed to equal runup elevations for most of southern California. There are locations where time-dependent effects (for example, lack of sufficient time to completely flood extensive low-lying or estuarine areas) or two-dimensional effects (for example, flow divergence or convergence) cause tsunami runup elevations not to be equal to elevations at the shoreline. It is recommended that for these areas inundation limits be determined using a numerical model developed recently at the U. S. Army Engineer Waterways Experiment Station (Houston and Butler 1979). This model is capable of handling land flooding for bays, harbors, developed areas such as cities, large low-lying areas, sand-dune protected areas, and other areas where there are topographical, roughness, or coastline variations.

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Table 1

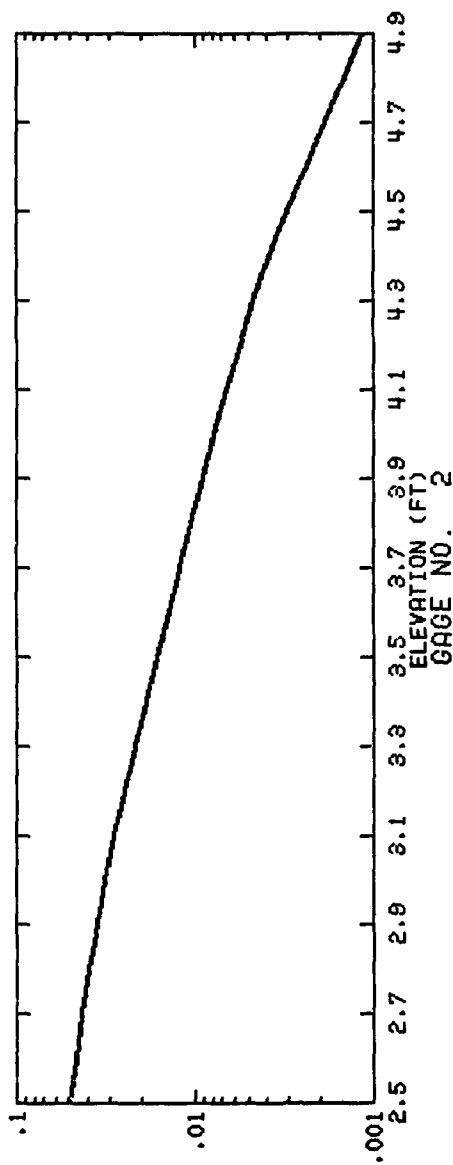
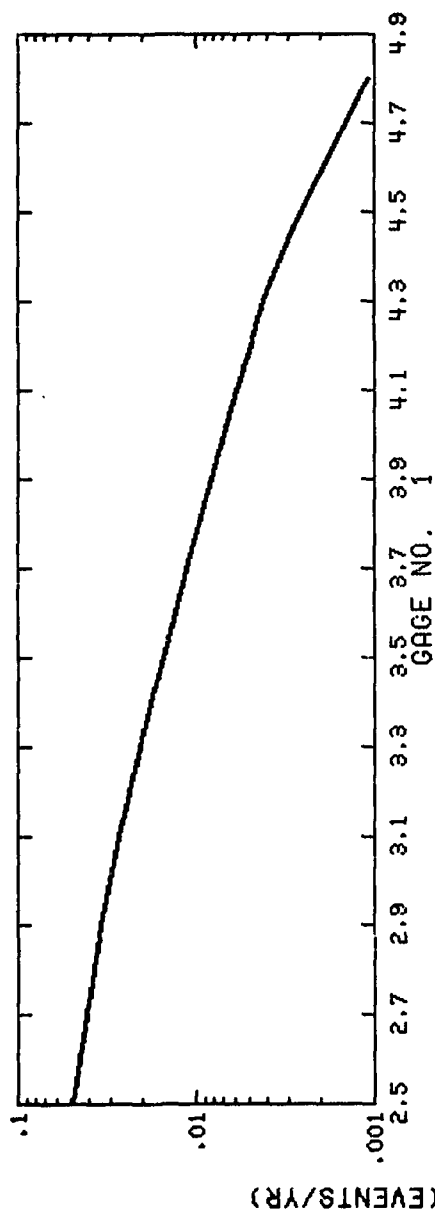
Location of Gages

GAGE NUMBER	IN DEGREES-MINUTES-SECONDS/SEC WITH ONE DECIMAL PLACE			GAGE LOCATIONS		
	LONGITUDE	LATITUDE	GAGE NUMBER	LONGITUDE	LATITUDE	
1	119 43 49.8	34 23 45.6	41	118 47 38.4	34 17 25.2	
2	119 41 49.2	34 24 39.6	42	118 47 13.2	34 17 11.2	
3	119 41 49.6	34 24 39.6	43	118 46 51.6	34 17 25.2	
4	119 40 49.4	34 25 1.2	44	118 46 25.8	34 17 25.2	
5	119 38 49.4	34 25 1.2	45	118 46 58.8	34 17 25.2	
6	119 38 49.4	34 25 1.2	46	118 46 58.8	34 17 25.2	
7	119 38 49.4	34 25 1.2	47	118 46 58.8	34 17 25.2	
8	119 38 49.4	34 25 1.2	48	118 46 58.8	34 17 25.2	
9	119 38 49.4	34 25 1.2	49	118 46 58.8	34 17 25.2	
10	119 38 49.4	34 25 1.2	50	118 46 58.8	34 17 25.2	
11	119 38 49.4	34 25 1.2	51	118 46 58.8	34 17 25.2	
12	119 38 49.4	34 25 1.2	52	118 46 58.8	34 17 25.2	
13	119 38 49.4	34 25 1.2	53	118 46 58.8	34 17 25.2	
14	119 38 49.4	34 25 1.2	54	118 46 58.8	34 17 25.2	
15	119 38 49.4	34 25 1.2	55	118 46 58.8	34 17 25.2	
16	119 38 49.4	34 25 1.2	56	118 46 58.8	34 17 25.2	
17	119 38 49.4	34 25 1.2	57	118 46 58.8	34 17 25.2	
18	119 38 49.4	34 25 1.2	58	118 46 58.8	34 17 25.2	
19	119 38 49.4	34 25 1.2	59	118 46 58.8	34 17 25.2	
20	119 38 49.4	34 25 1.2	60	118 46 58.8	34 17 25.2	
21	119 38 49.4	34 25 1.2	61	118 46 58.8	34 17 25.2	
22	119 38 49.4	34 25 1.2	62	118 46 58.8	34 17 25.2	
23	119 38 49.4	34 25 1.2	63	118 46 58.8	34 17 25.2	
24	119 38 49.4	34 25 1.2	64	118 46 58.8	34 17 25.2	
25	119 38 49.4	34 25 1.2	65	118 46 58.8	34 17 25.2	
26	119 38 49.4	34 25 1.2	66	118 46 58.8	34 17 25.2	
27	119 38 49.4	34 25 1.2	67	118 46 58.8	34 17 25.2	
28	119 38 49.4	34 25 1.2	68	118 46 58.8	34 17 25.2	
29	119 38 49.4	34 25 1.2	69	118 46 58.8	34 17 25.2	
30	119 38 49.4	34 25 1.2	70	118 46 58.8	34 17 25.2	
31	119 38 49.4	34 25 1.2	71	118 46 58.8	34 17 25.2	
32	119 38 49.4	34 25 1.2	72	118 46 58.8	34 17 25.2	
33	119 38 49.4	34 25 1.2	73	118 46 58.8	34 17 25.2	
34	119 38 49.4	34 25 1.2	74	118 46 58.8	34 17 25.2	
35	119 38 49.4	34 25 1.2	75	118 46 58.8	34 17 25.2	
36	119 38 49.4	34 25 1.2	76	118 46 58.8	34 17 25.2	
37	119 38 49.4	34 25 1.2	77	118 46 58.8	34 17 25.2	
38	119 38 49.4	34 25 1.2	78	118 46 58.8	34 17 25.2	
39	119 38 49.4	34 25 1.2	79	118 46 58.8	34 17 25.2	
40	119 38 49.4	34 25 1.2	80	118 46 58.8	34 17 25.2	
41	119 38 49.4	34 25 1.2	81	118 46 58.8	34 17 25.2	
42	119 38 49.4	34 25 1.2	82	118 46 58.8	34 17 25.2	
43	119 38 49.4	34 25 1.2	83	118 46 58.8	34 17 25.2	
44	119 38 49.4	34 25 1.2	84	118 46 58.8	34 17 25.2	
45	119 38 49.4	34 25 1.2	85	118 46 58.8	34 17 25.2	
46	119 38 49.4	34 25 1.2	86	118 46 58.8	34 17 25.2	
47	119 38 49.4	34 25 1.2	87	118 46 58.8	34 17 25.2	
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53	119 38 49.4	34 25 1.2	93	118 46 58.8	34 17 25.2	
54	119 38 49.4	34 25 1.2	94	118 46 58.8	34 17 25.2	
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56	119 38 49.4	34 25 1.2	96	118 46 58.8	34 17 25.2	
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60	119 38 49.4	34 25 1.2	100	118 46 58.8	34 17 25.2	
61	119 38 49.4	34 25 1.2	101	118 46 58.8	34 17 25.2	
62	119 38 49.4	34 25 1.2	102	118 46 58.8	34 17 25.2	
63	119 38 49.4	34 25 1.2	103	118 46 58.8	34 17 25.2	
64	119 38 49.4	34 25 1.2	104	118 46 58.8	34 17 25.2	
65	119 38 49.4	34 25 1.2	105	118 46 58.8	34 17 25.2	
66	119 38 49.4	34 25 1.2	106	118 46 58.8	34 17 25.2	
67	119 38 49.4	34 25 1.2	107	118 46 58.8	34 17 25.2	
68	119 38 49.4	34 25 1.2	108	118 46 58.8	34 17 25.2	
69	119 38 49.4	34 25 1.2	109	118 46 58.8	34 17 25.2	
70	119 38 49.4	34 25 1.2	110	118 46 58.8	34 17 25.2	
71	119 38 49.4	34 25 1.2	111	118 46 58.8	34 17 25.2	
72	119 38 49.4	34 25 1.2	112	118 46 58.8	34 17 25.2	
73	119 38 49.4	34 25 1.2	113	118 46 58.8	34 17 25.2	
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75	119 38 49.4	34 25 1.2	115	118 46 58.8	34 17 25.2	
76	119 38 49.4	34 25 1.2	116	118 46 58.8	34 17 25.2	
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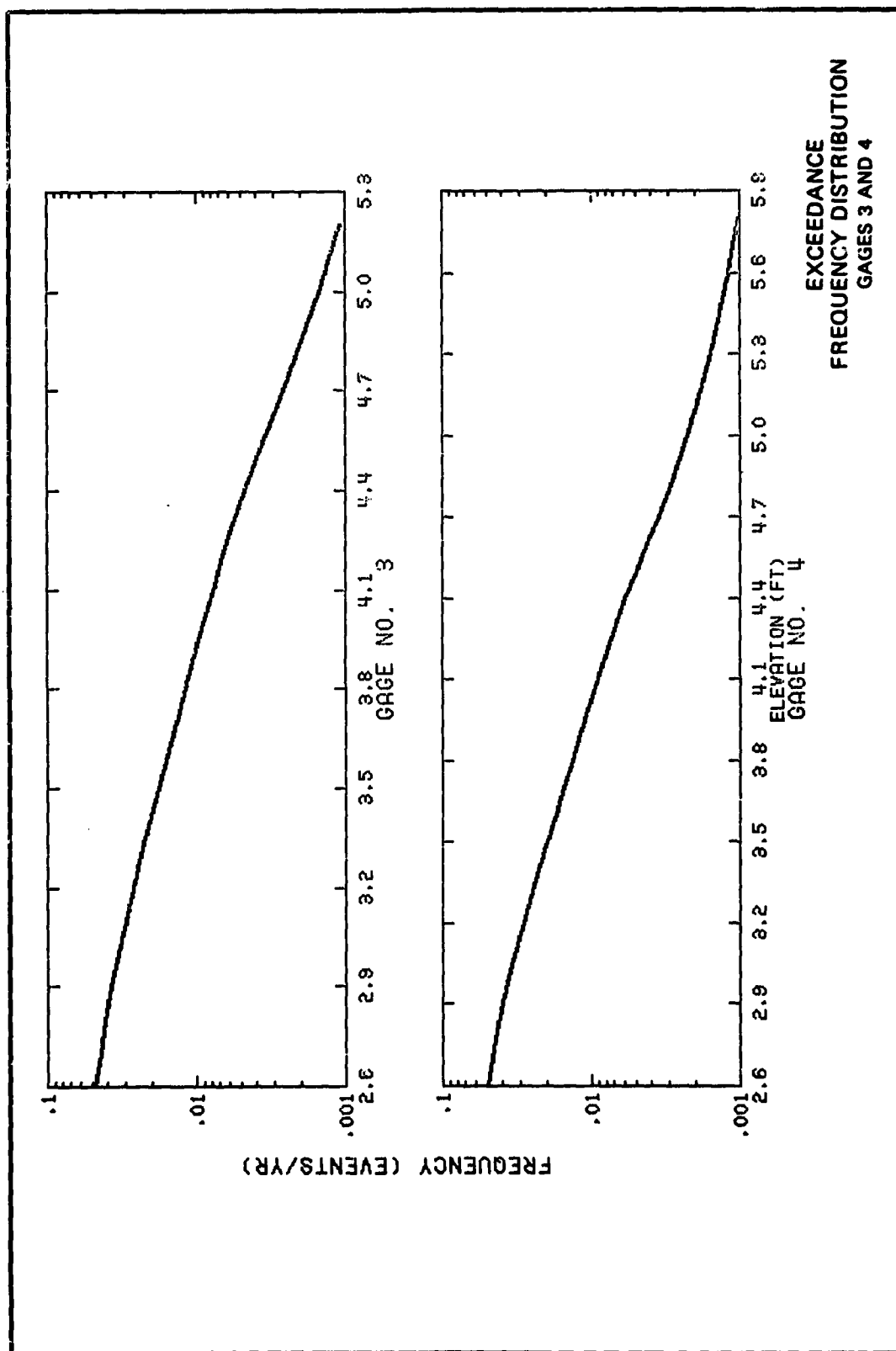
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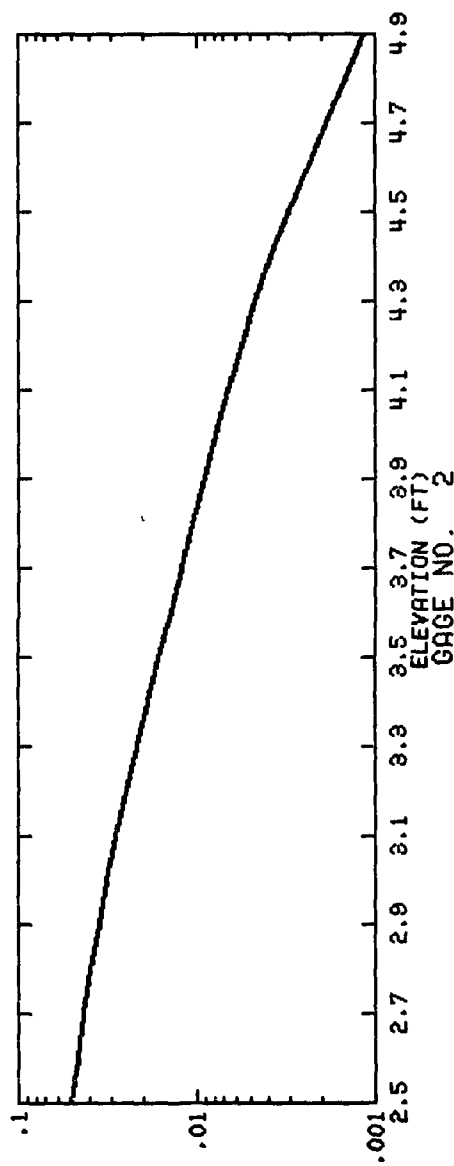
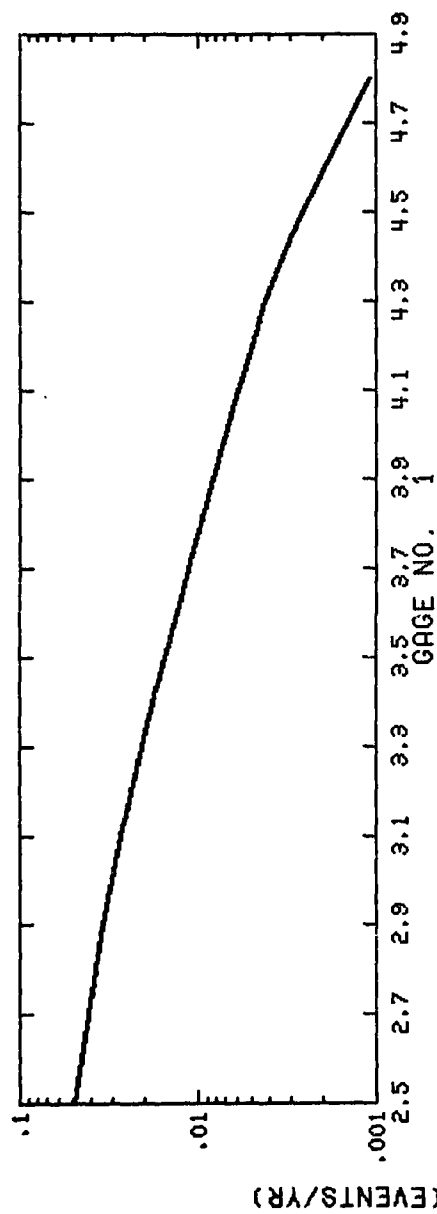
Table 1 (Concluded)

GAGE NUMBER	LONGITUDE	LATITUDE	GAGE NUMBER	LONGITUDE	LATITUDE
121	117 59 27.6	33 30 56.4	181	117 16 48.0	33 54.3
122	117 58 27.6	33 30 27.6	182	117 16 26.4	32 59 52.8
123	117 57 43.2	33 37 51.6	183	117 16 12.0	32 58 48.0
124	117 56 49.2	33 37 30.0	184	117 15 54.0	32 57 50.4
125	117 55 55.2	33 36 43.2	185	117 15 39.6	32 56 45.6
126	117 54 50.4	33 36 18.0	186	117 15 21.6	32 55 37.2
127	117 53 49.2	33 36 3.6	187	117 15 13.8	32 54 32.4
128	117 52 37.2	33 35 49.2	188	117 15 1.2	32 53 31.2
129	117 51 54.0	33 35 20.4	189	117 15 0.0	32 52 12.0
130	117 51 7.2	33 34 48.0	190	117 15 46.8	32 51 52.8
131	117 50 6.0	33 34 19.2	191	117 16 4.8	32 51 38.4
132	117 49 19.2	33 33 50.4	192	117 16 33.6	32 49 22.8
133	117 48 36.0	33 33 14.4	193	117 16 4.8	32 48 39.6
134	117 47 49.2	33 34 19.2	194	117 15 25.2	32 48 7.2
135	117 46 51.6	33 32 20.4	195	117 15 7.2	32 46 58.8
136	117 46 8.4	33 31 44.4	196	117 15 3.6	32 45 43.2
137	117 45 32.4	33 31 1.2	197	117 15 17.8	32 44 27.6
138	117 44 49.2	33 3 25.2	198	117 15 18.0	32 43 33.6
139	117 43 4.8	33 29 38.4	199	117 15 25.2	32 42 21.6
140	117 43 8.4	33 28 48.0	200	117 15 19.8	32 41 45.6
141	117 42 7.2	33 28 1.2	201	117 14 32.8	32 41 40.8
142	117 42 48.0	33 27 32.4	202	117 14 6.0	32 40 4.8
143	117 39 57.6	33 27 3.6	203	117 14 16.8	32 40 31.2
144	117 39 12.8	33 26 36.8	204	117 14 9.6	32 40 36.0
145	117 38 2.4	33 26 2.4	205	117 13 26.4	32 43 8.4
146	117 37 4.8	33 25 26.4	206	117 13 26.4	32 43 44.4
147	117 36 54.0	33 24 48.0	207	117 12 14.4	32 43 33.6
148	117 36 18.0	33 24 3.6	208	117 12 12.0	32 42 39.6
149	117 35 39.6	33 23 16.8	209	117 9 28.8	32 42 3.6
150	117 35 4.8	33 22 35.2	210	117 8 58.8	32 41 34.8
151	117 33 5.0	33 22 30.0	211	117 7 58.8	32 41 58.8
152	117 33 3.6	33 22 1.2	212	117 7 12.0	32 41 30.0
153	117 32 16.8	33 21 21.6	213	117 7 1.2	32 39 28.8
154	117 31 3.0	33 2 45.6	214	117 6 56.0	32 38 9.6
155	117 30 4.8	33 20 20.4	215	117 5 49.2	32 37 12.0
156	117 29 56.4	33 19 43.8	216	117 5 43.6	32 36 36.0
157	117 29 13.2	33 19 4.8	217	117 7 26.4	32 36 18.0
158	117 28 37.2	33 18 14.4	218	117 7 44.4	32 37 12.0
159	117 27 57.6	33 17 34.8	219	117 8 16.8	32 38 9.6
160	117 27 18.0	33 16 51.6	220	117 8 34.8	32 39 3.6
161	117 26 42.0	33 16 12.0	221	117 9 14.4	32 39 46.8
162	117 26 6.0	33 15 28.8	222	117 9 36.0	32 4 55.2
163	117 25 26.4	33 14 42.0	223	117 10 1.2	32 41 52.8
164	117 24 50.4	33 14 2.4	224	117 10 44.4	32 42 14.4
165	117 24 21.6	33 13 15.6	225	117 11 27.6	32 42 50.4
166	117 23 42.0	33 12 26.8	226	117 12 54.0	32 42 39.6
167	117 23 9.6	33 11 49.2	227	117 13 30.0	32 42 7.2
168	117 22 33.6	33 11 9.6	228	117 13 22.8	32 41 6.0
169	117 21 57.6	33 1 26.4	229	117 13 52.8	32 41 13.2
170	117 21 14.4	33 9 39.6	230	117 13 48.0	32 41 51.6
171	117 20 45.6	33 8 3.6	231	117 10 8.4	32 4 30.0
172	117 20 9.6	33 6 9.6	232	117 9 32.4	32 39 32.4
173	117 19 4.8	33 7 19.2	233	117 8 56.4	32 38 42.0
174	117 19 8.4	33 6 21.6	234	117 8 31.2	32 37 55.2
175	117 18 50.4	33 5 24.0	235	117 8 9.6	32 36 50.4
176	117 18 5.4	33 4 12.0	236	117 7 58.8	32 35 42.0
177	117 16 0.0	33 3 39.6	237	117 7 31.6	32 34 44.4
178	117 17 52.8	33 2 27.6	238	117 7 44.4	32 33 28.8
179	117 17 9.6	33 1 51.6	239	117 7 30.0	32 32 31.2
180			240		

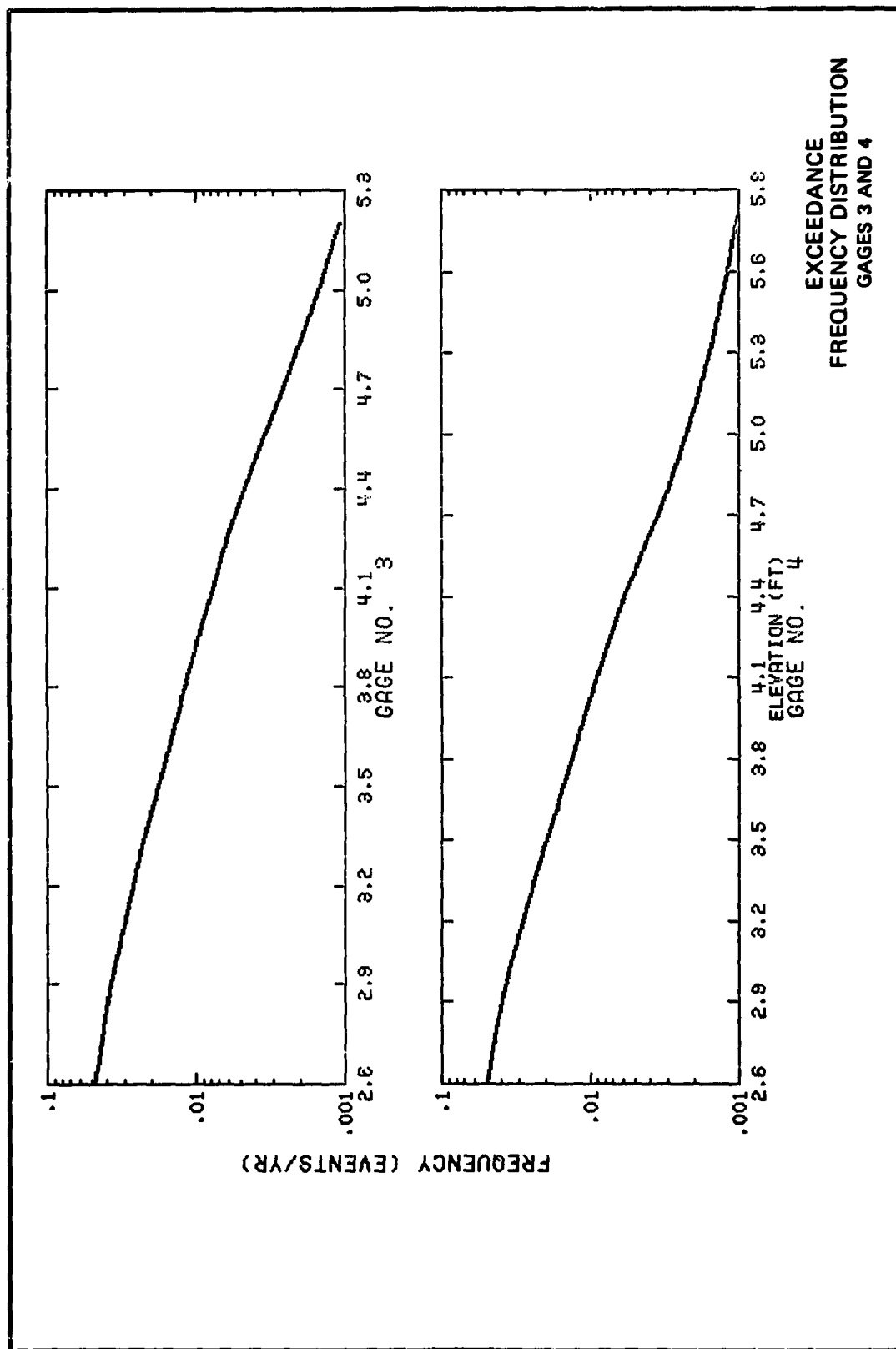


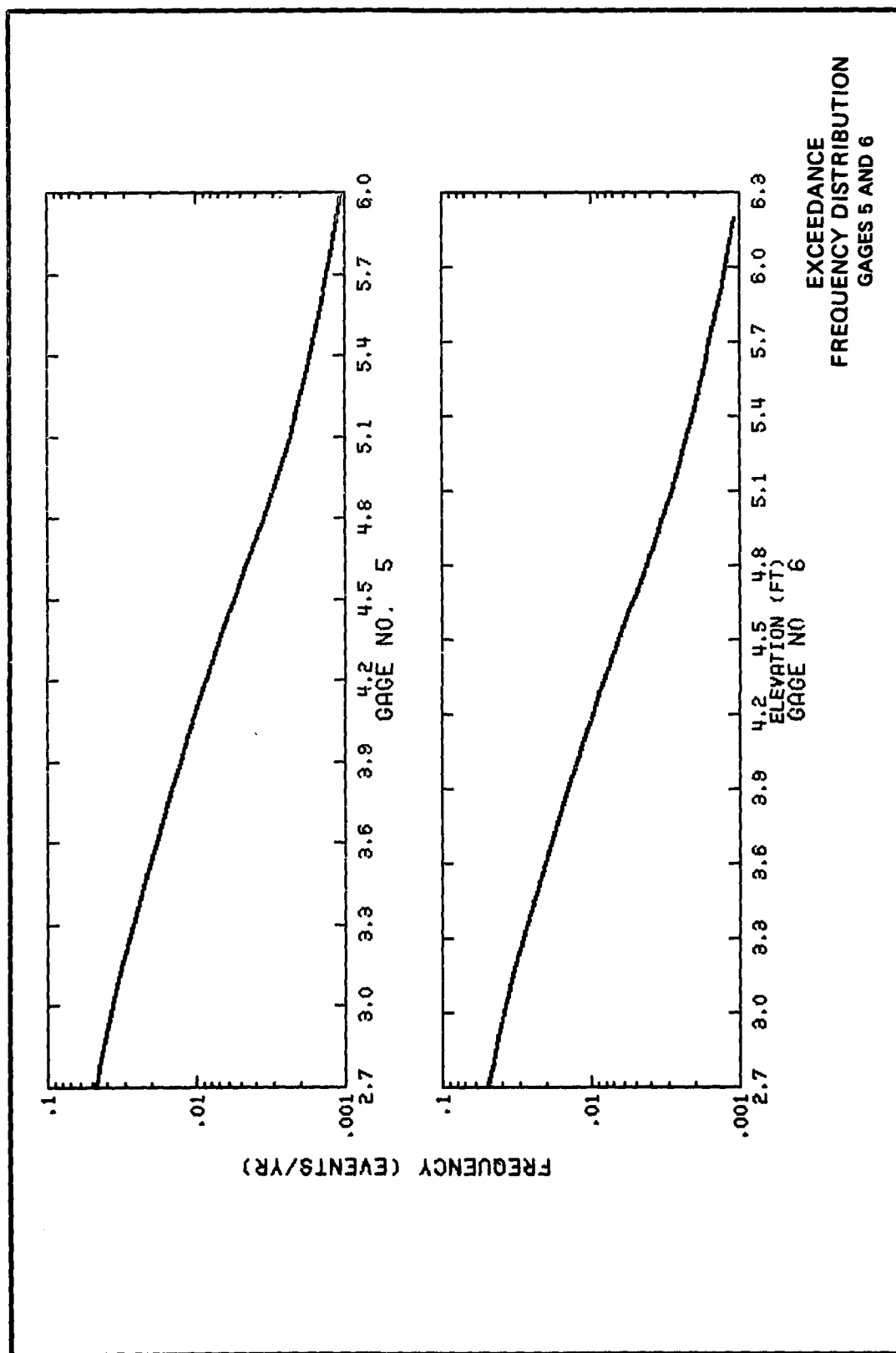
EXCEEDANCE
FREQUENCY DISTRIBUTION
GAGES 1 AND 2

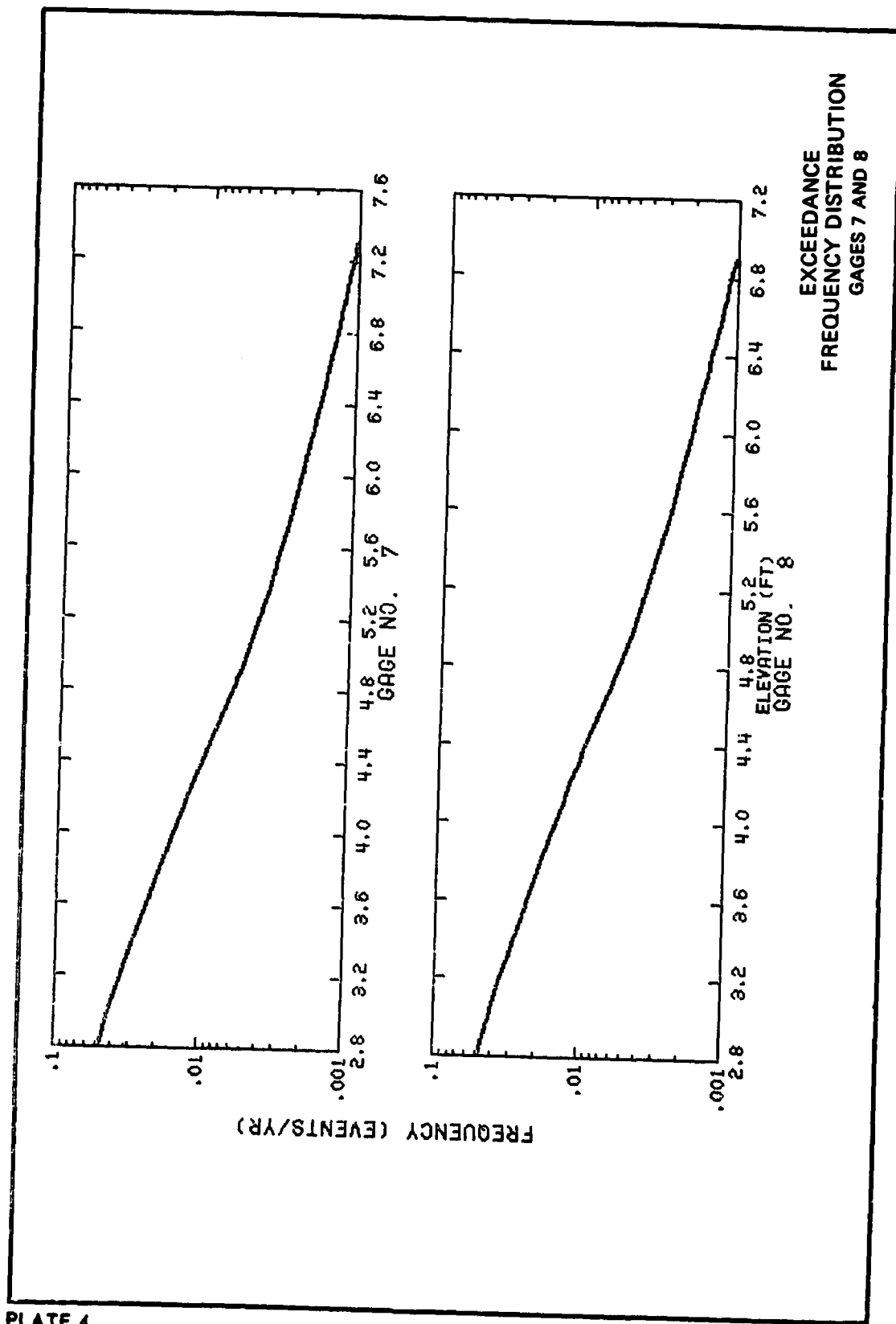


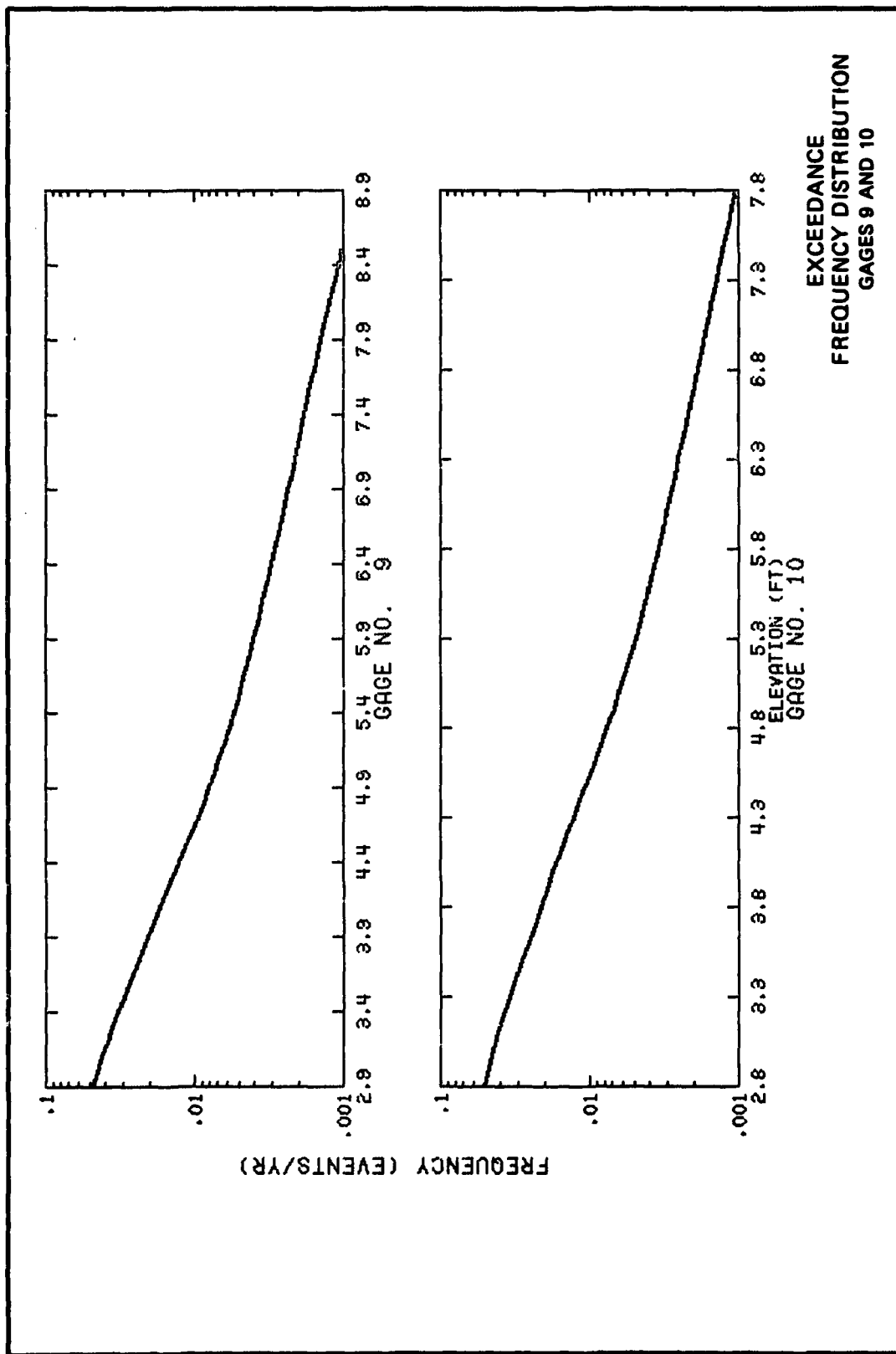


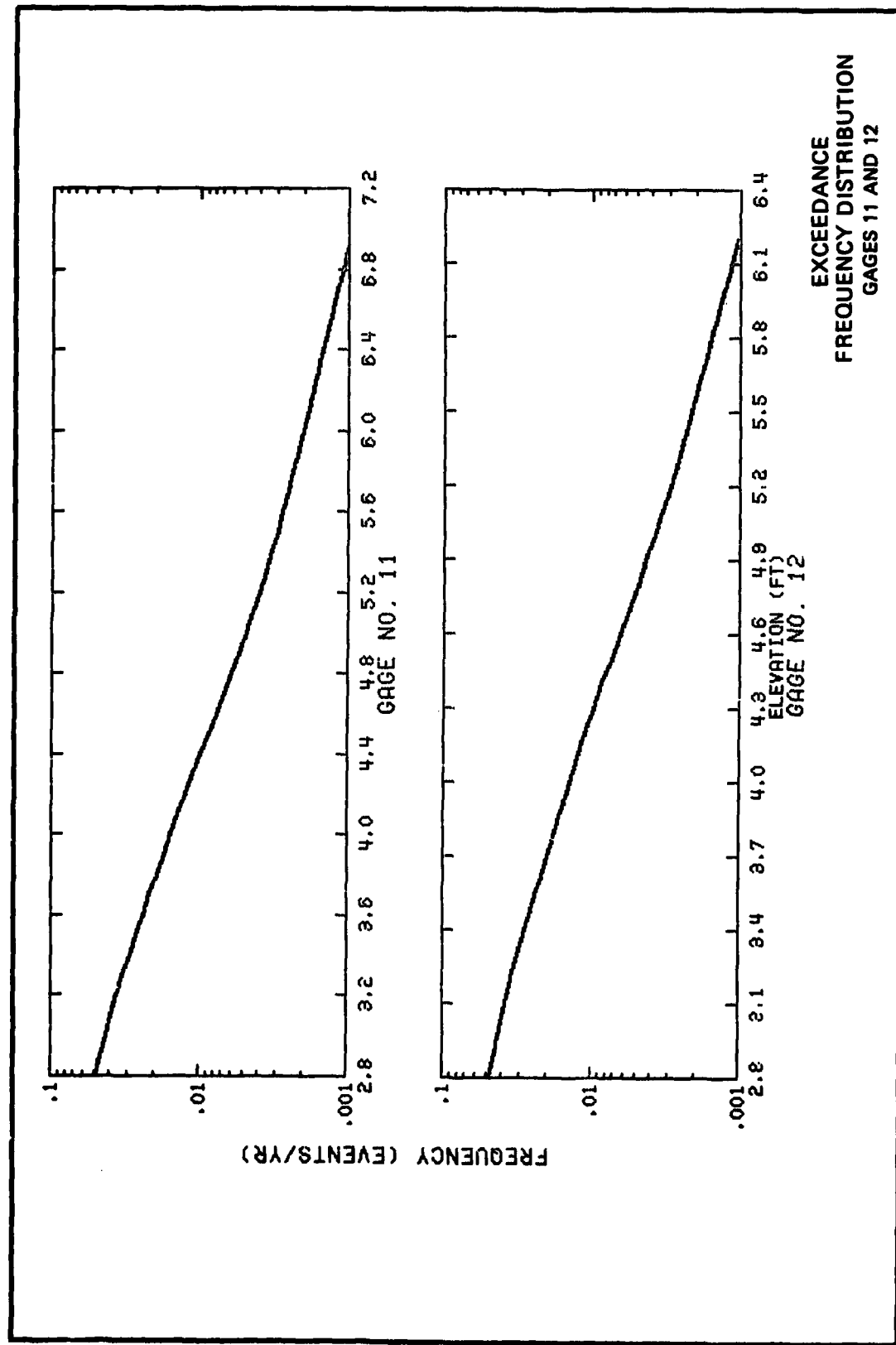
EXCEEDANCE
FREQUENCY DISTRIBUTION
GAGES 1 AND 2

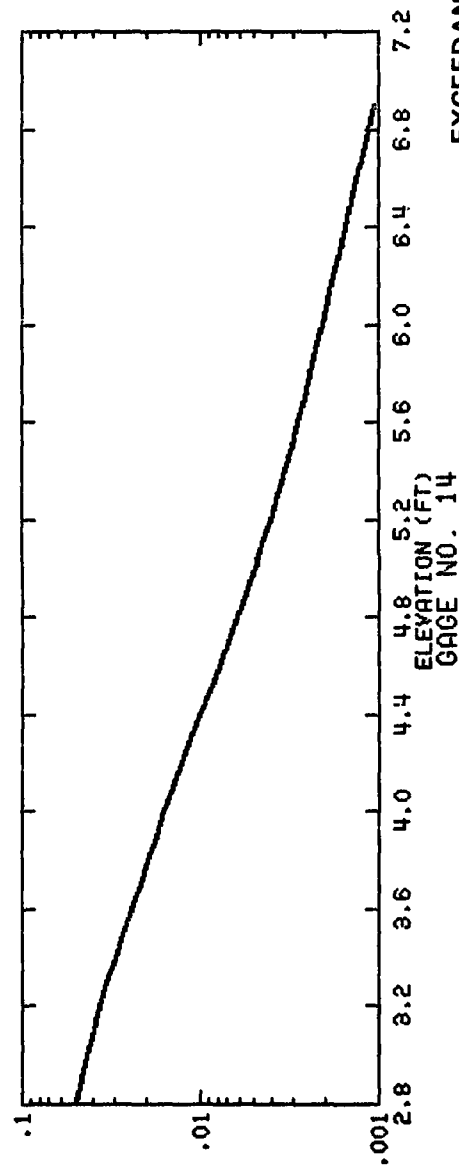
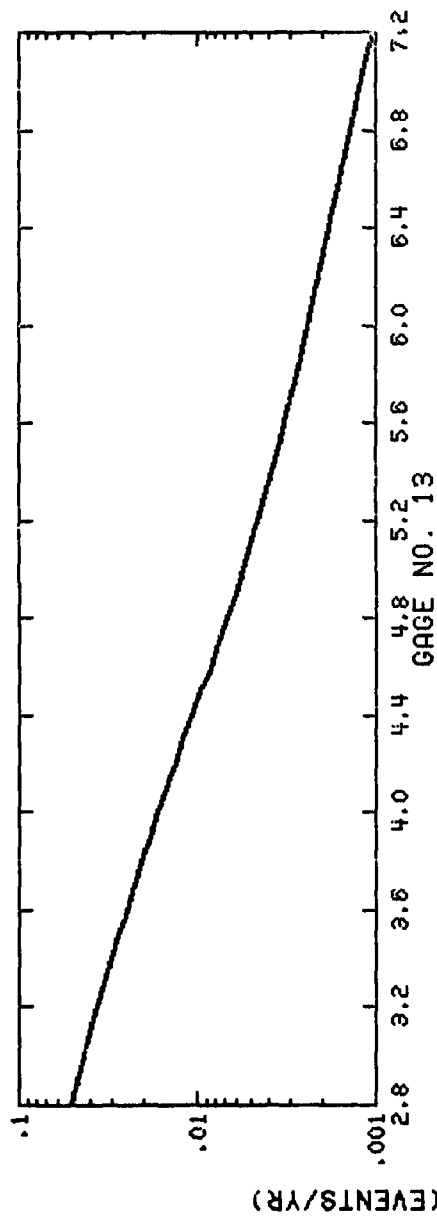




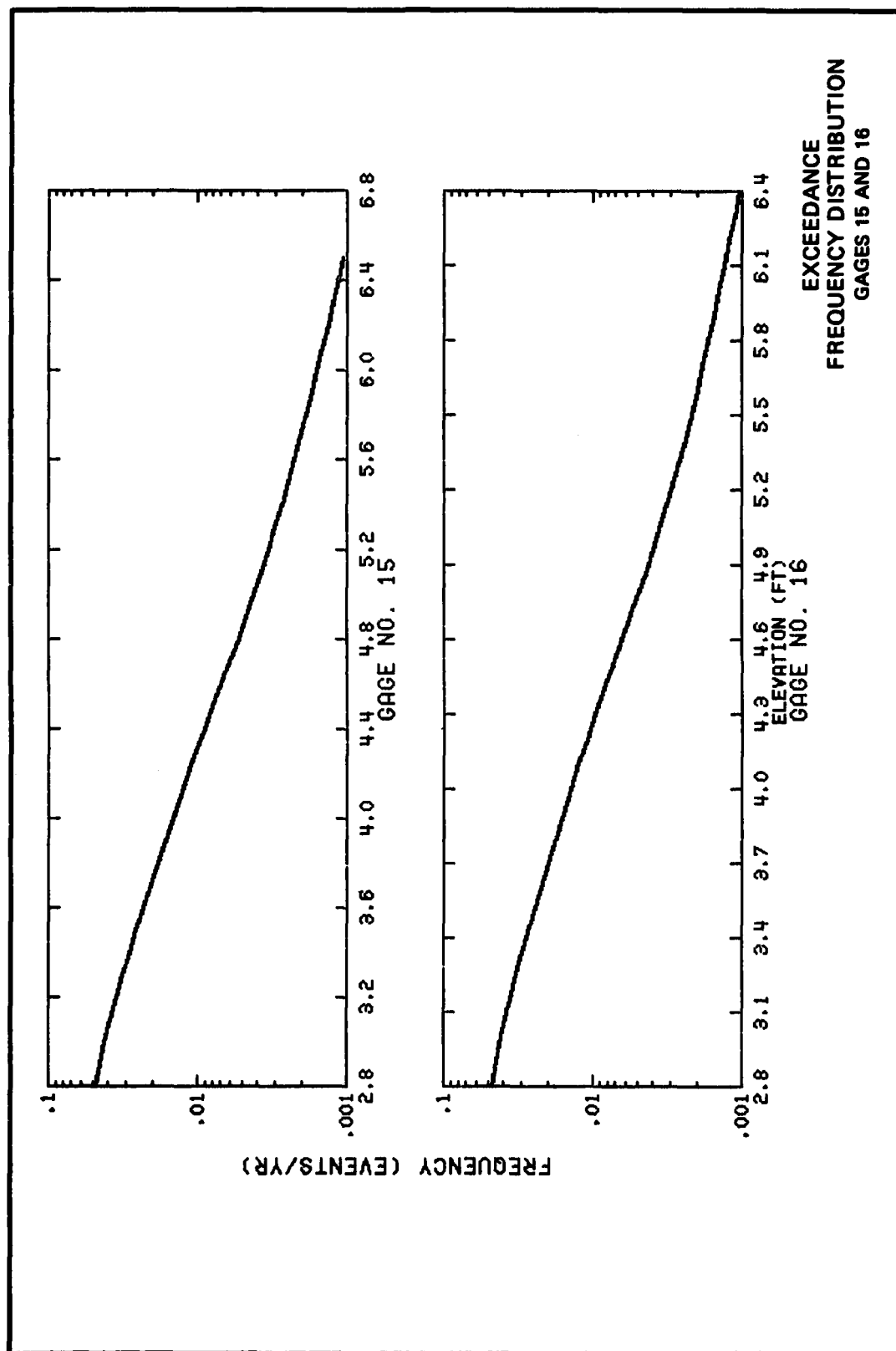


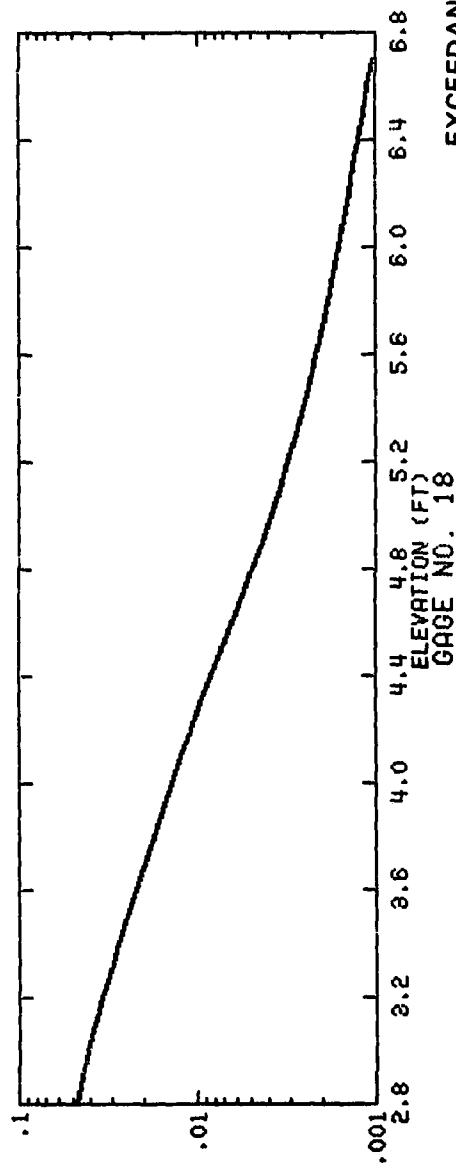
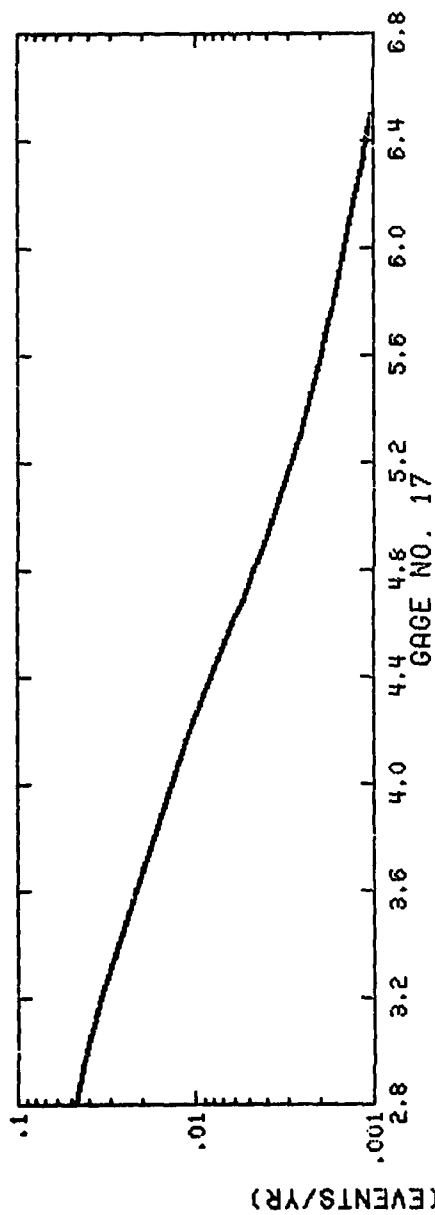






EXCEEDANCE
FREQUENCY DISTRIBUTION
GAGES 13 AND 14





EXCEEDANCE
FREQUENCY DISTRIBUTION
GAGES 17 AND 18

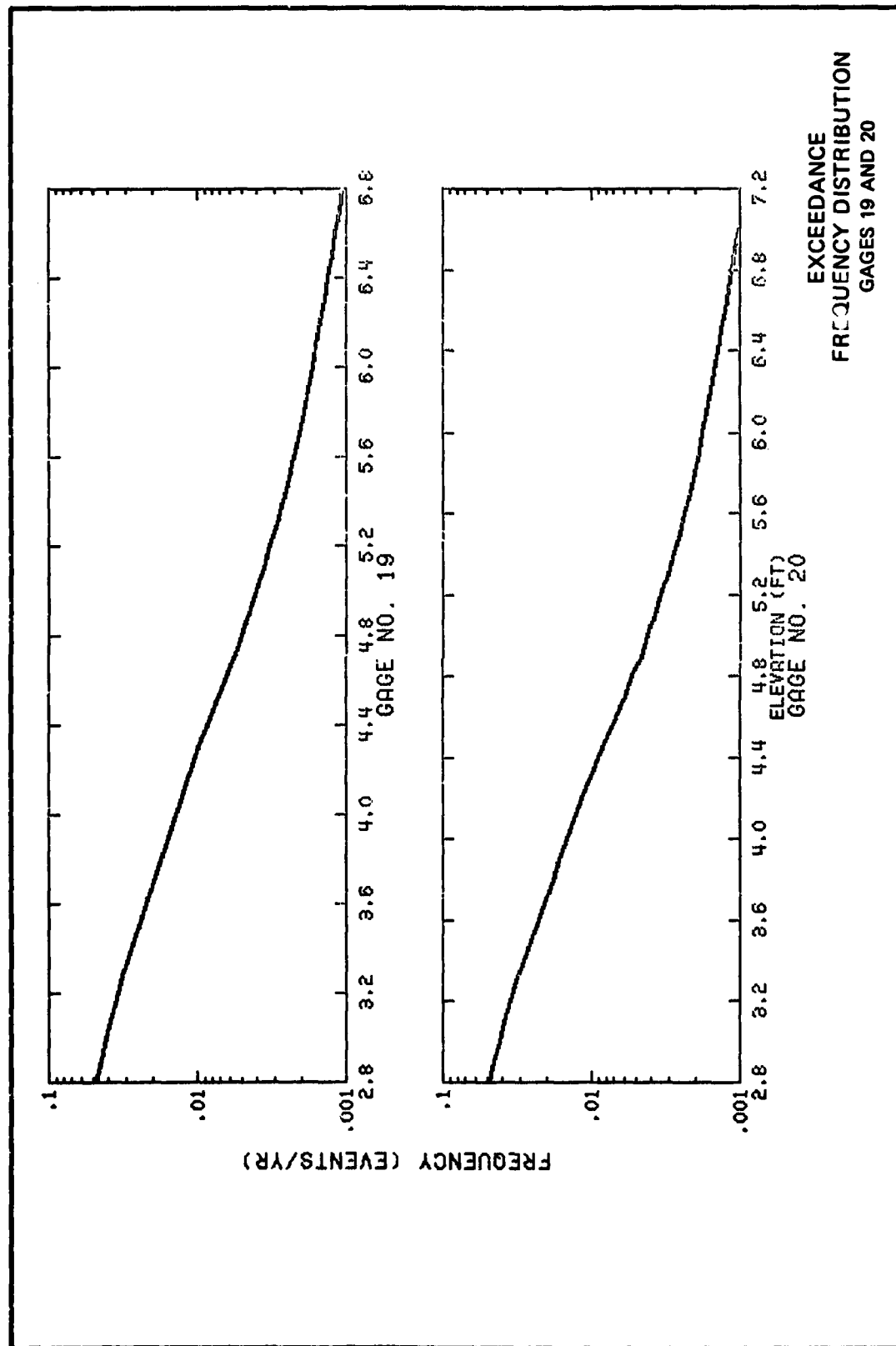
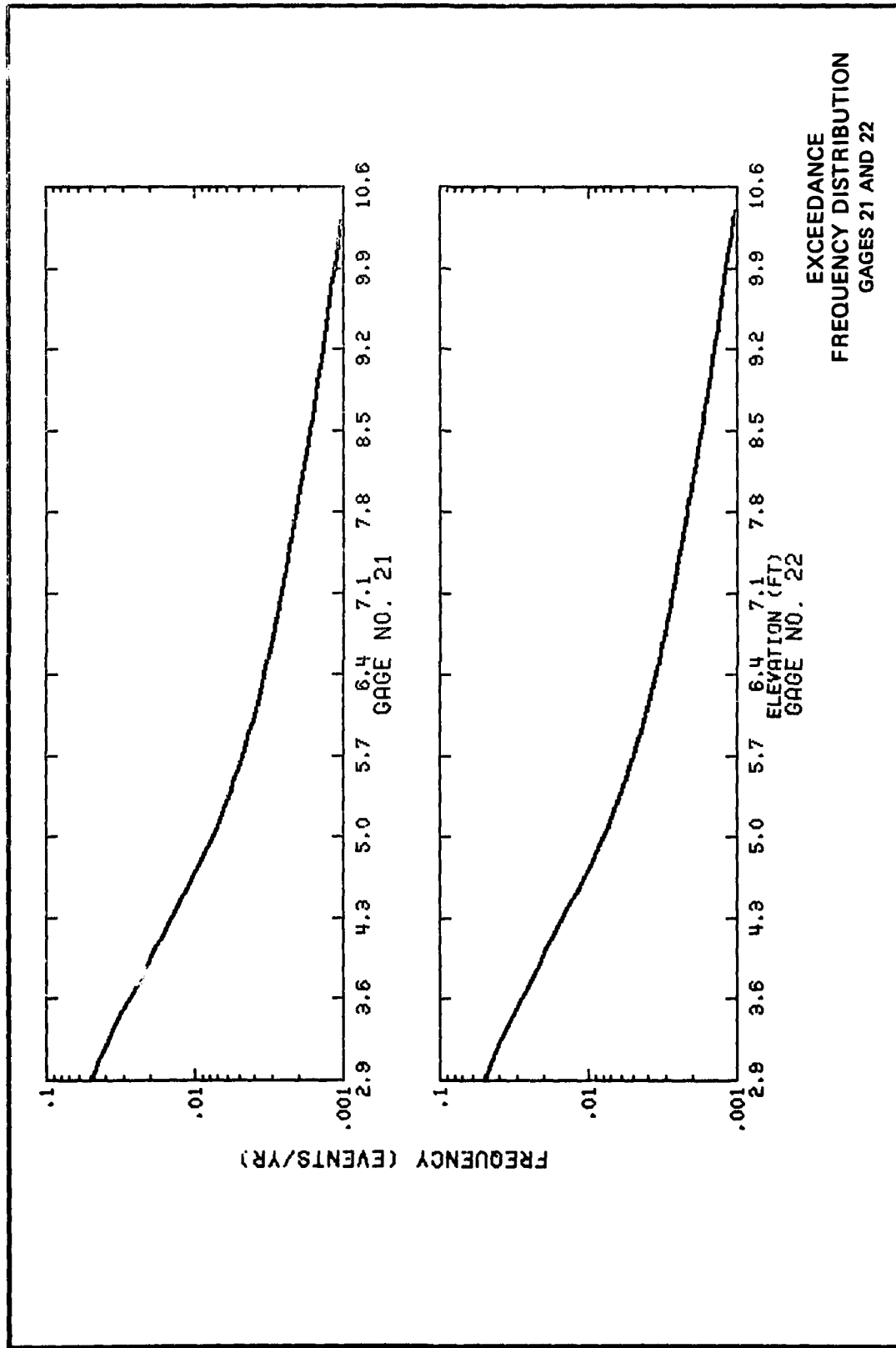
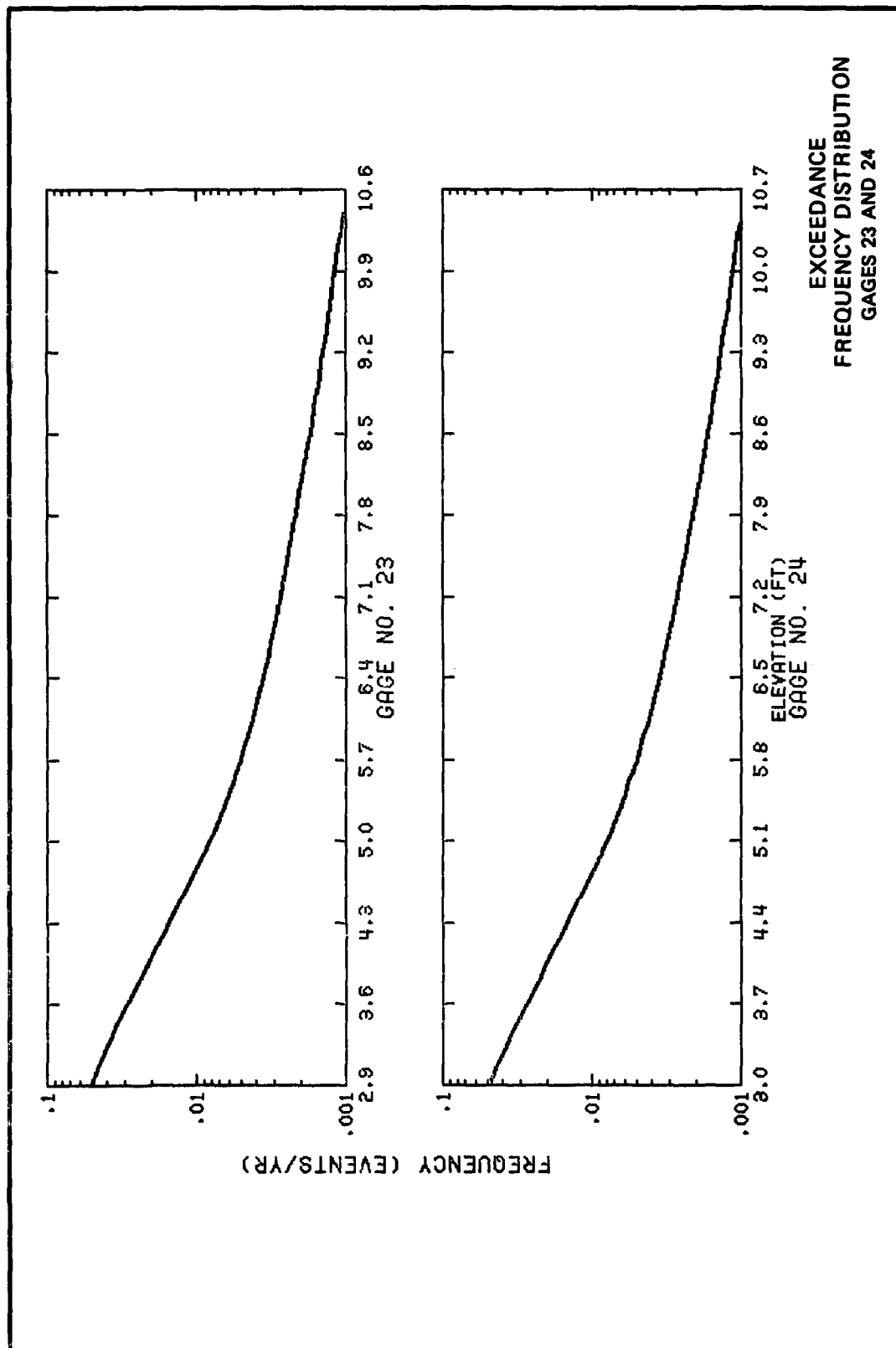
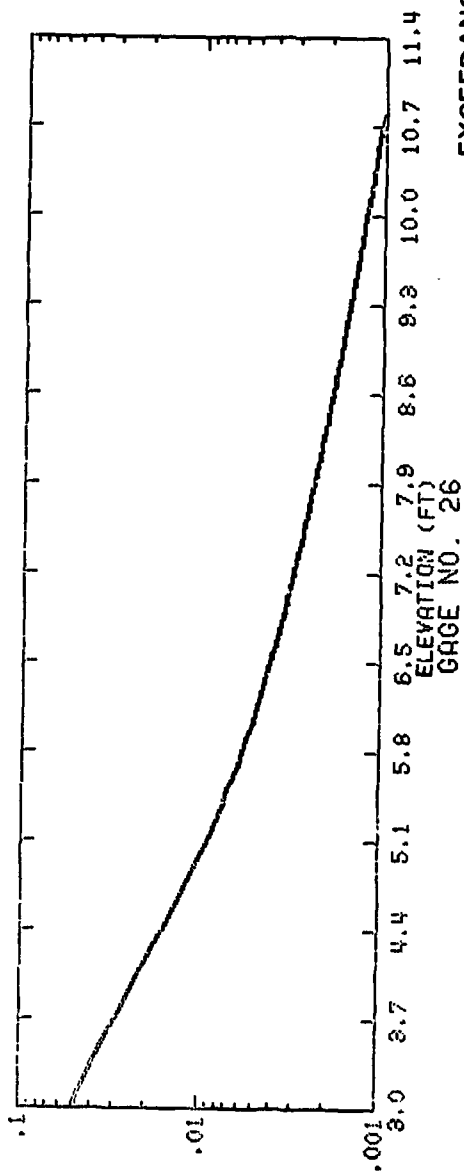
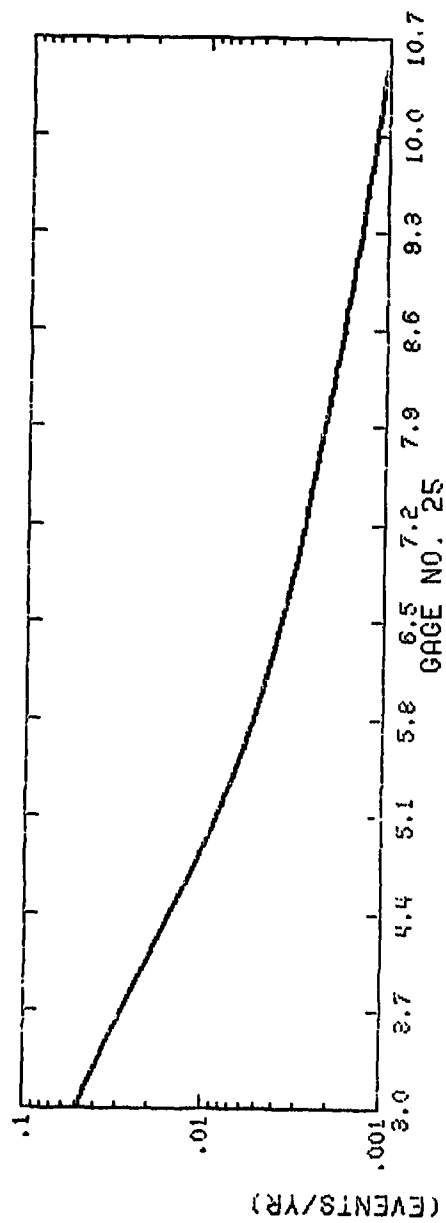


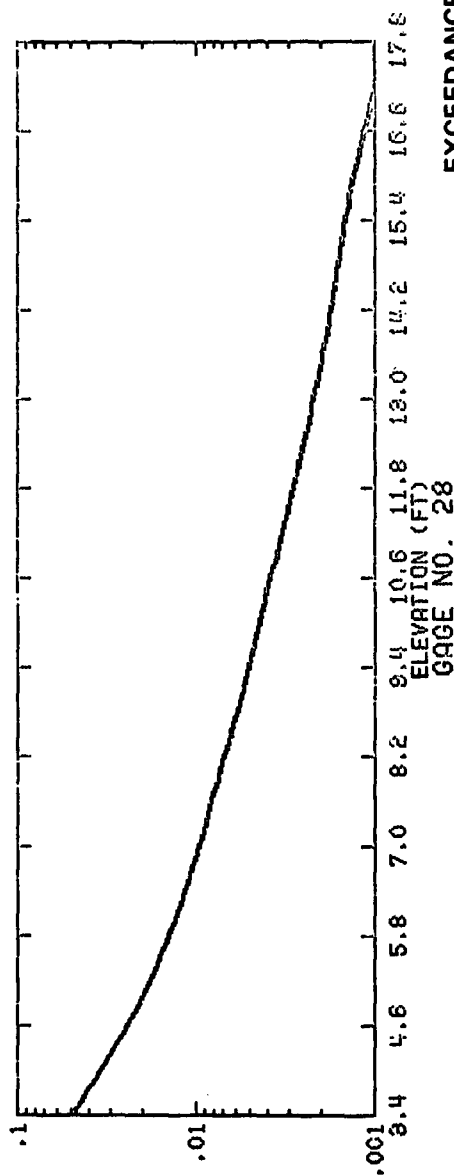
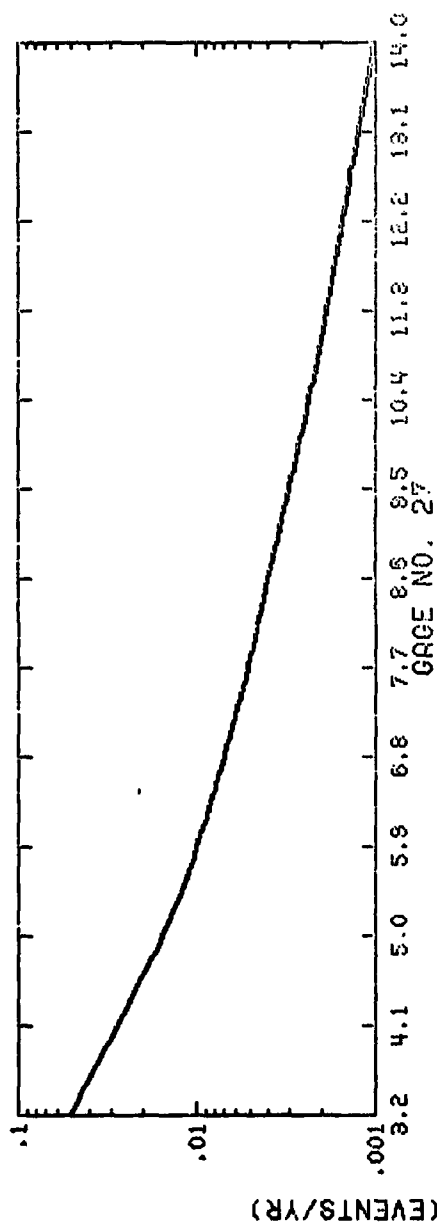
PLATE 10



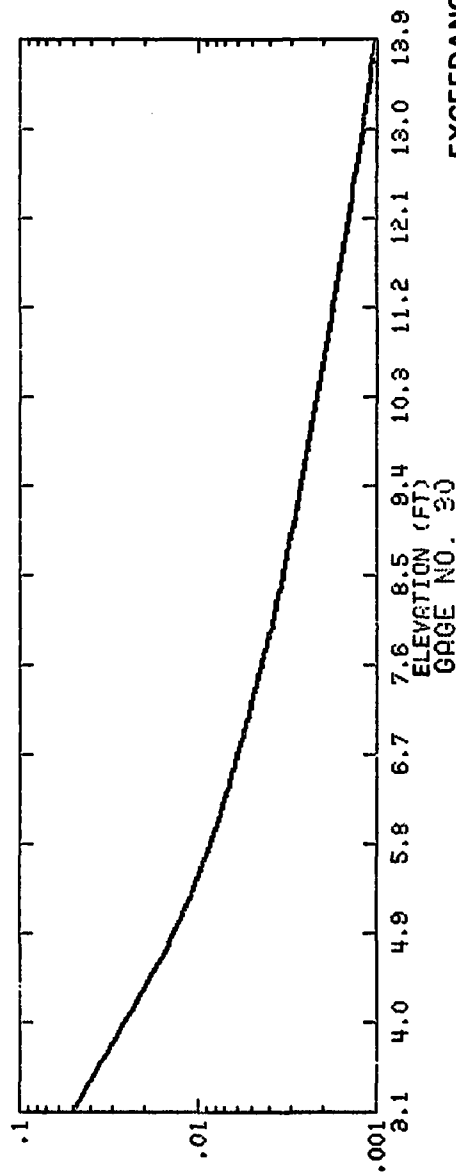
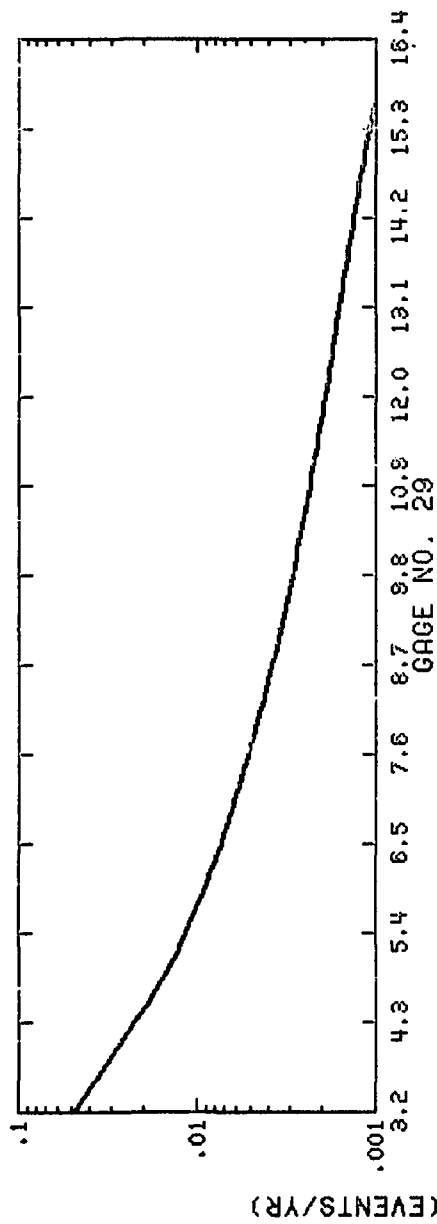




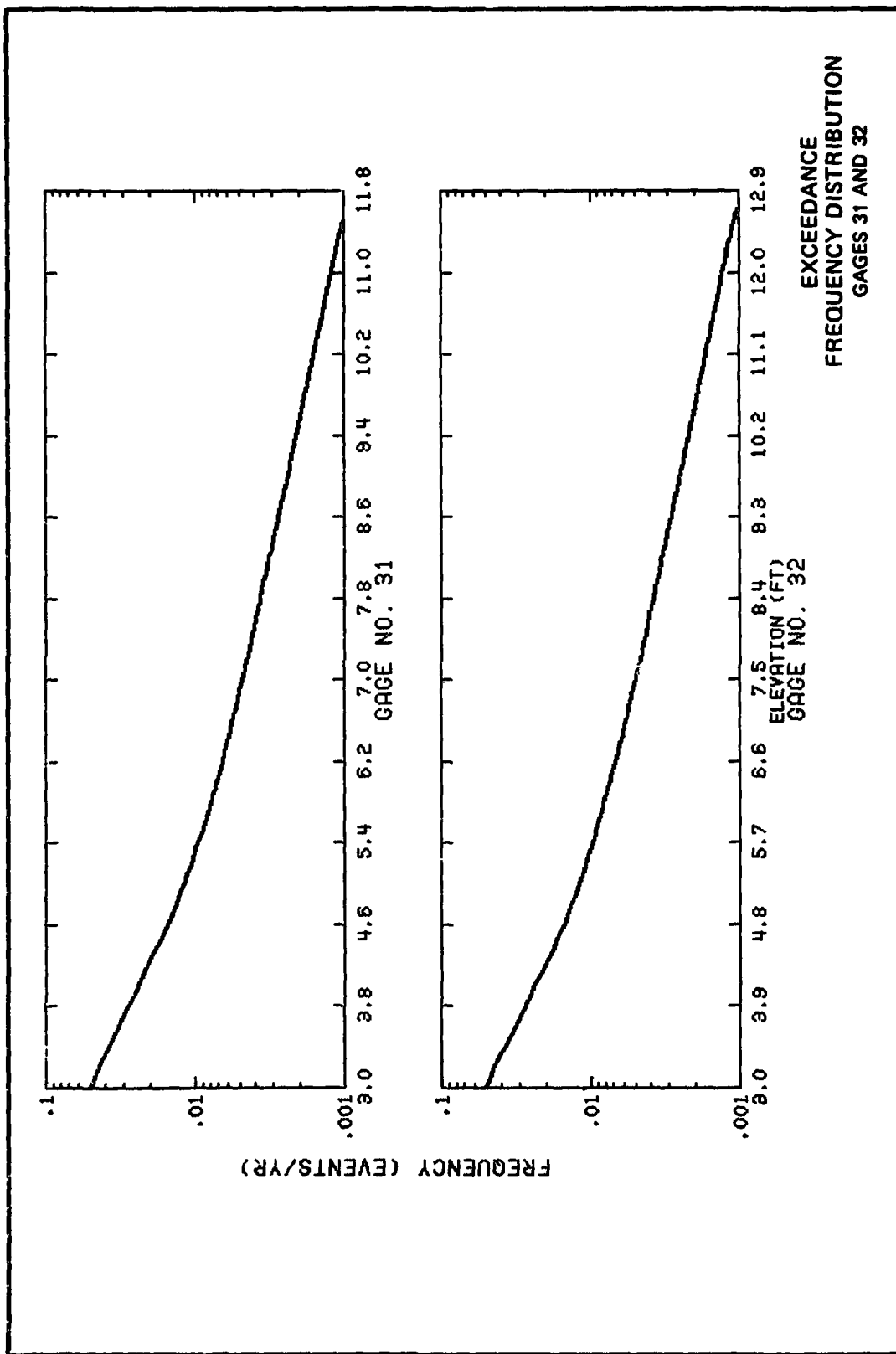
EXCEEDANCE
FREQUENCY DISTRIBUTION
GAGES 25 AND 26

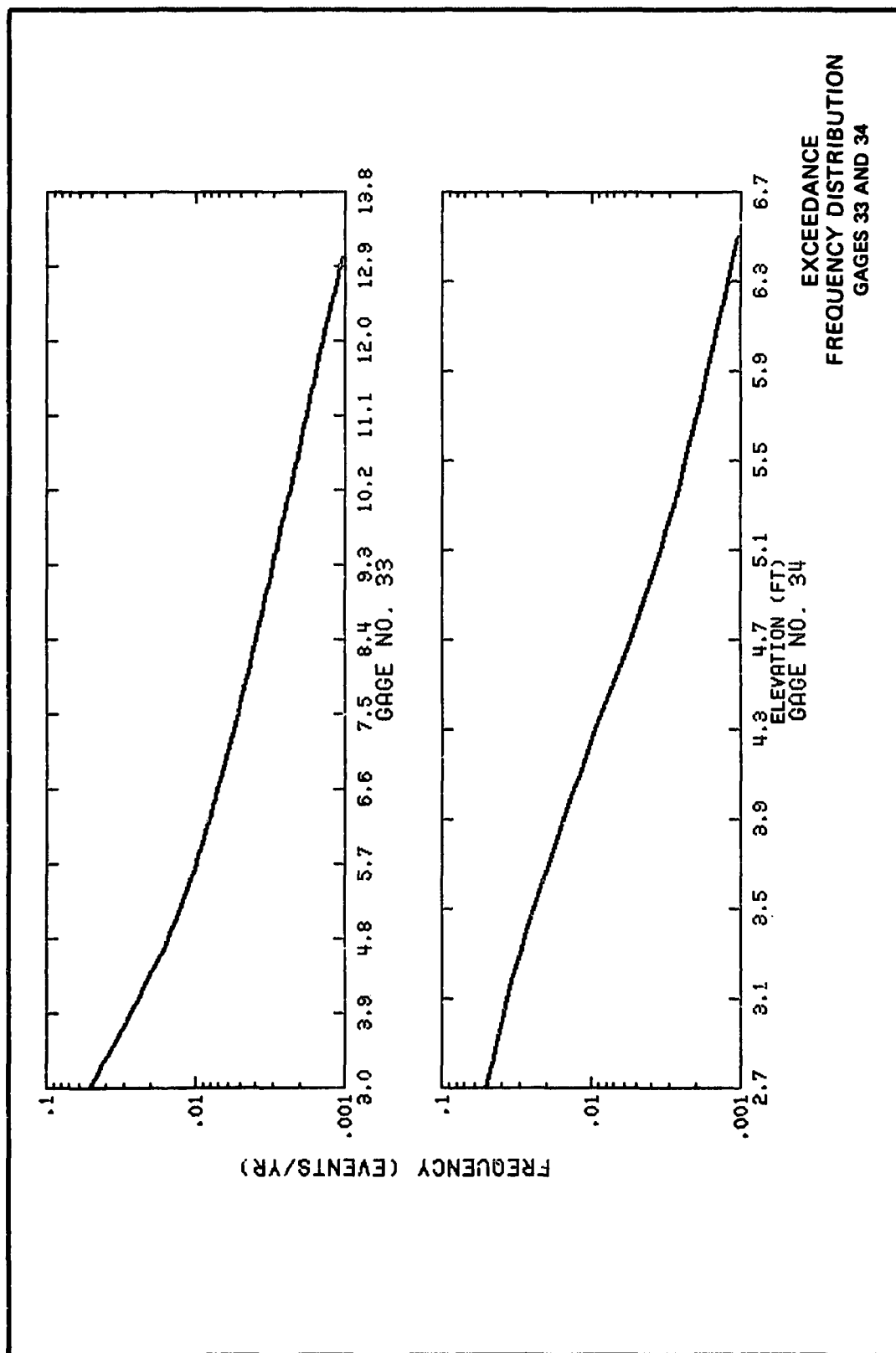


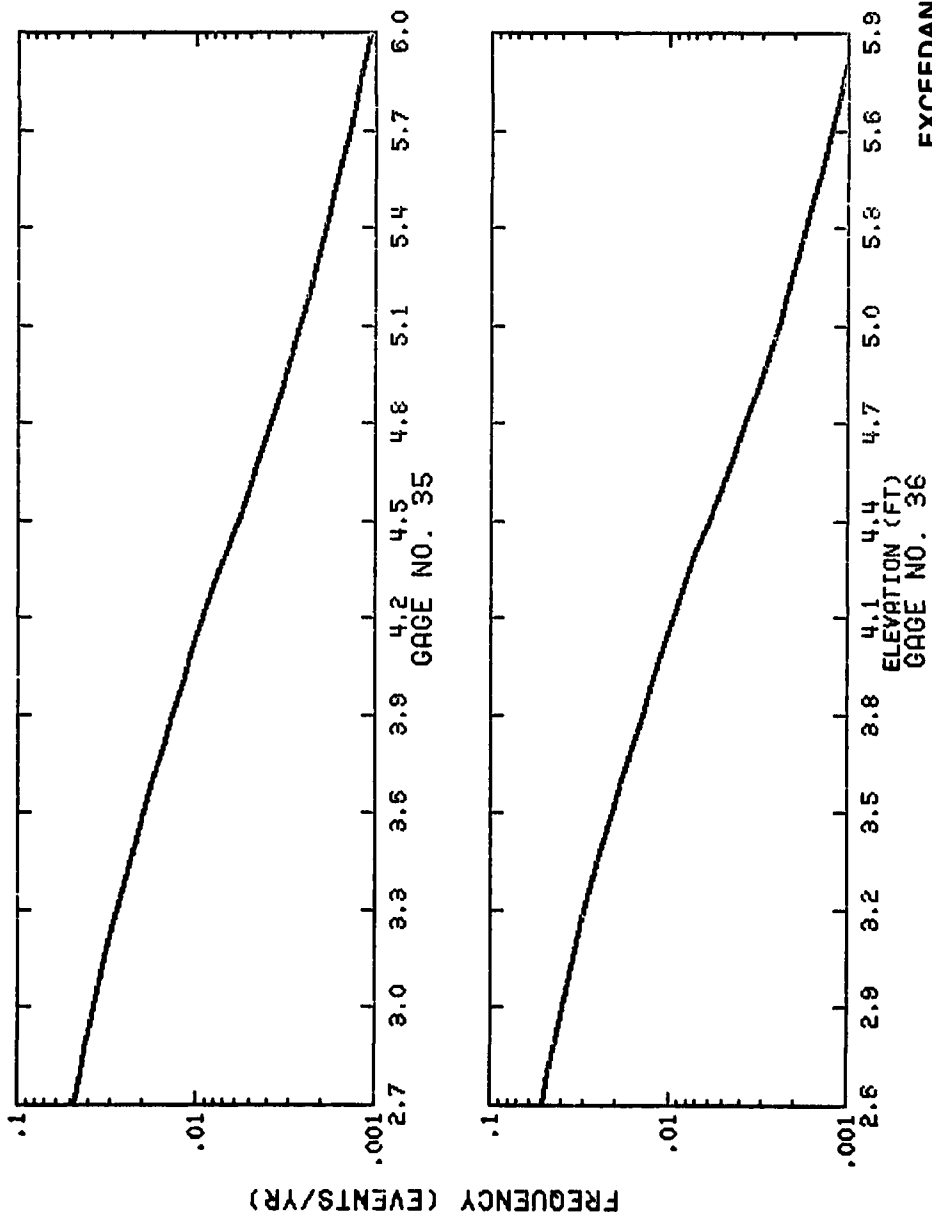
EXCEEDANCE
FREQUENCY DISTRIBUTION
GAGES 27 AND 28



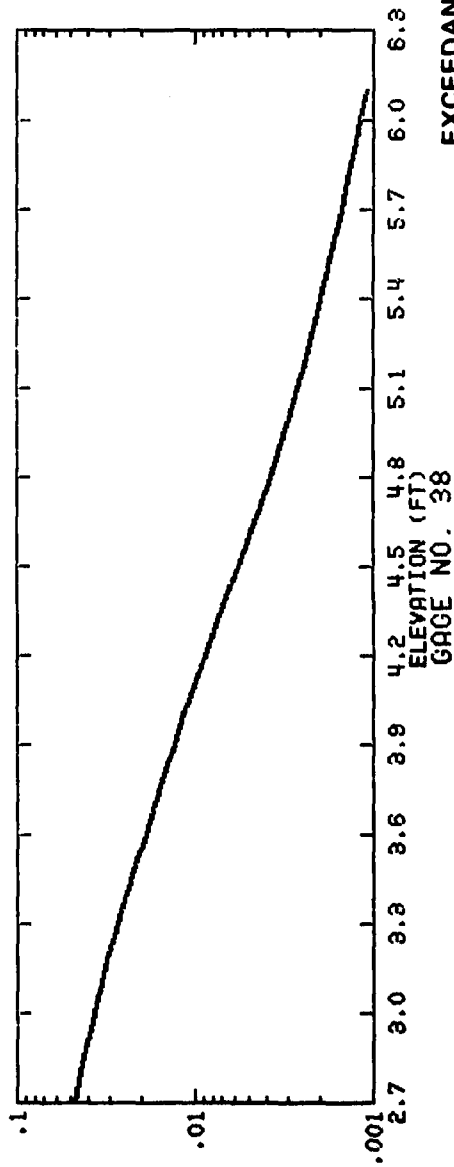
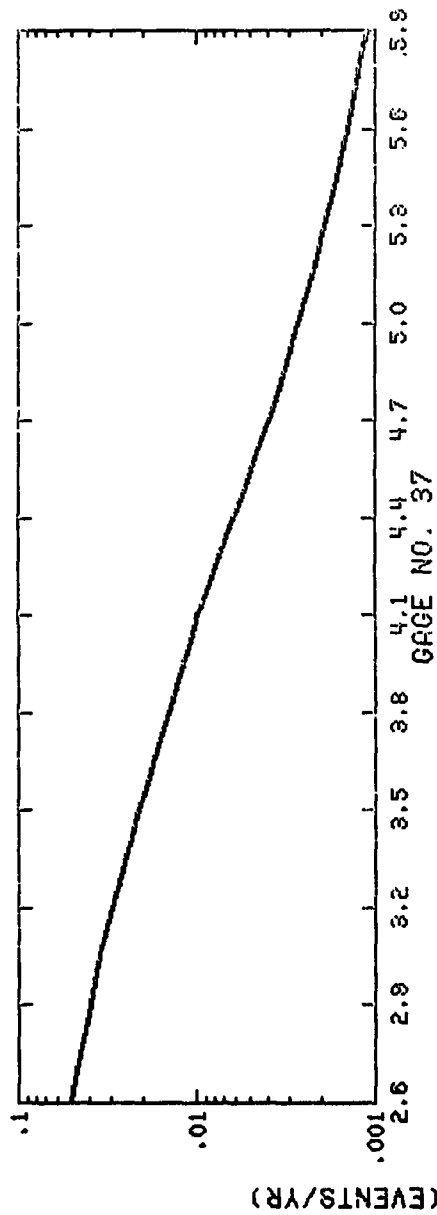
EXCEEDANCE
FREQUENCY DISTRIBUTION
GAGES 29 AND 30



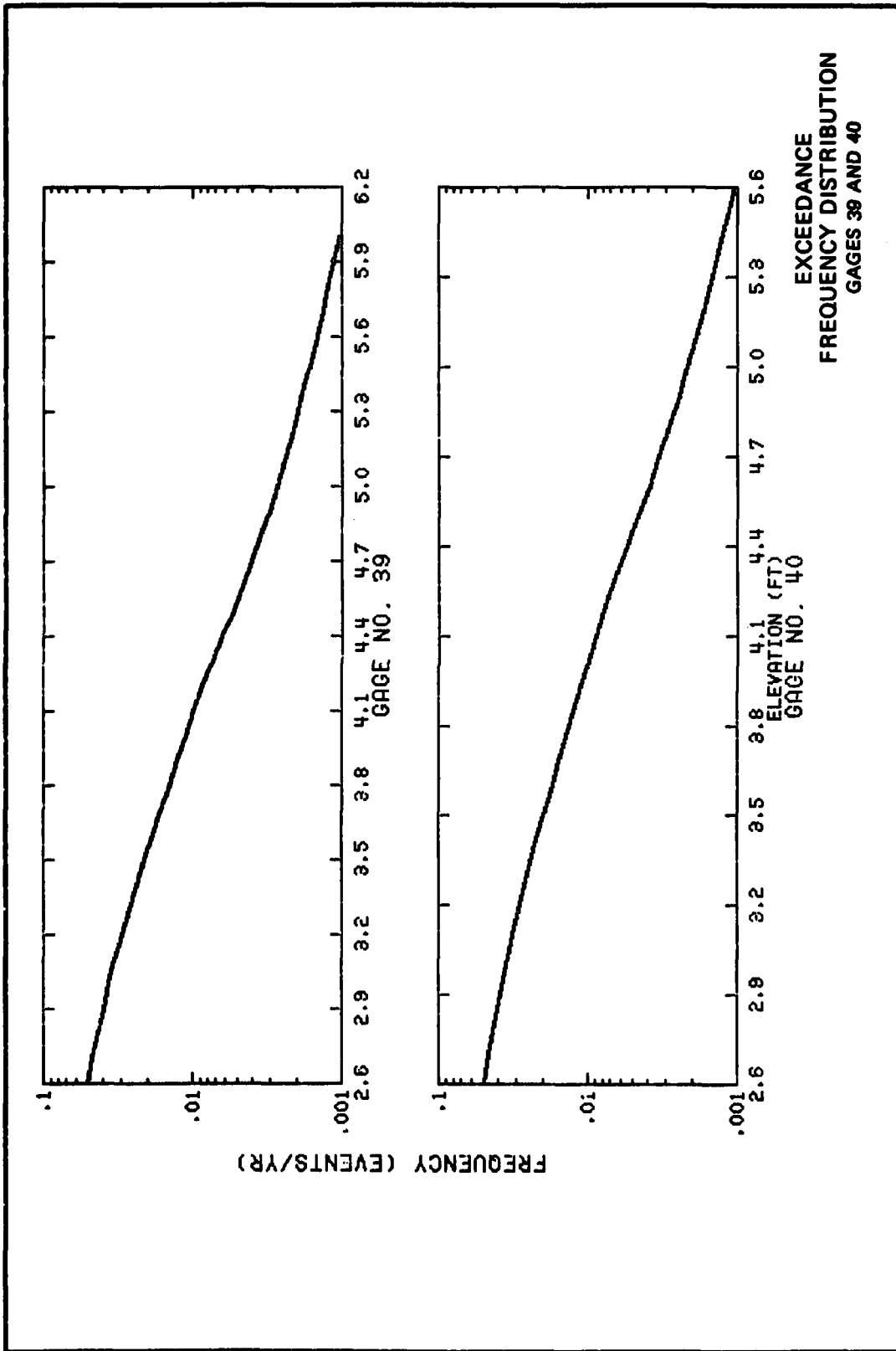


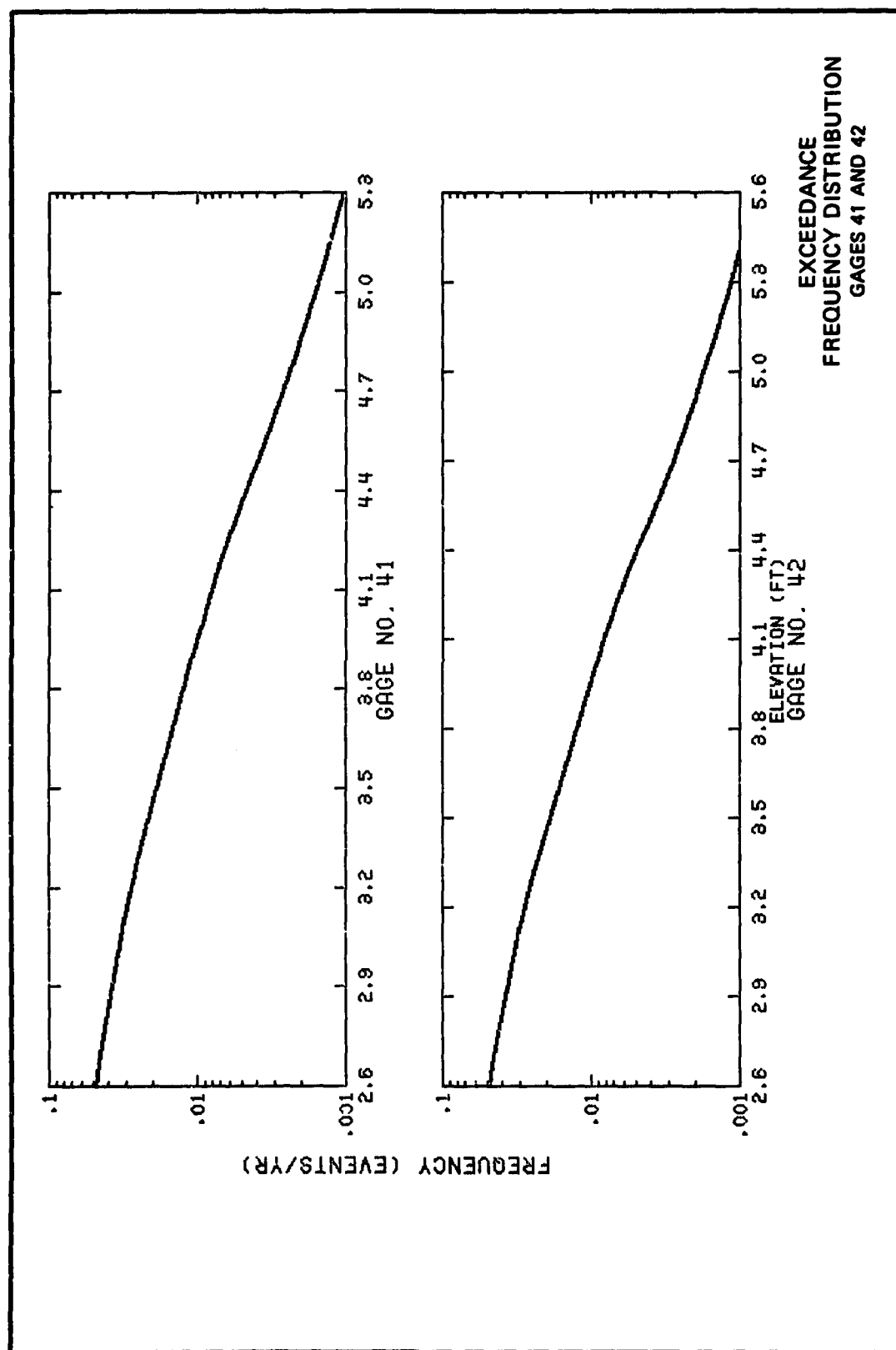


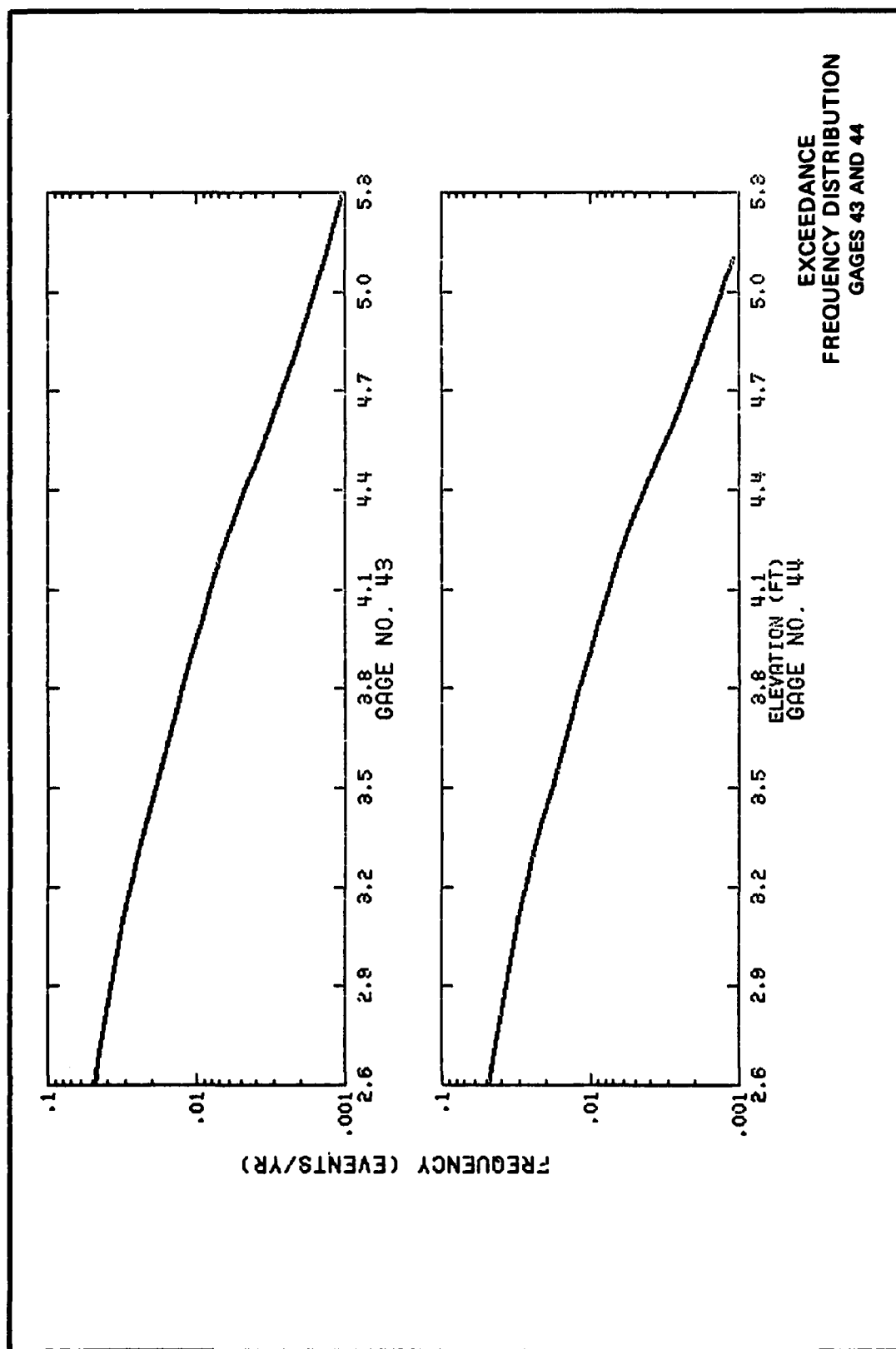
EXCEEDANCE
FREQUENCY DISTRIBUTION
GAGES 35 AND 36

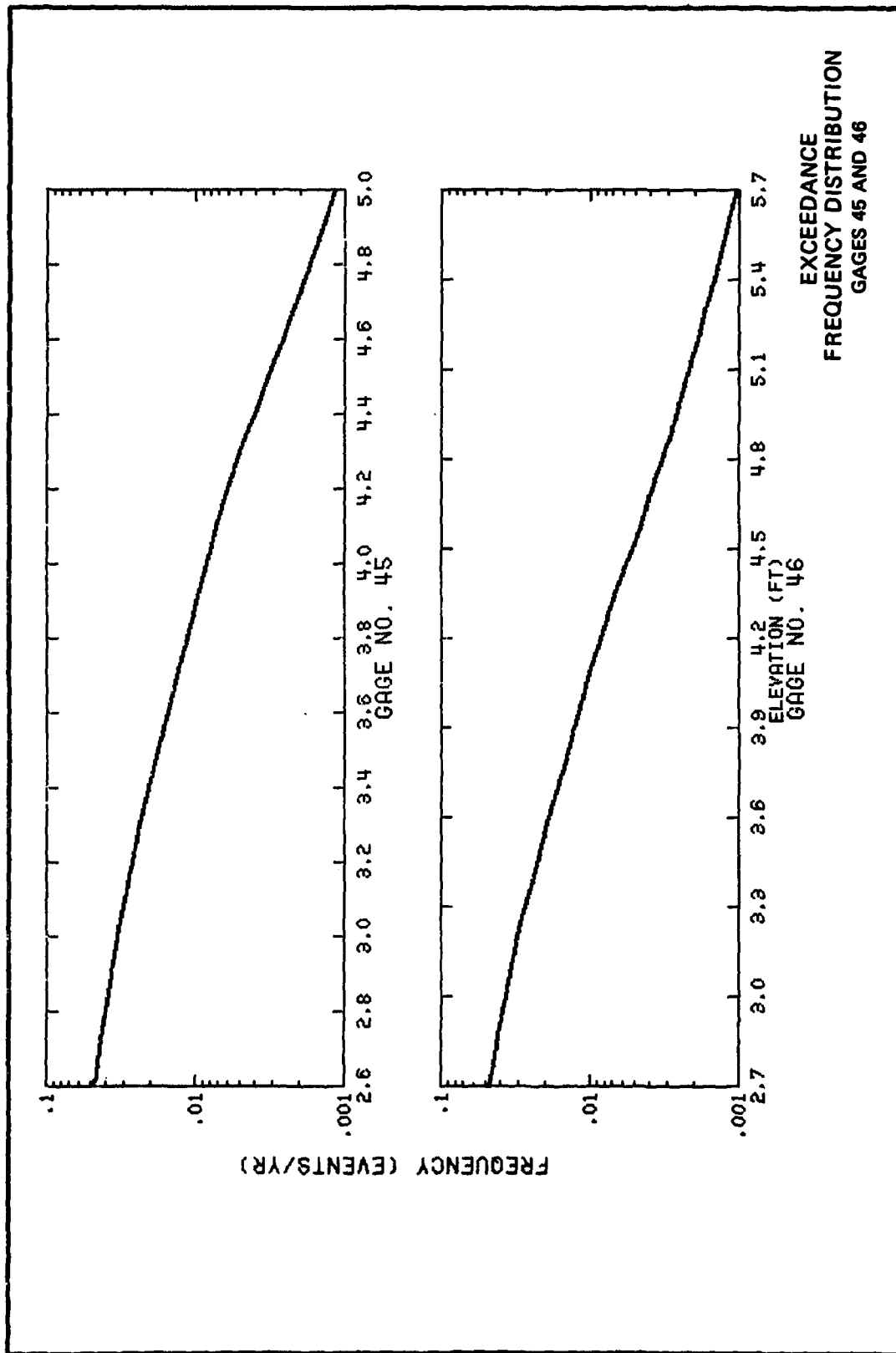


EXCEEDANCE
FREQUENCY DISTRIBUTION
GAGES 37 AND 38









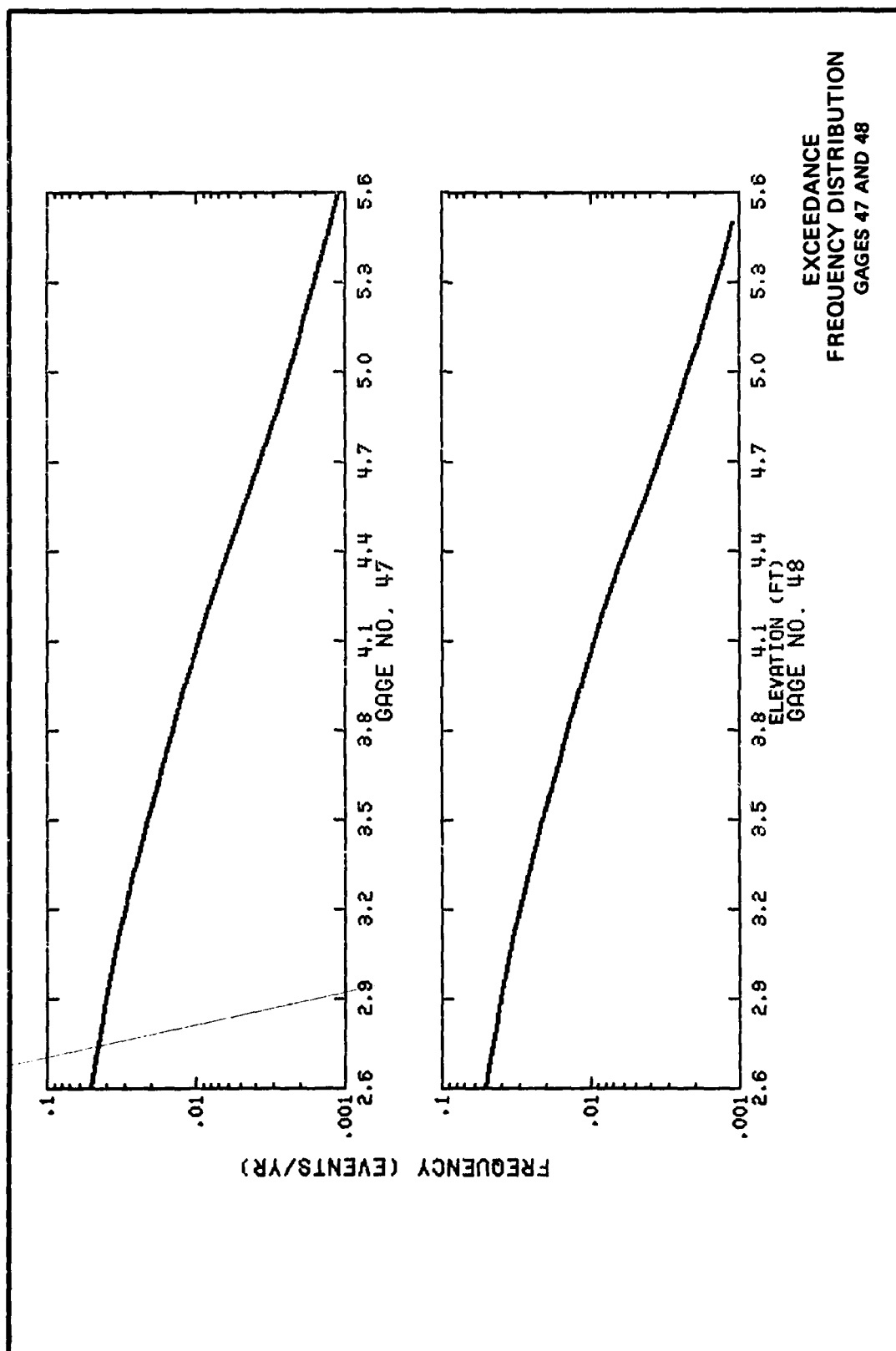
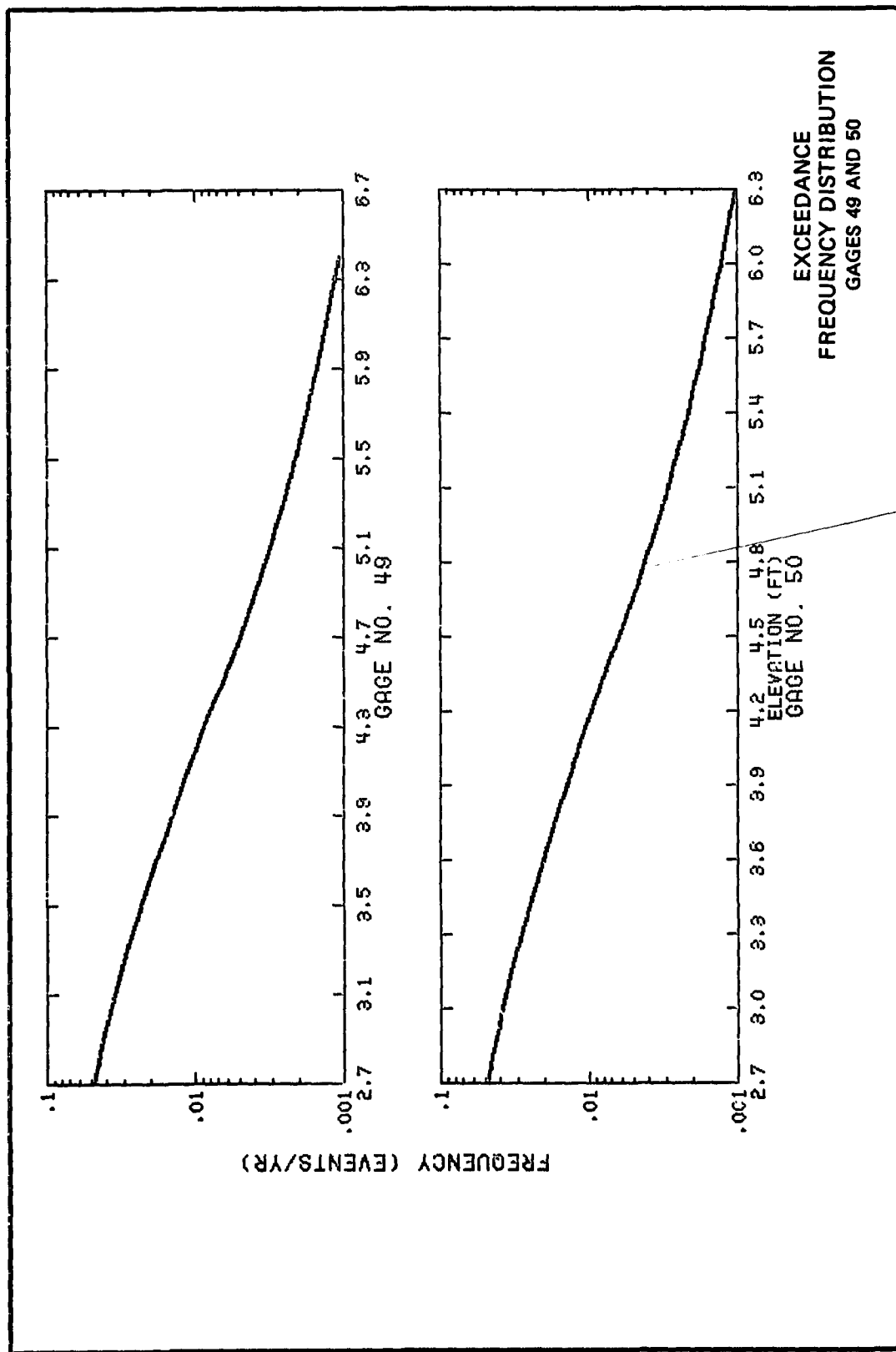
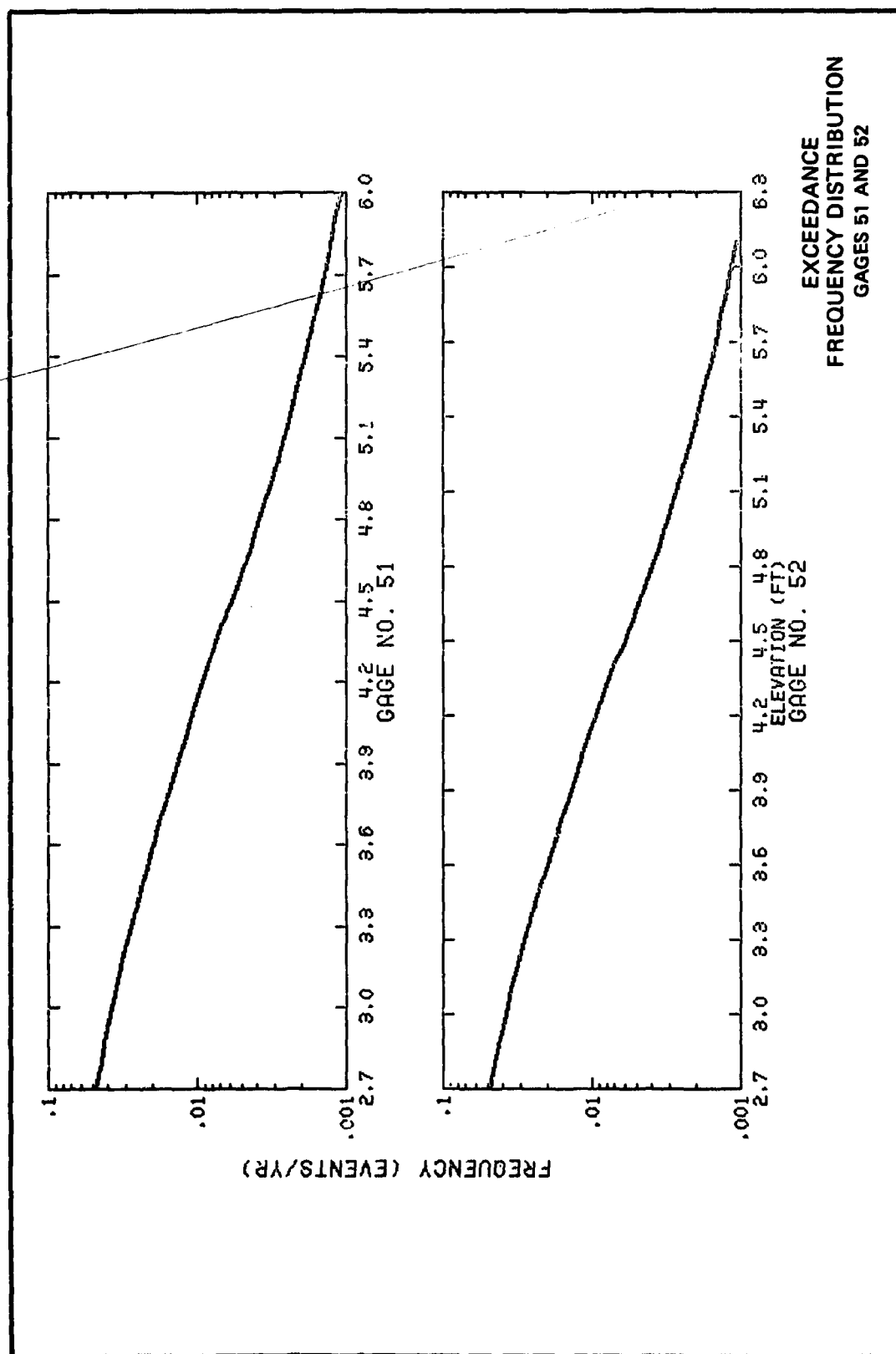
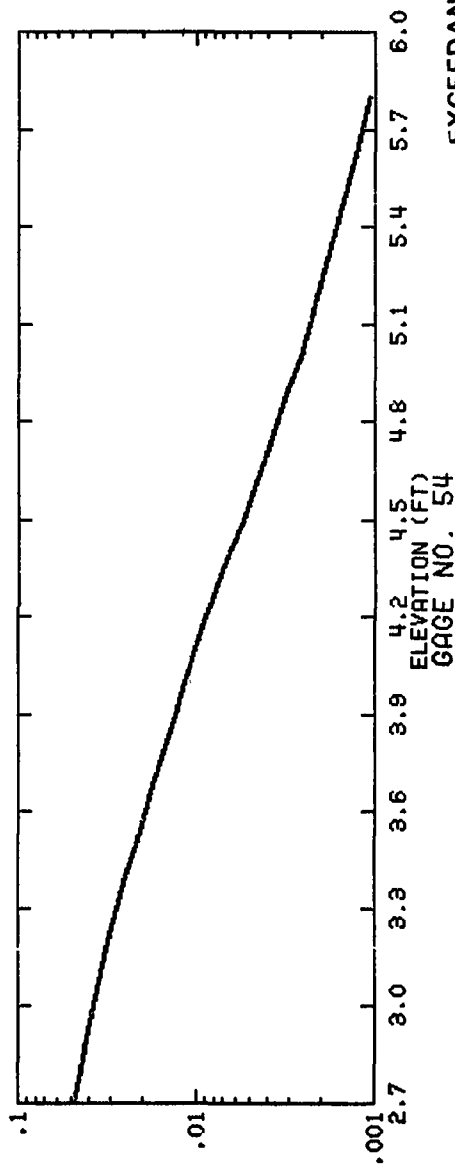
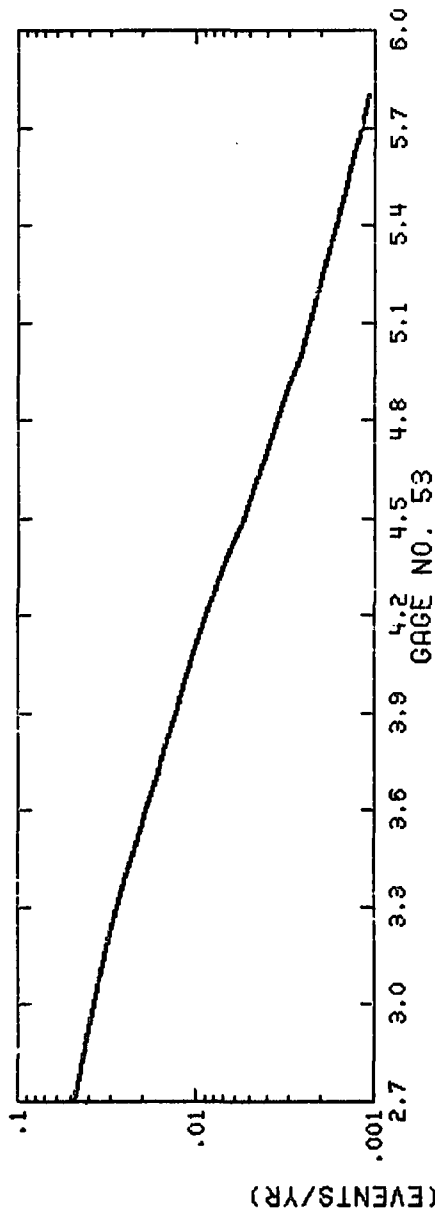


PLATE 24







EXCEEDANCE
FREQUENCY DISTRIBUTION
GAGES 53 AND 54

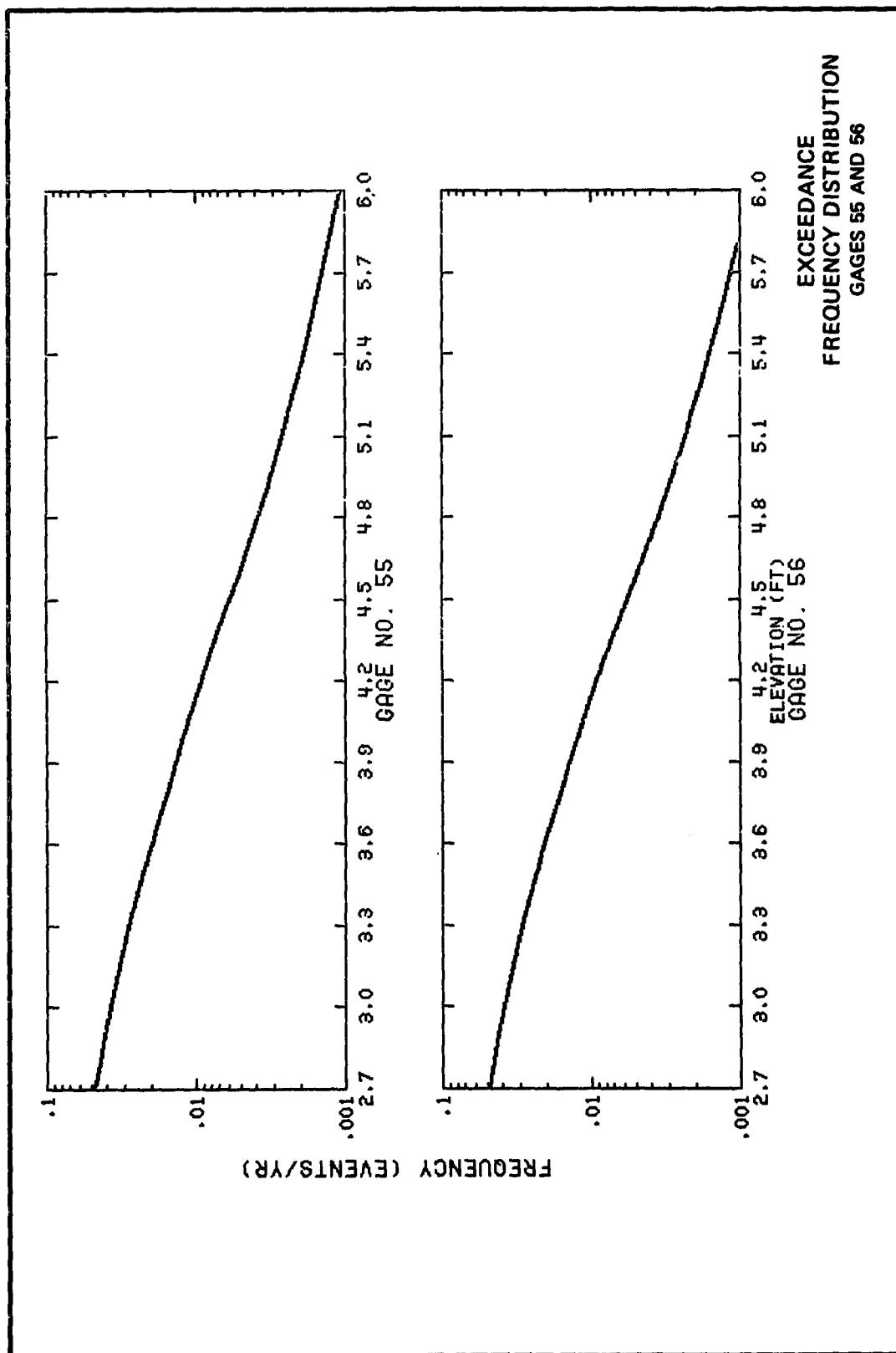
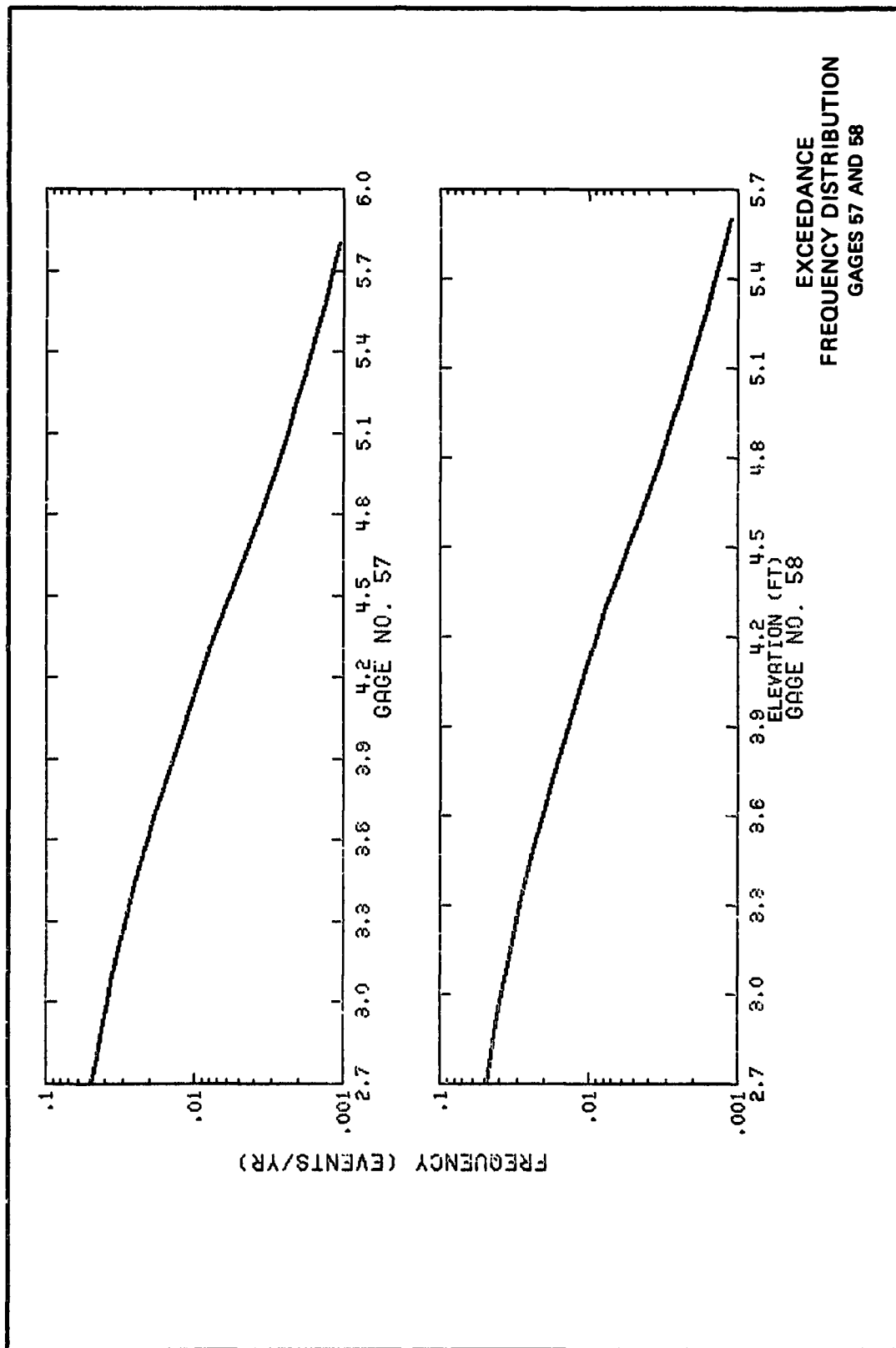
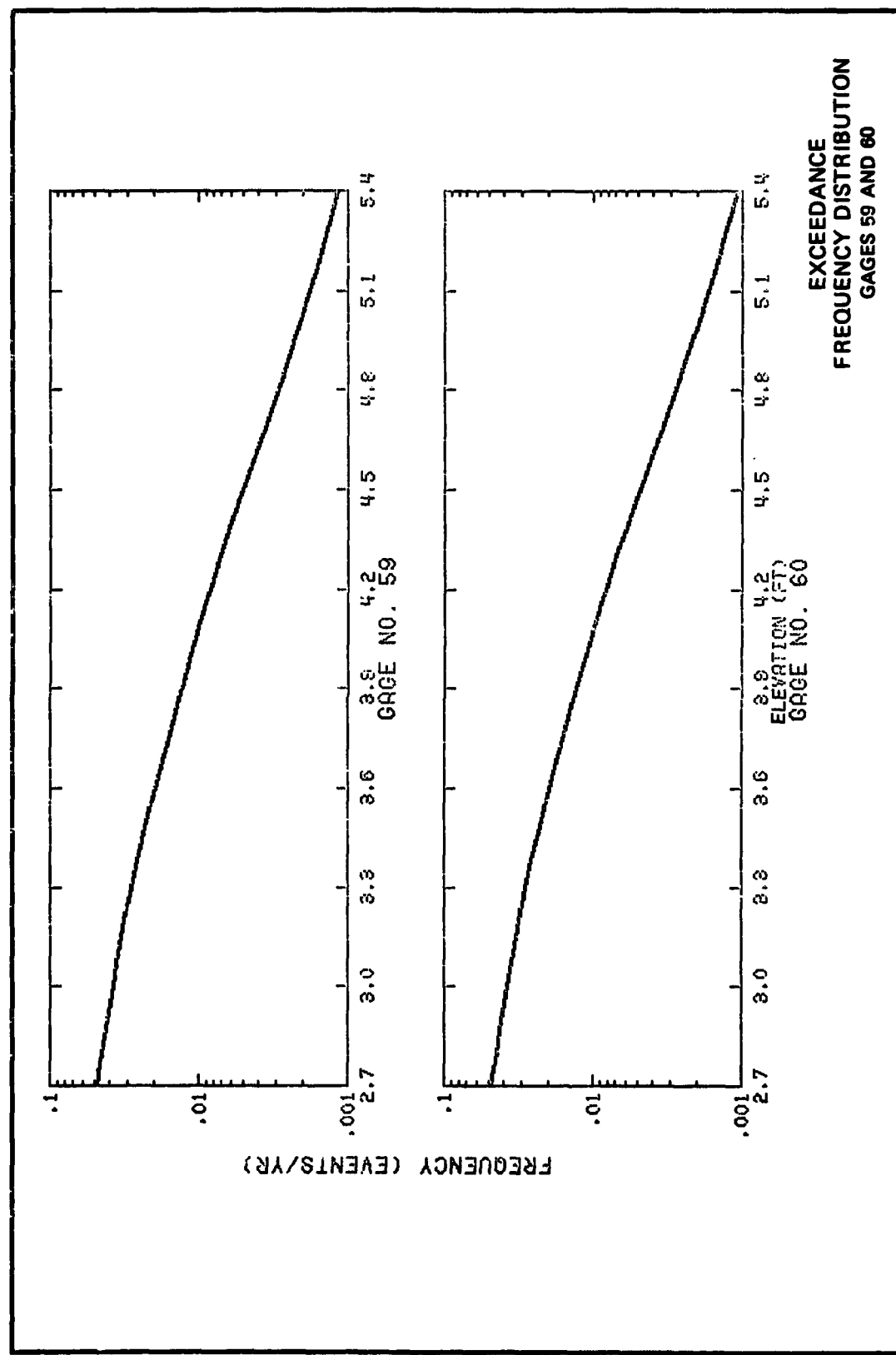
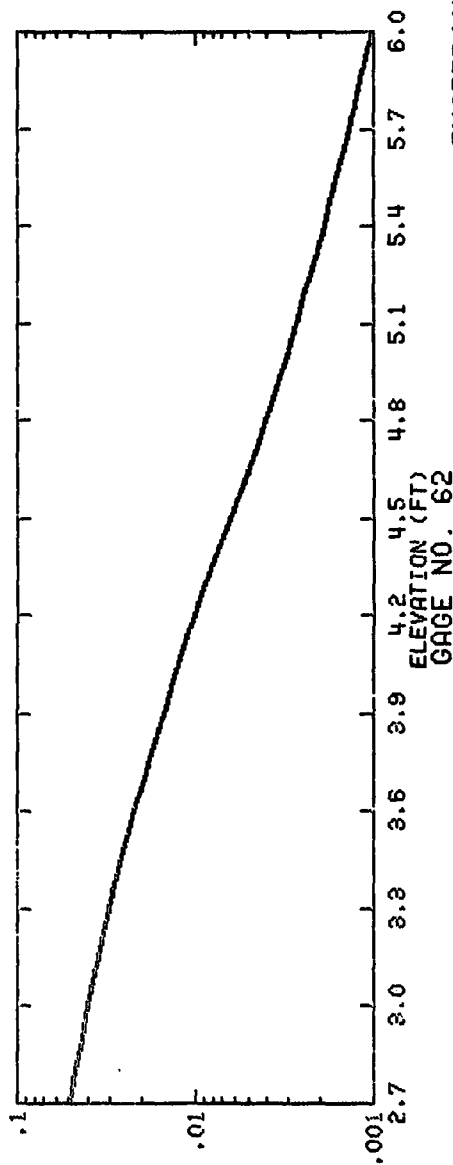
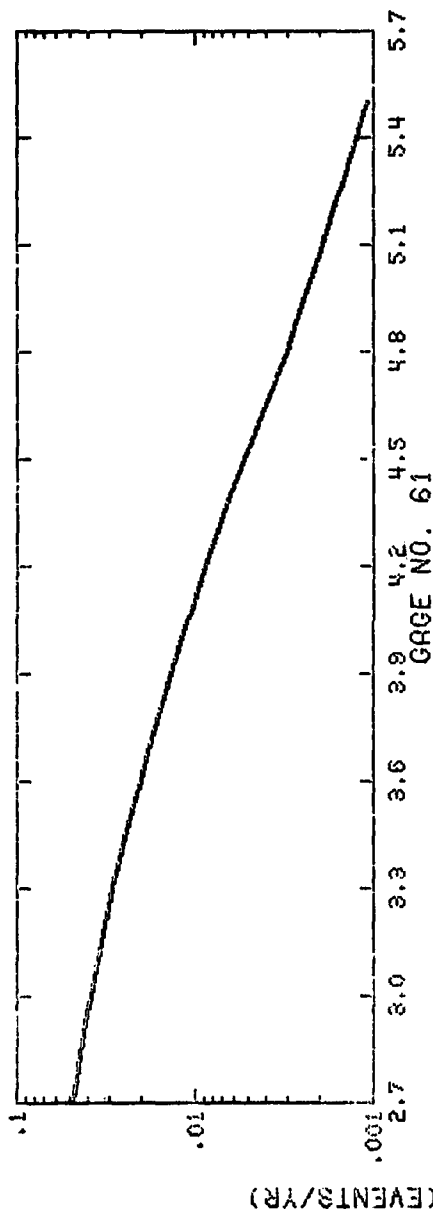


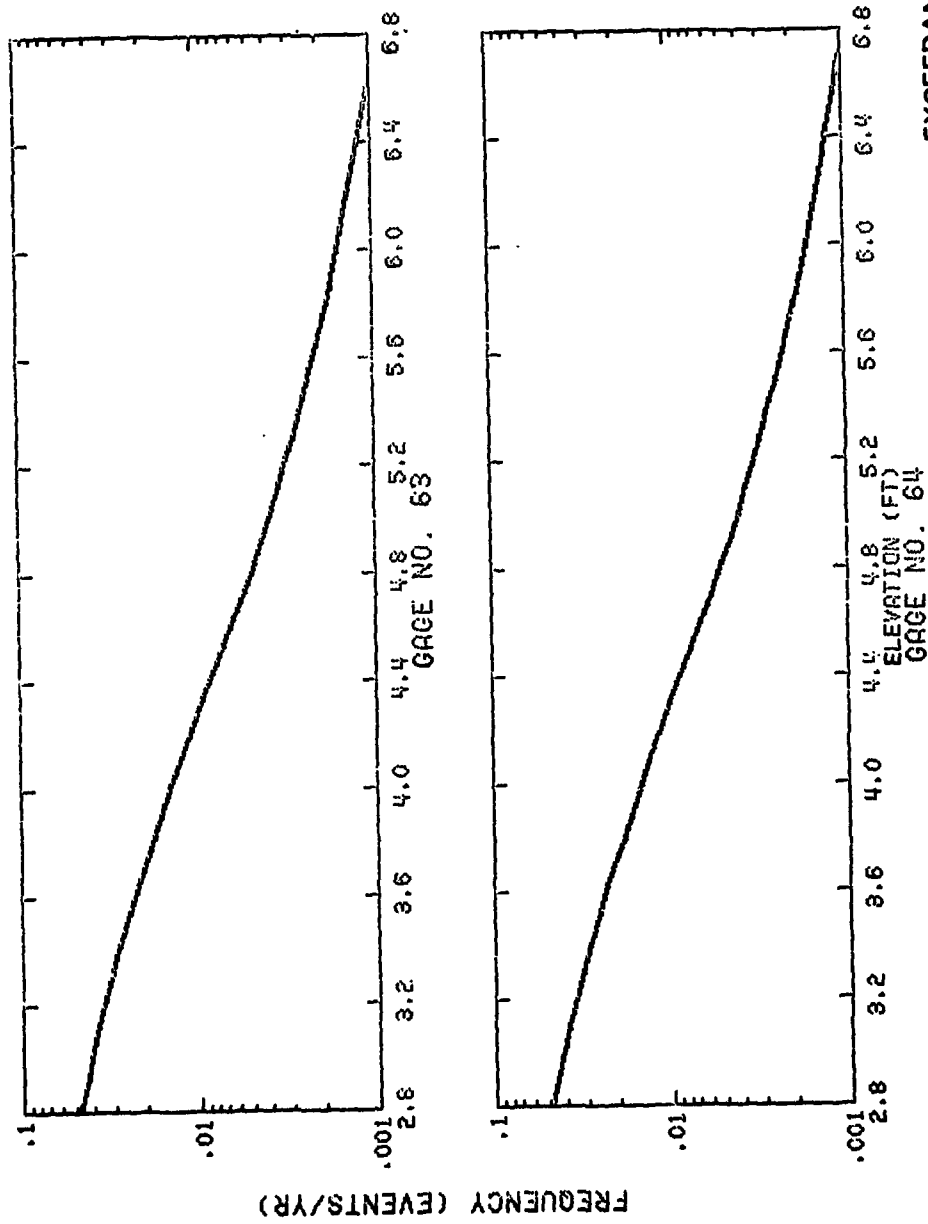
PLATE 28



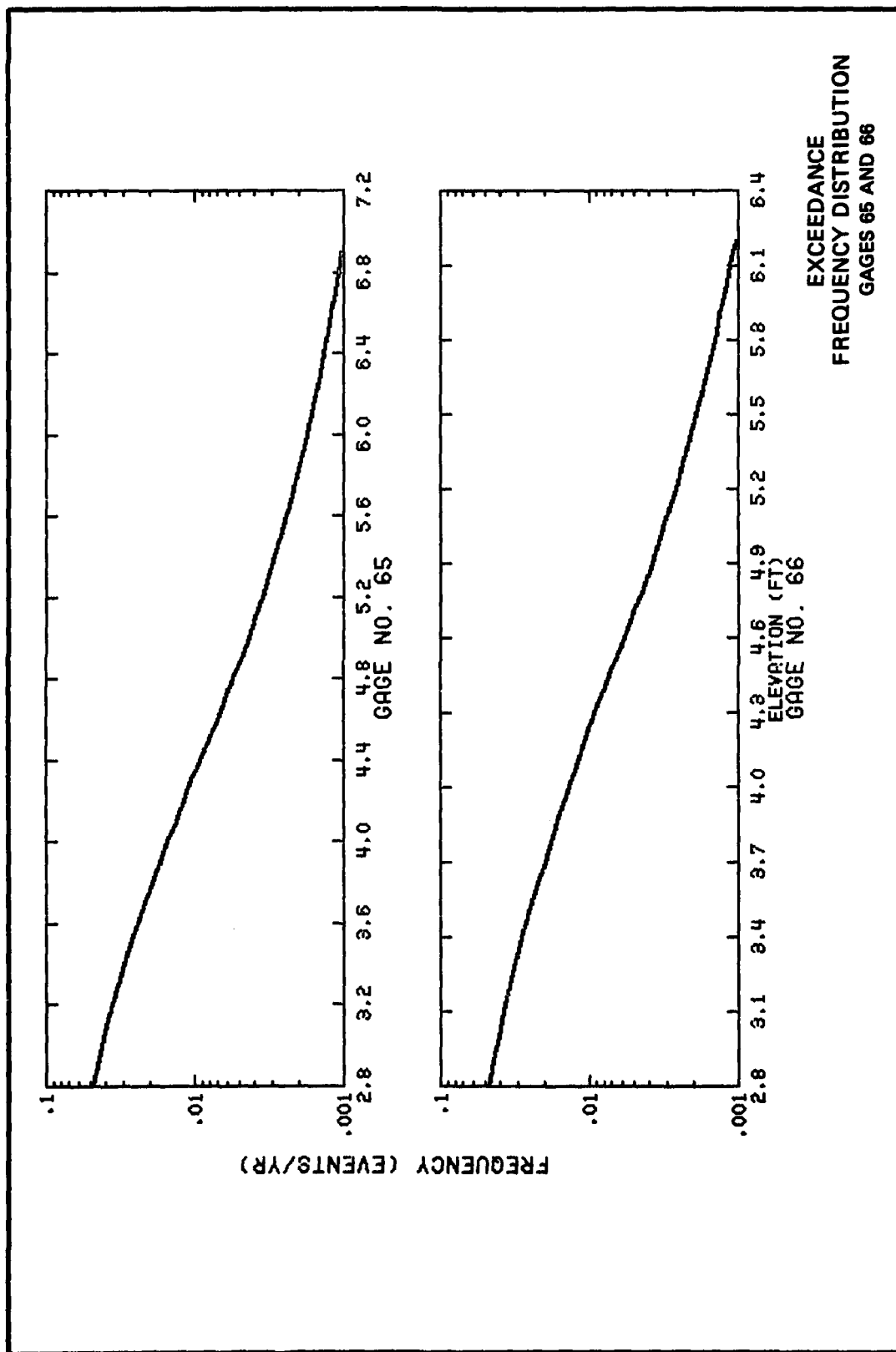




EXCEEDANCE
FREQUENCY DISTRIBUTION
GAGES 61 AND 62



EXCEEDANCE
FREQUENCY DISTRIBUTION
GAGES 63 AND 64



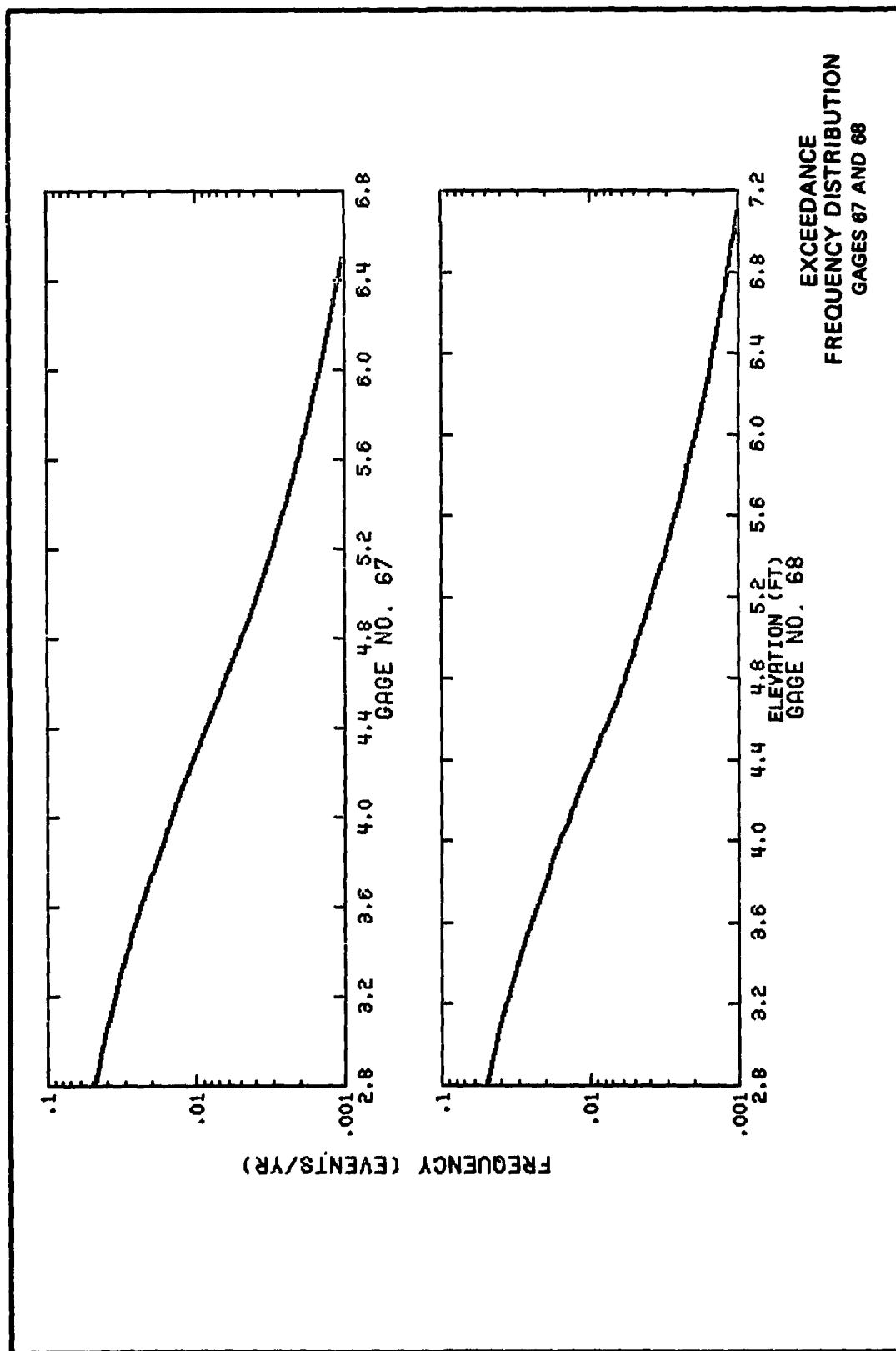
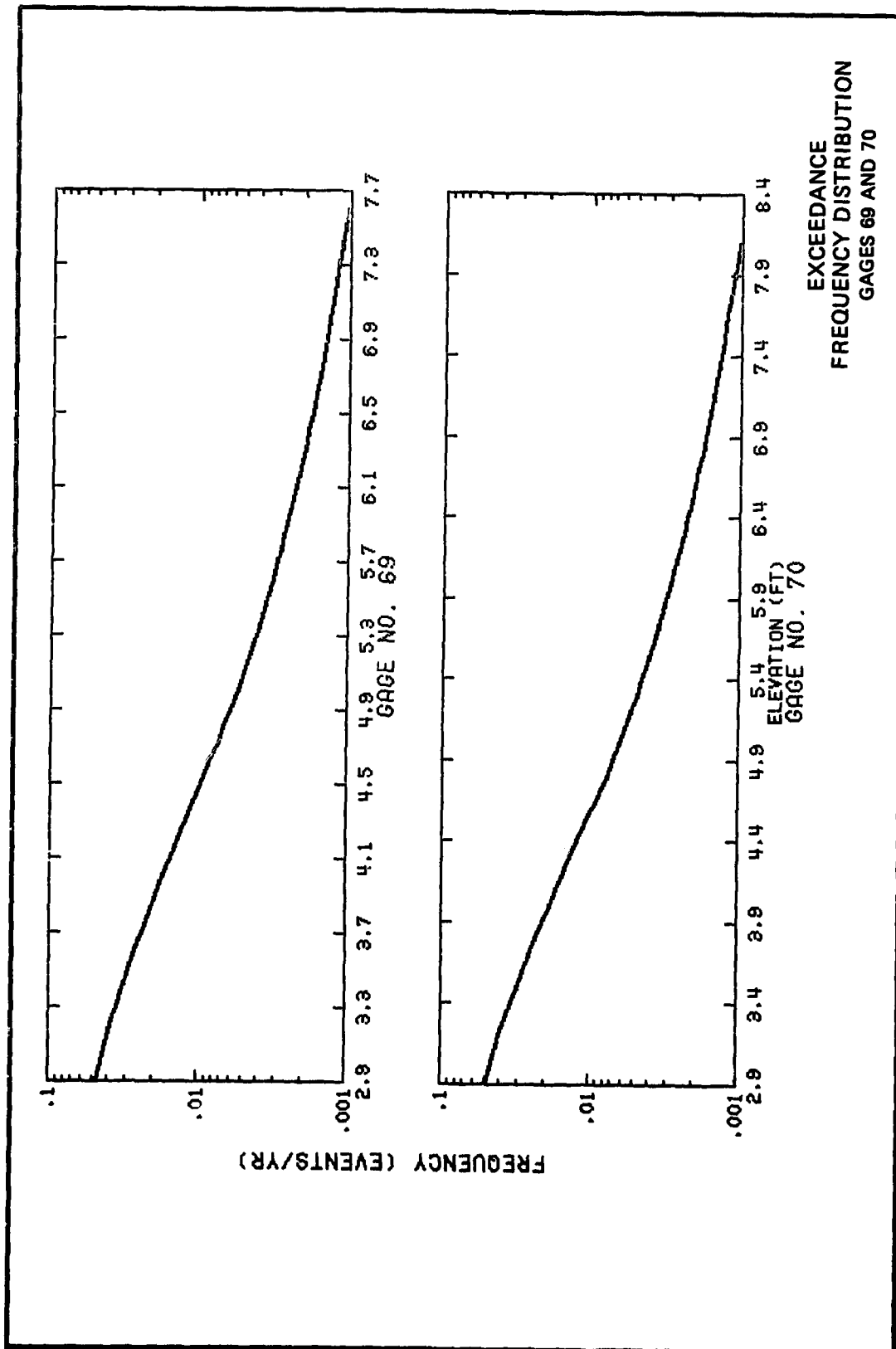
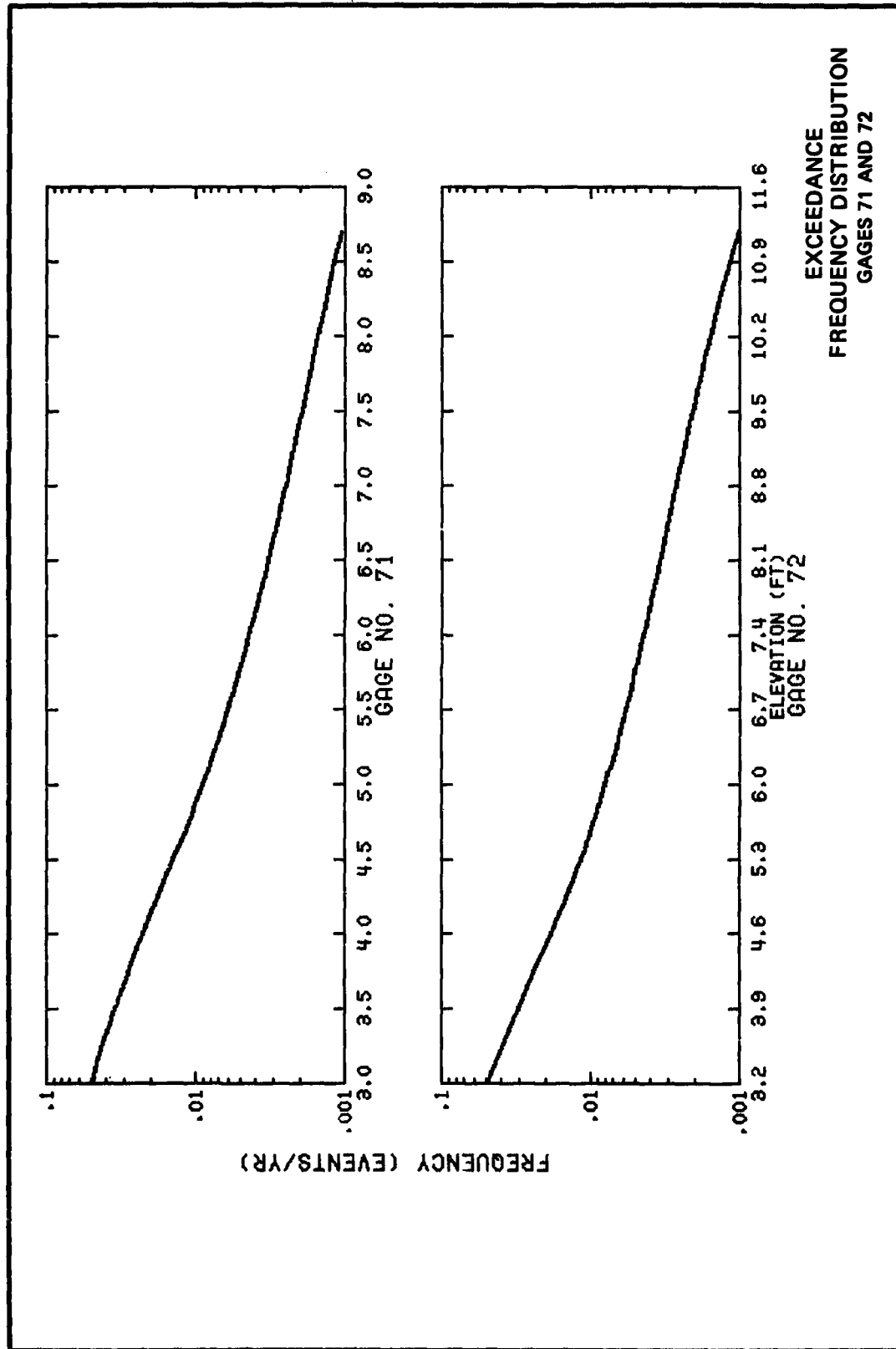
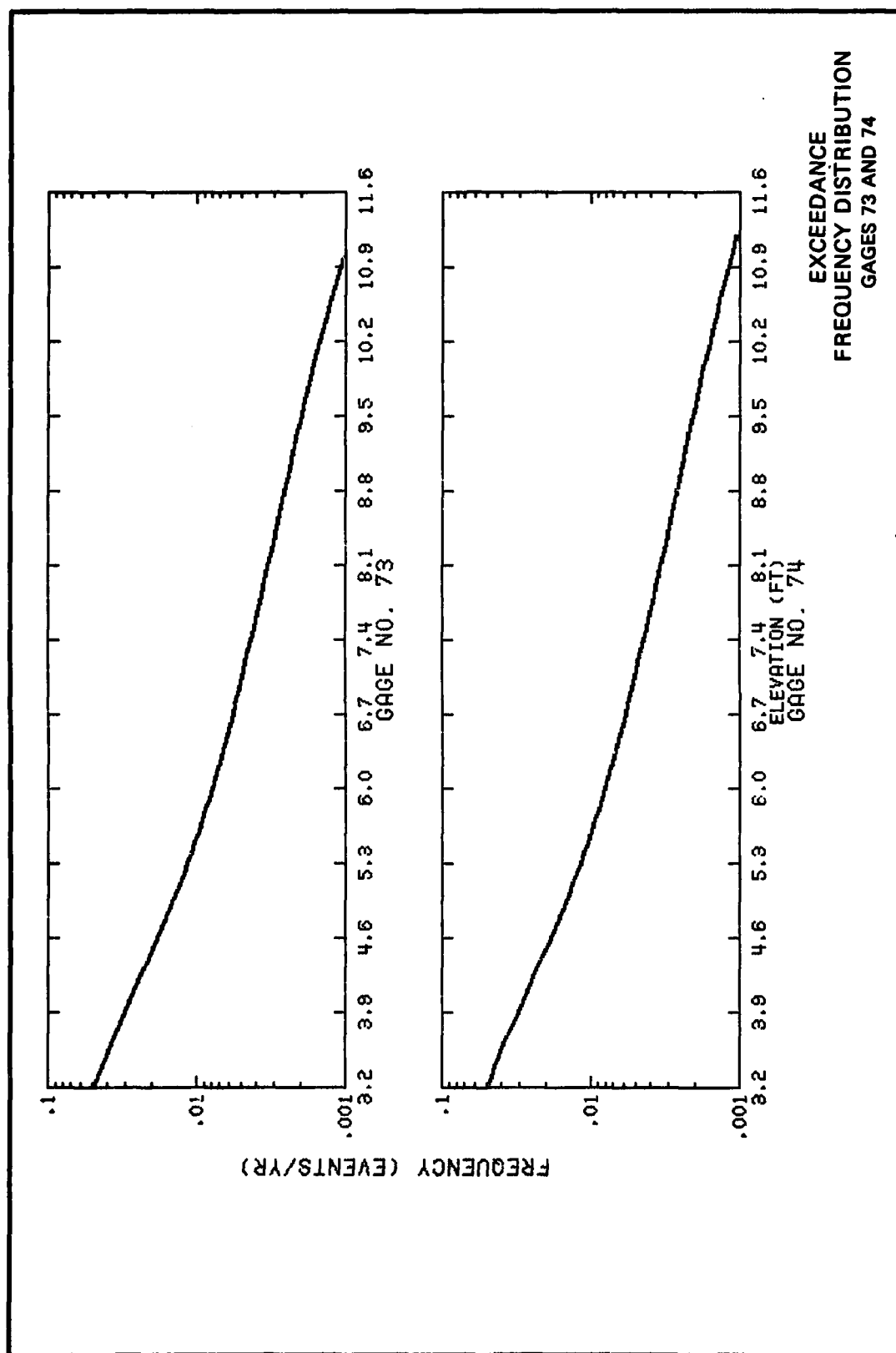
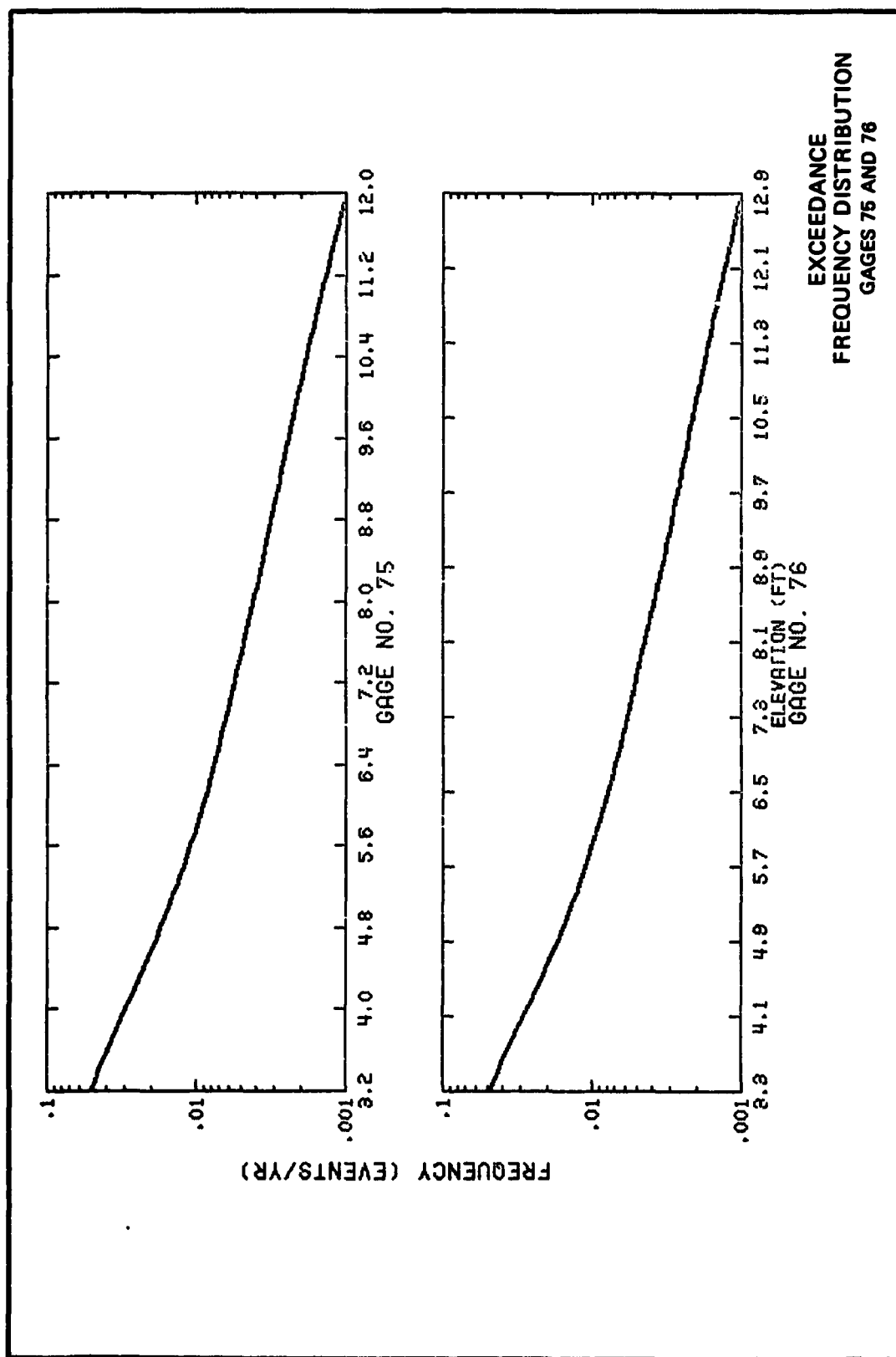


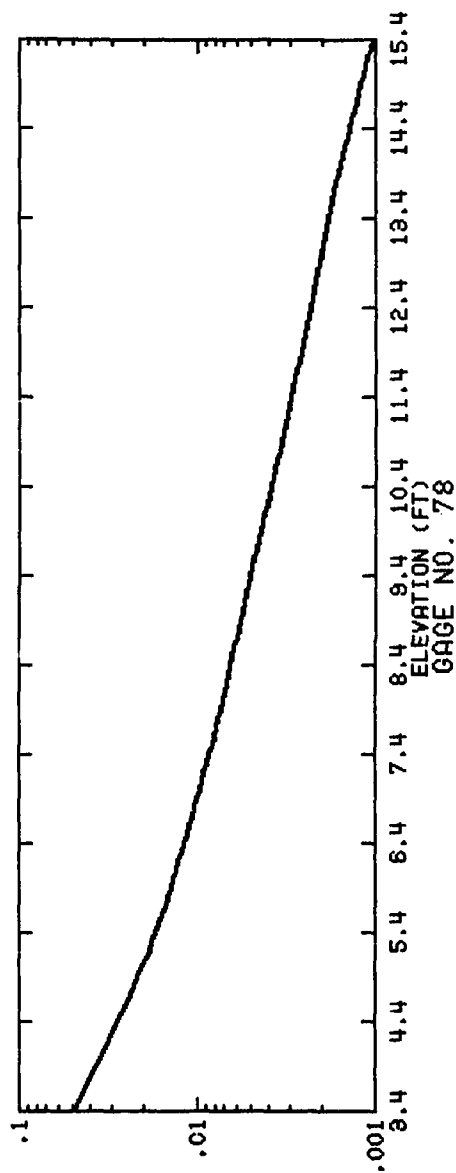
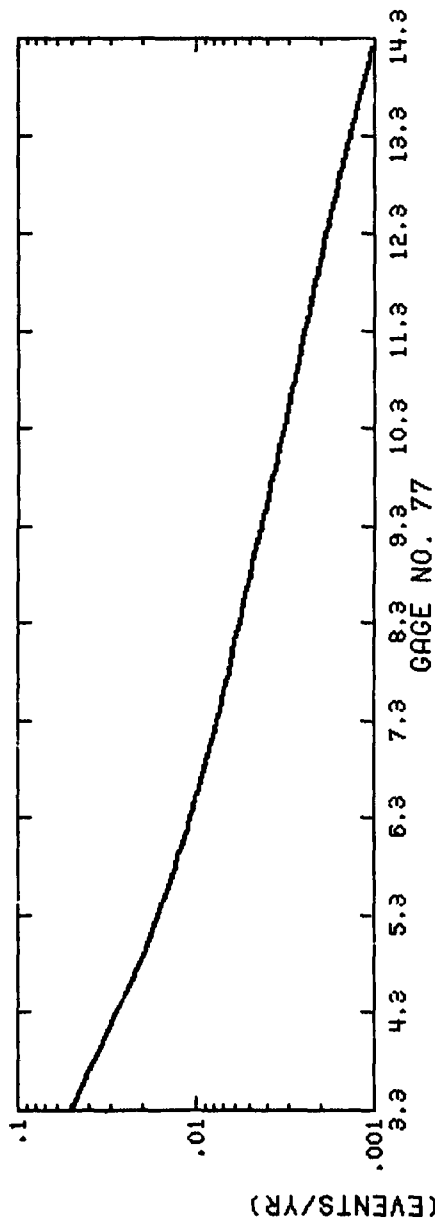
PLATE 34



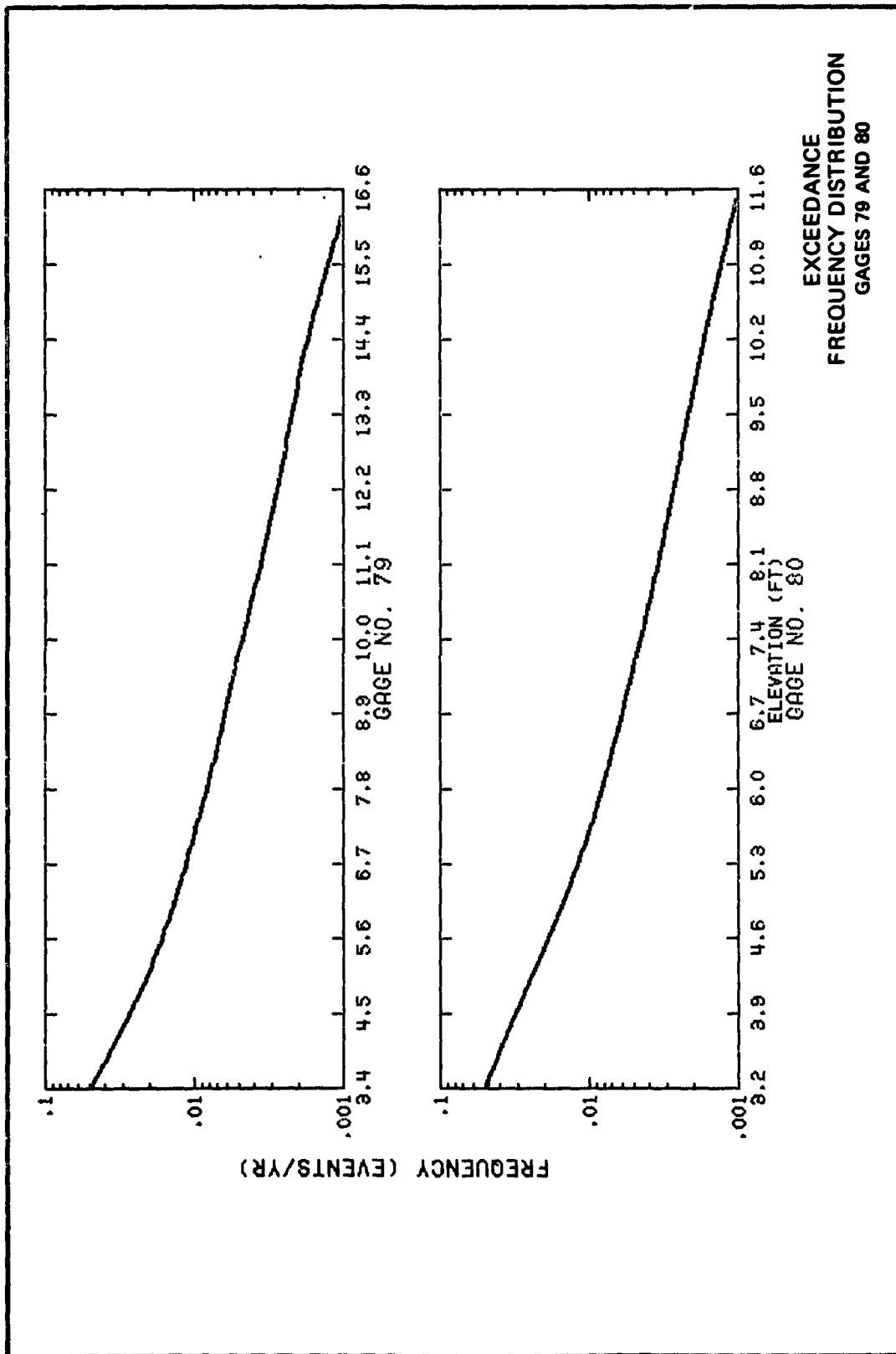








EXCEEDANCE
FREQUENCY DISTRIBUTION
GAGES 77 AND 78



AD-A091 657

ARMY ENGINEER WATERWAYS EXPERIMENT STATION VICKSBURG--ETC F/G 8/3
TYPE 19 FLOOD INSURANCE STUDY: TSUNAMI PREDICTIONS FOR SOUTHERN--ETC(U)
SEP 80 J R HOUSTON FEMA-IAA-H-9-79
WES/TR/NL-80-18 NL

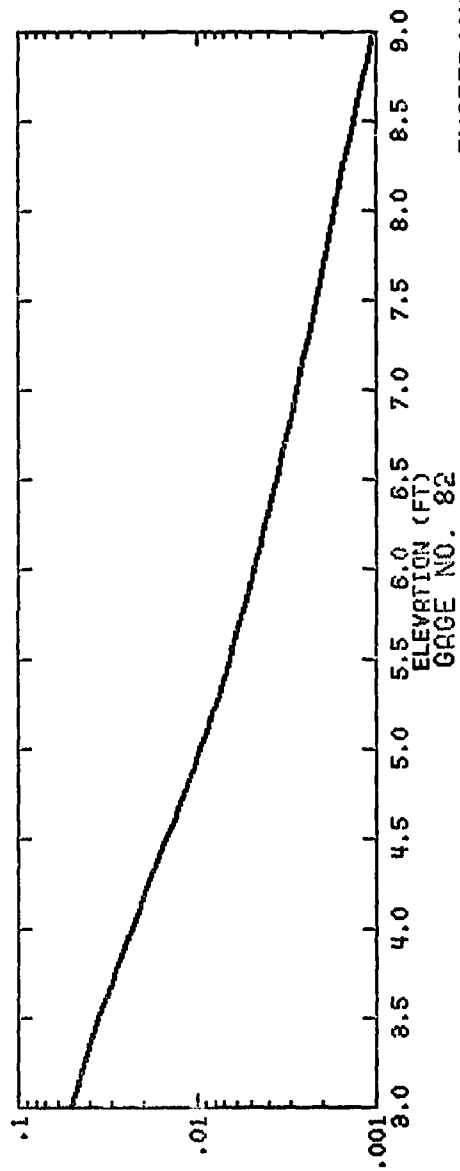
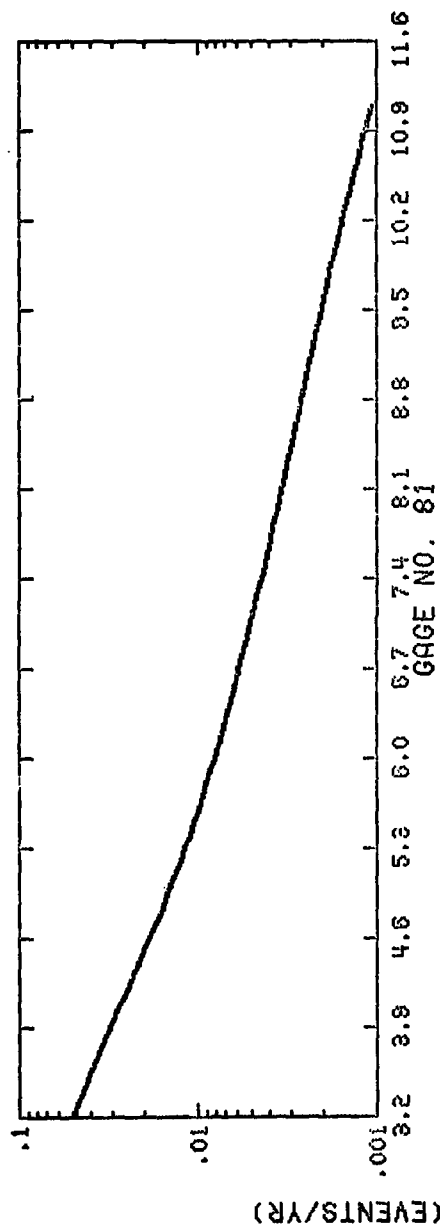
UNCLASSIFIED

2 of 2

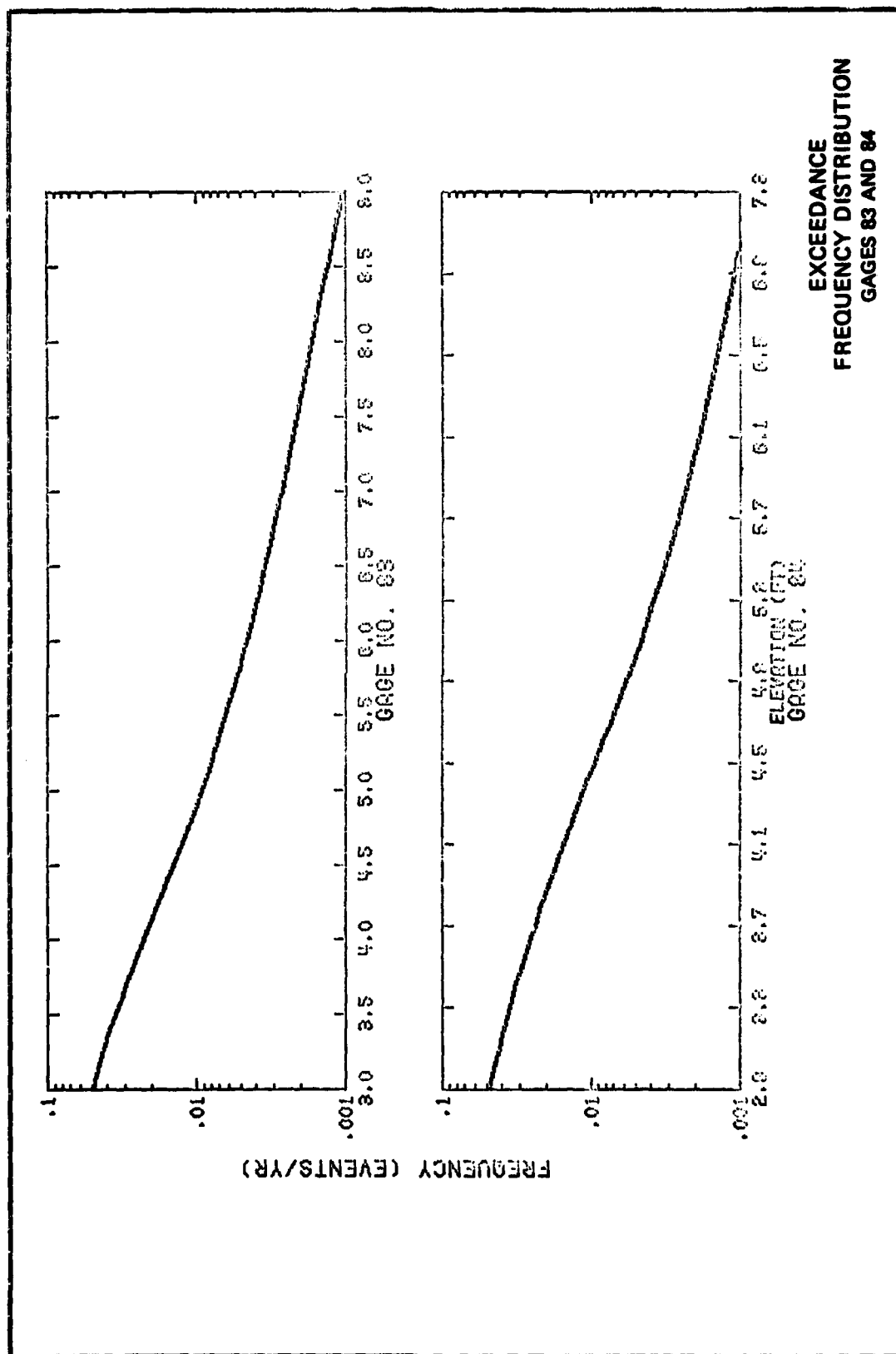
25-30-1

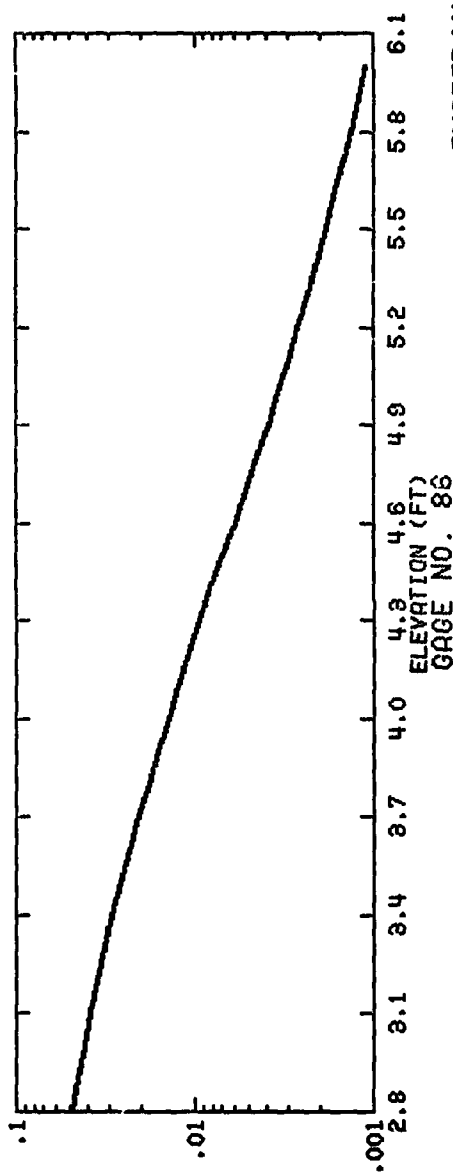
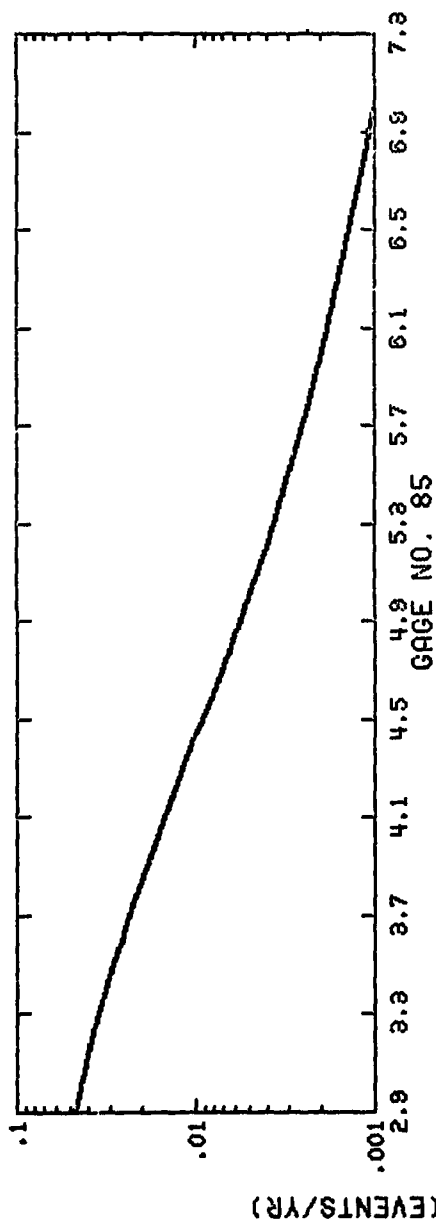


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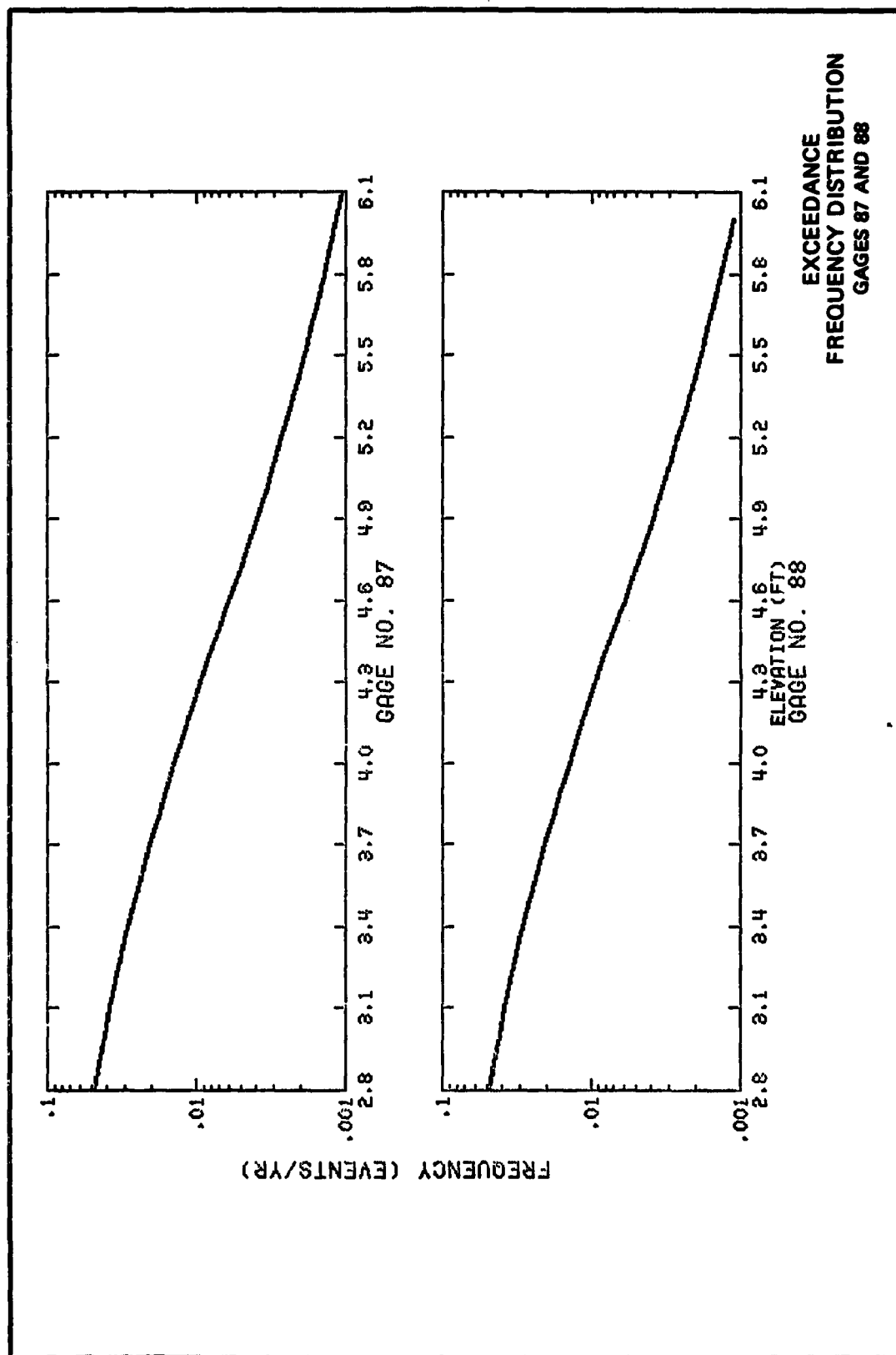


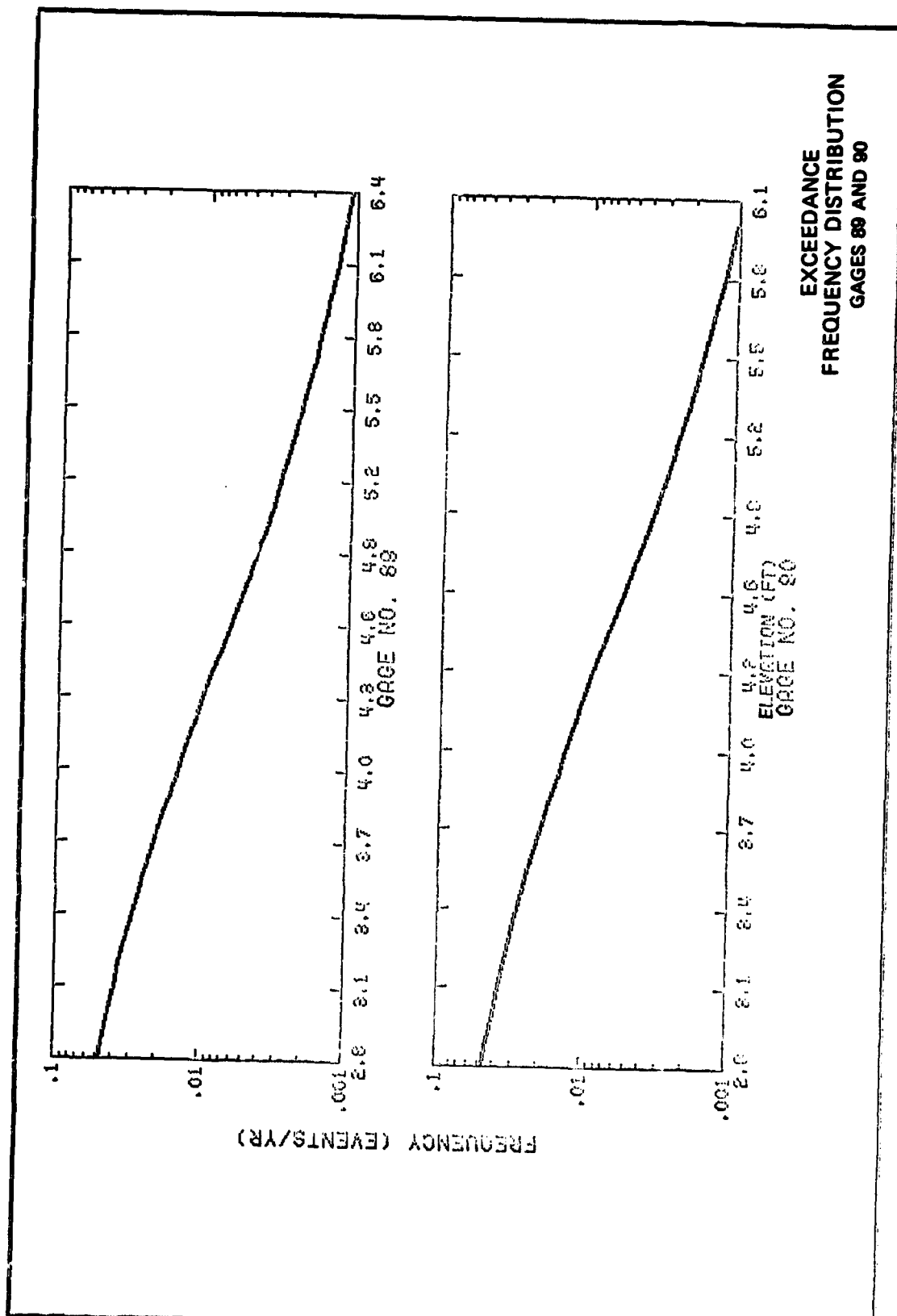
EXCEEDANCE
FREQUENCY DISTRIBUTION
GAGES 81 AND 82

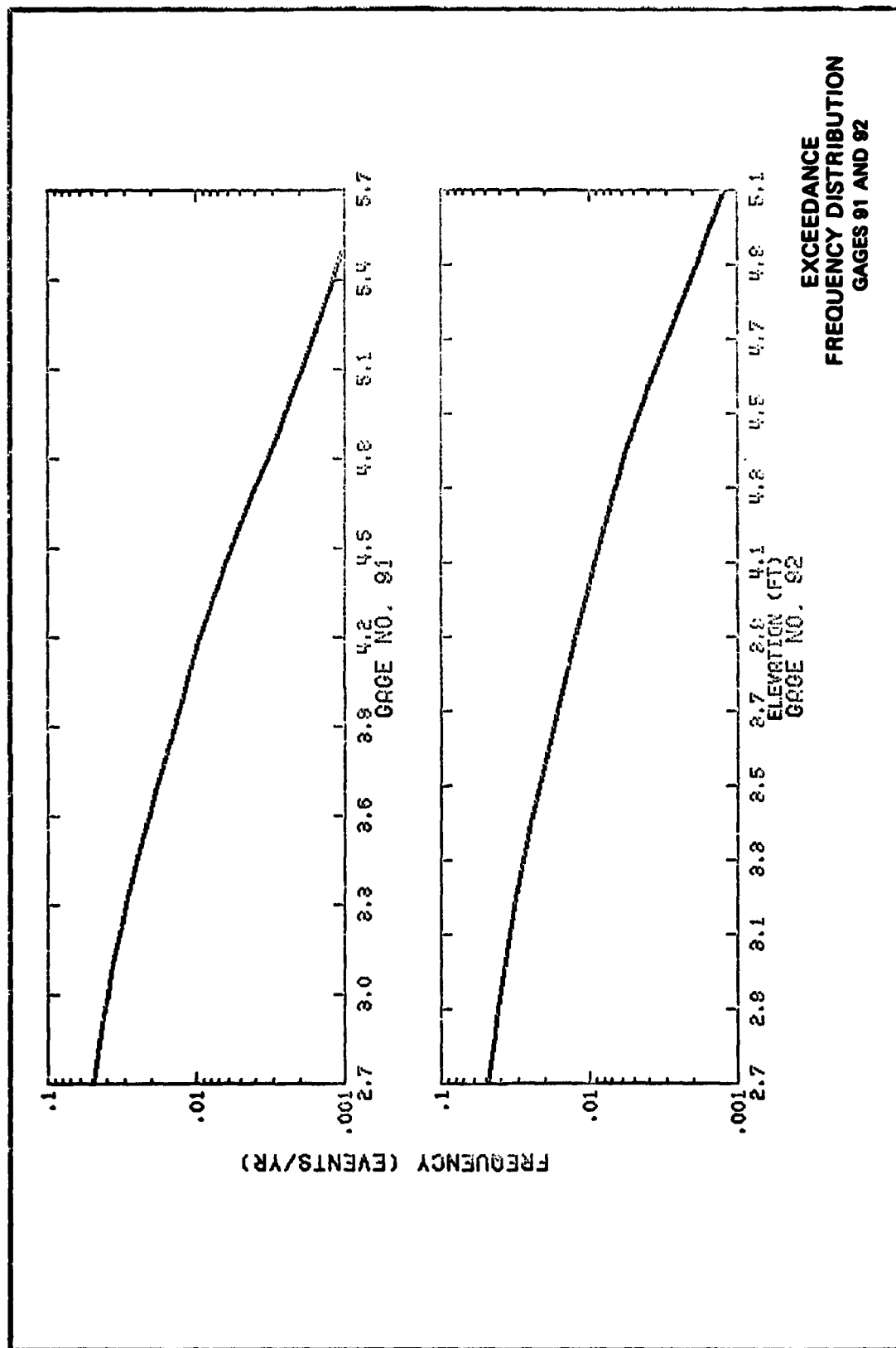


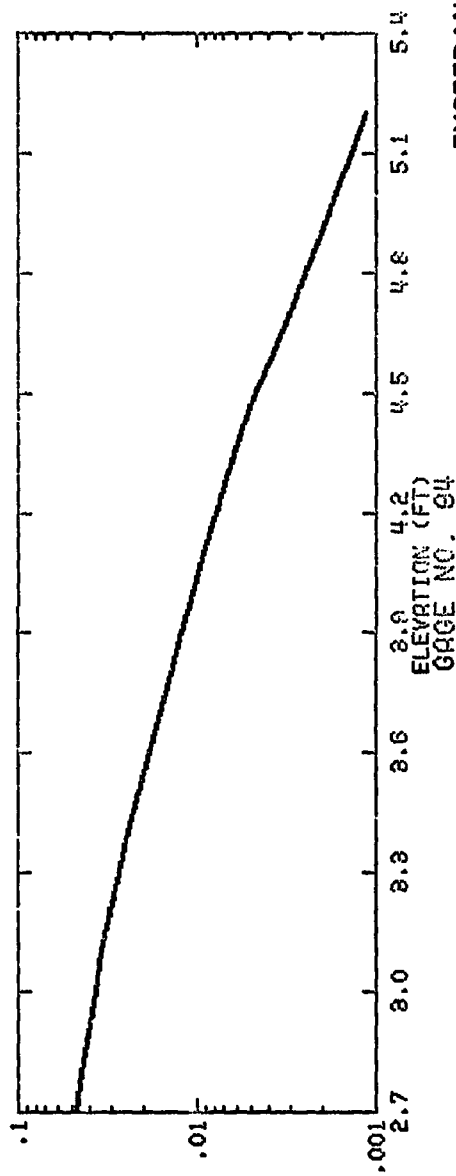
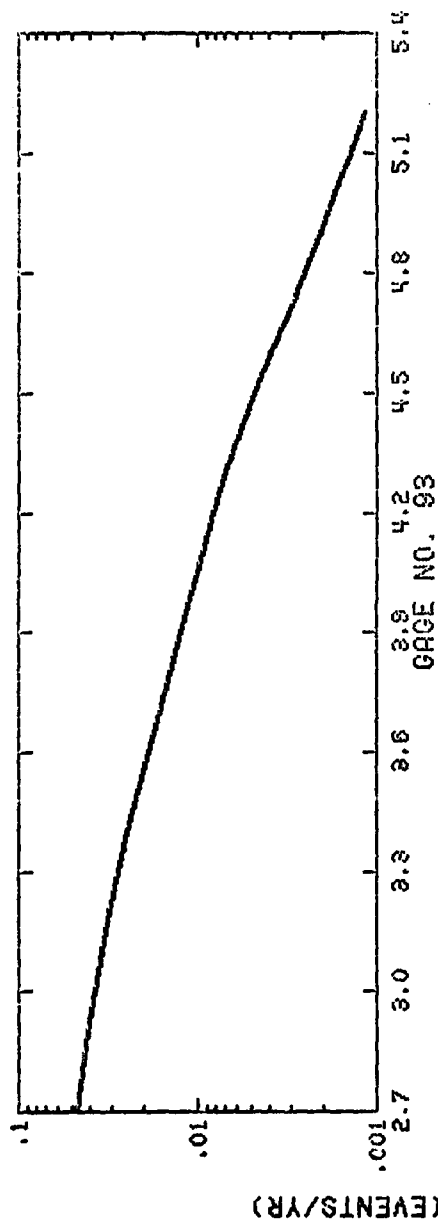


EXCEEDANCE
FREQUENCY DISTRIBUTION
GAGES 85 AND 86

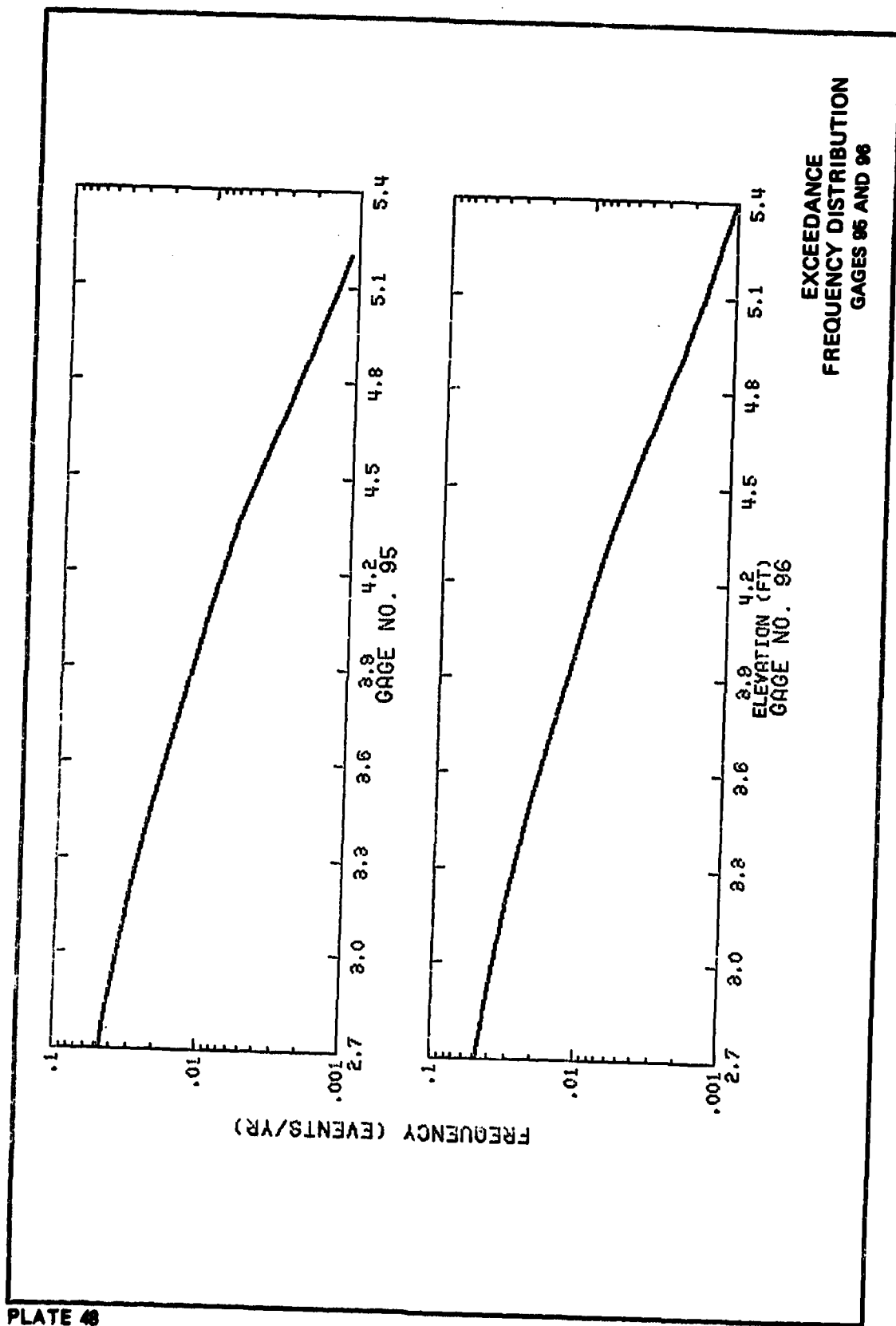


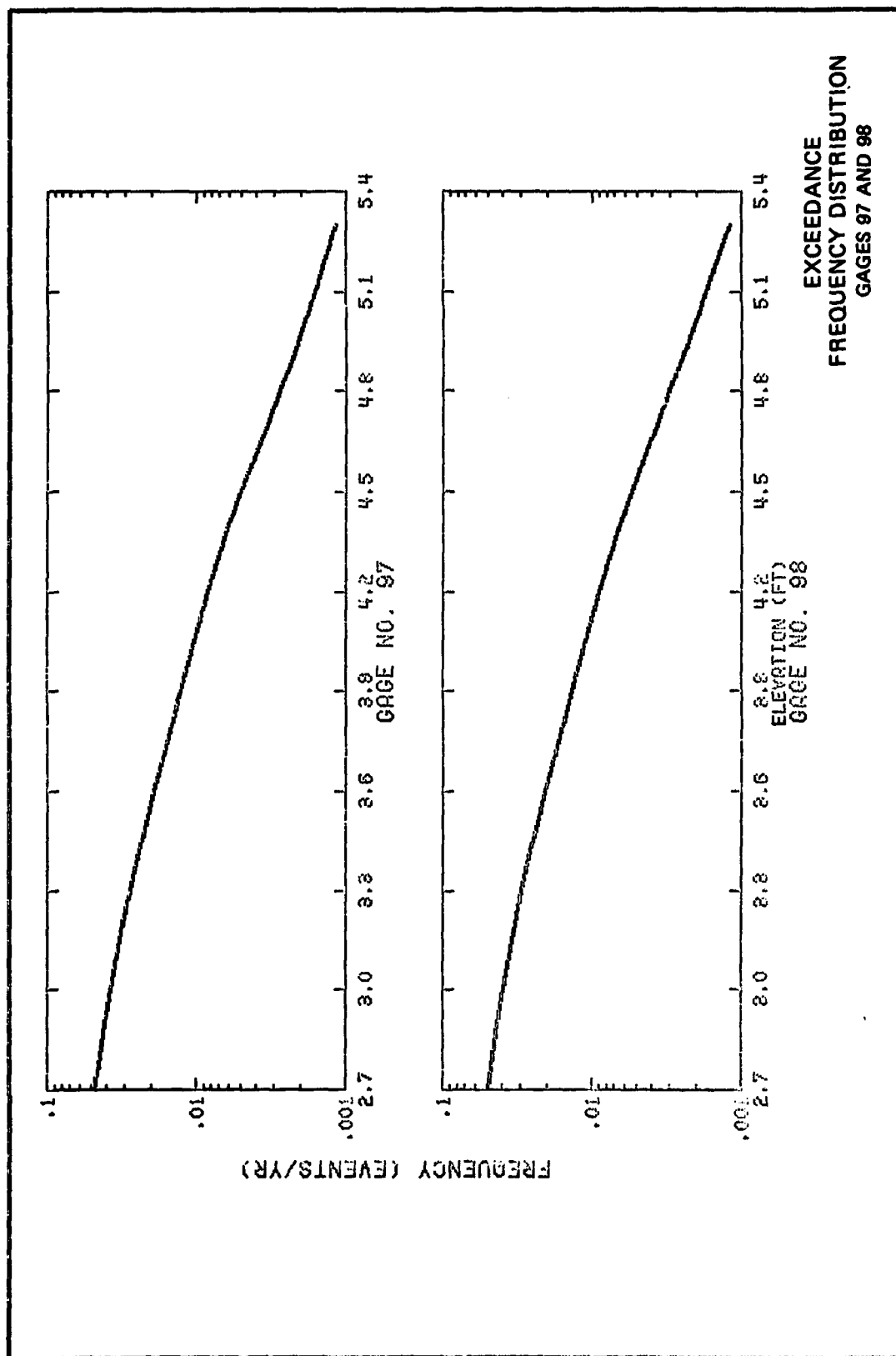


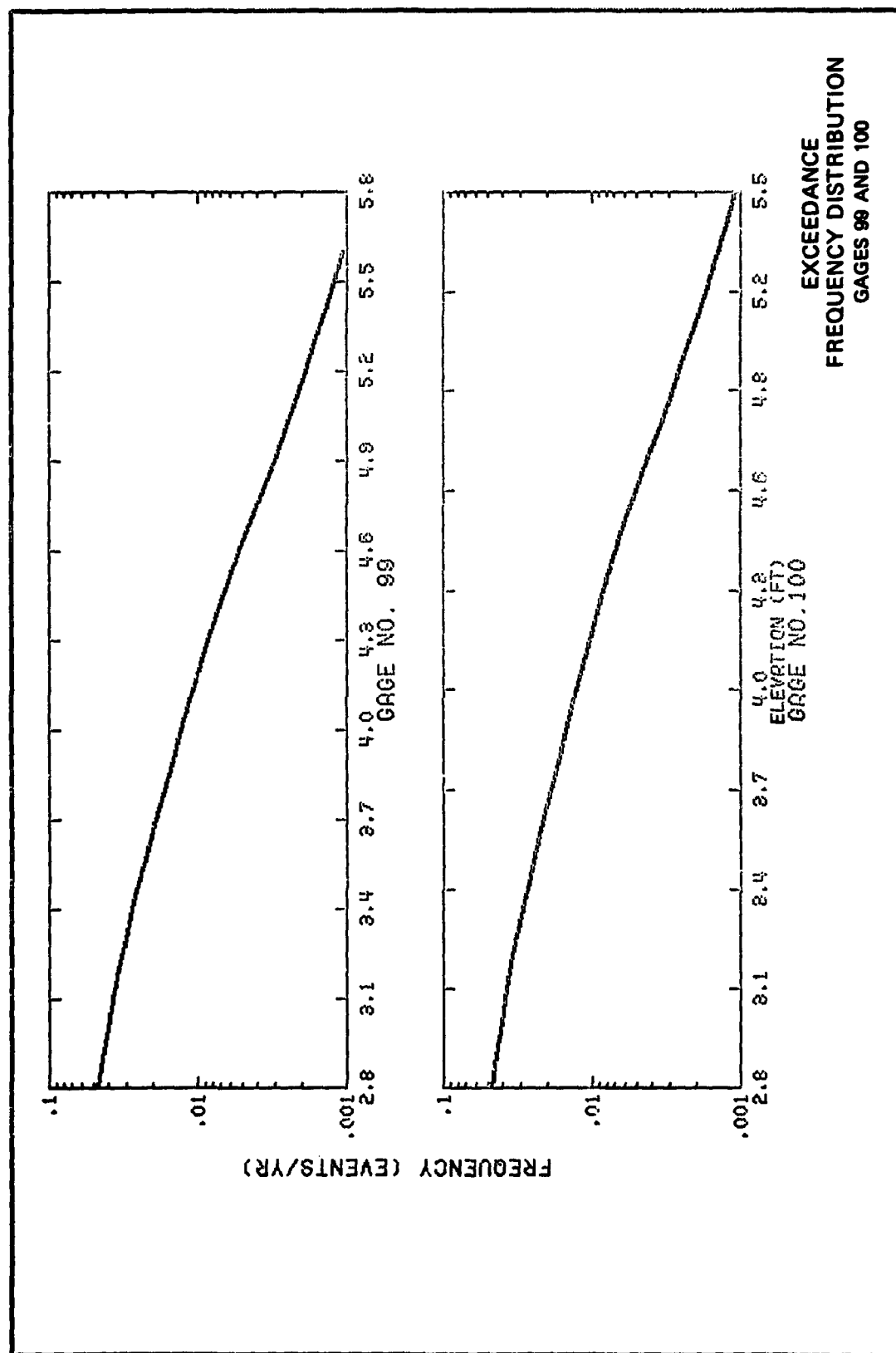


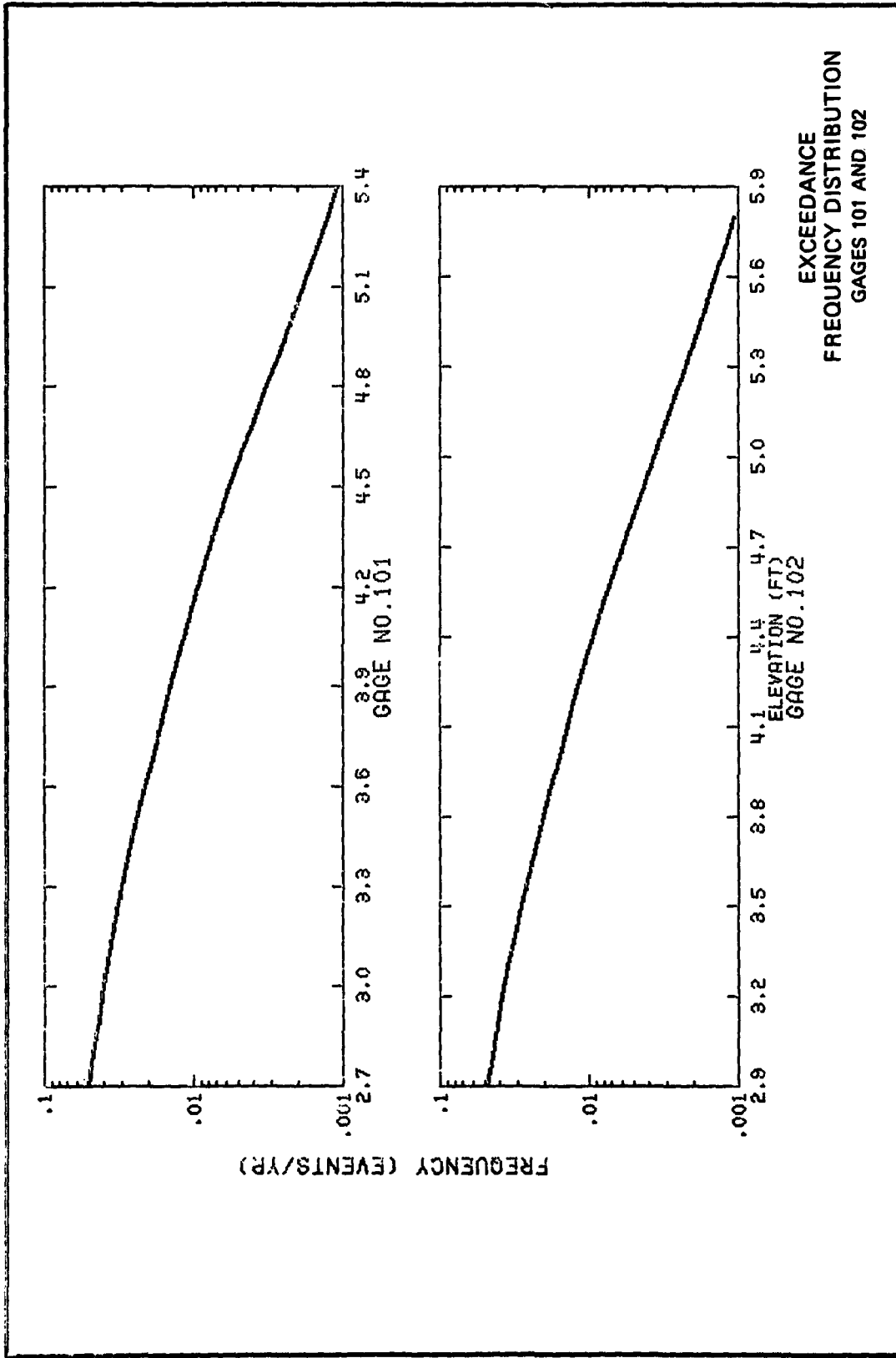


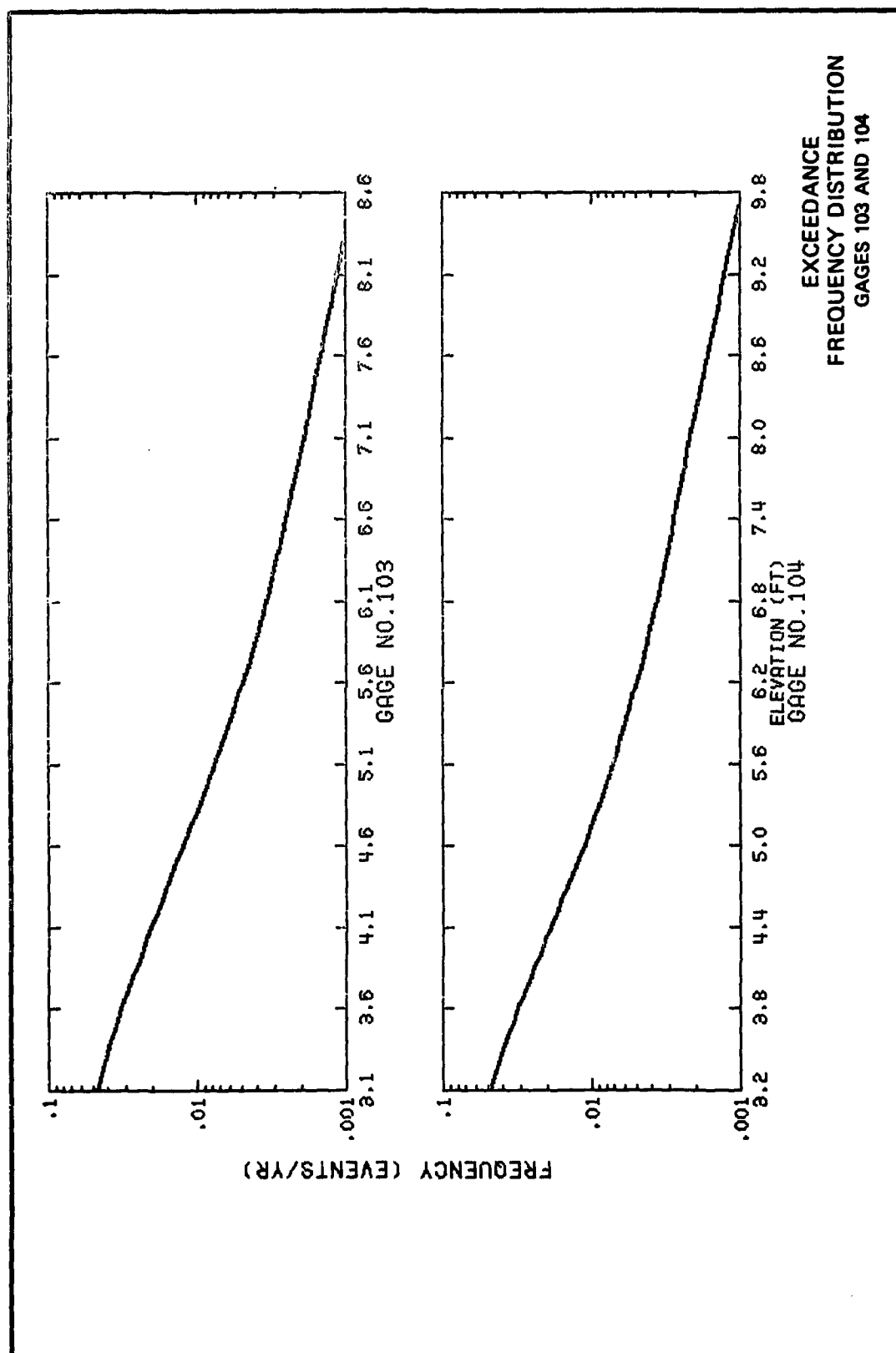
EXCEEDANCE
FREQUENCY DISTRIBUTION
GAGES 93 AND 94

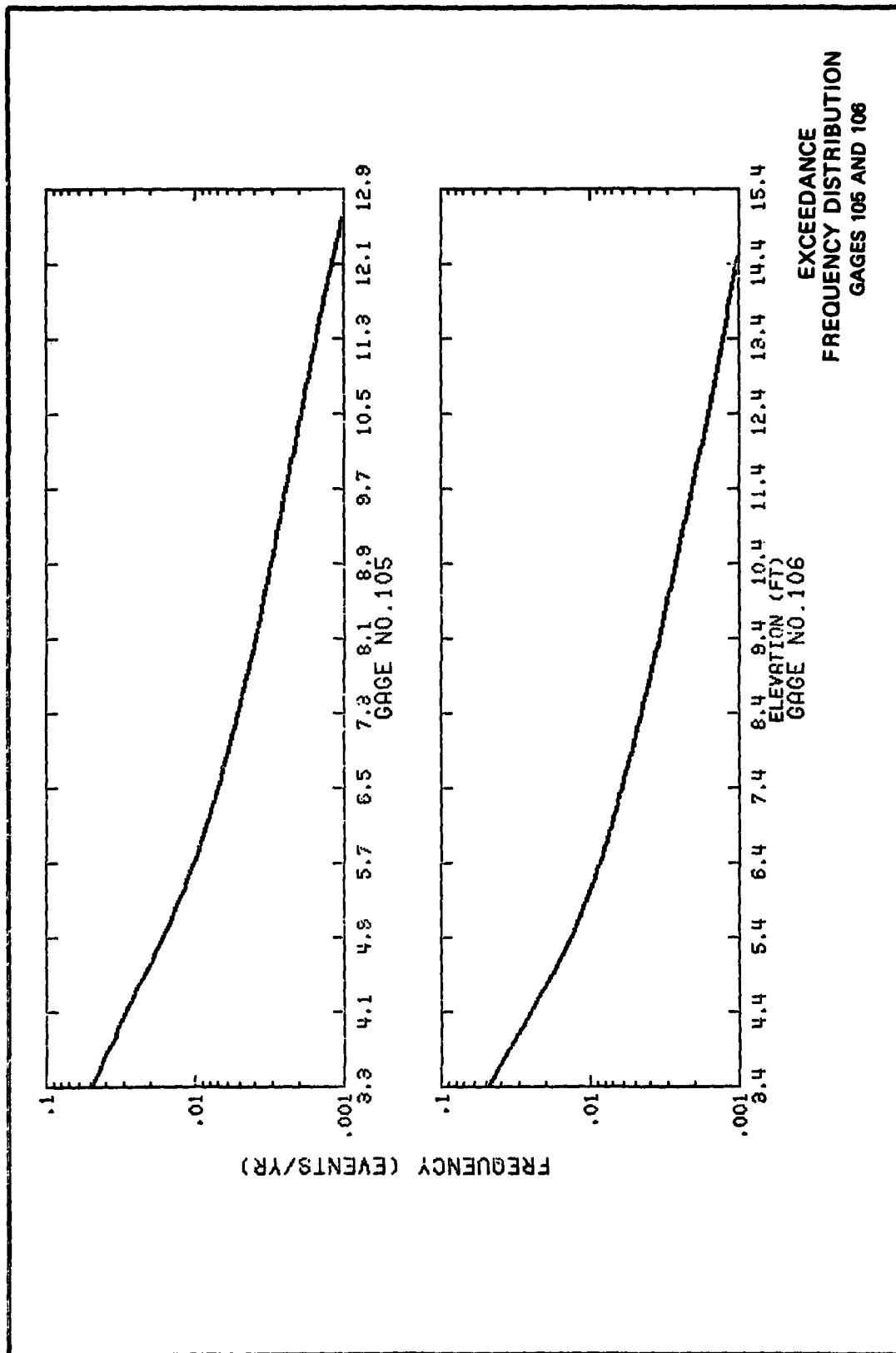


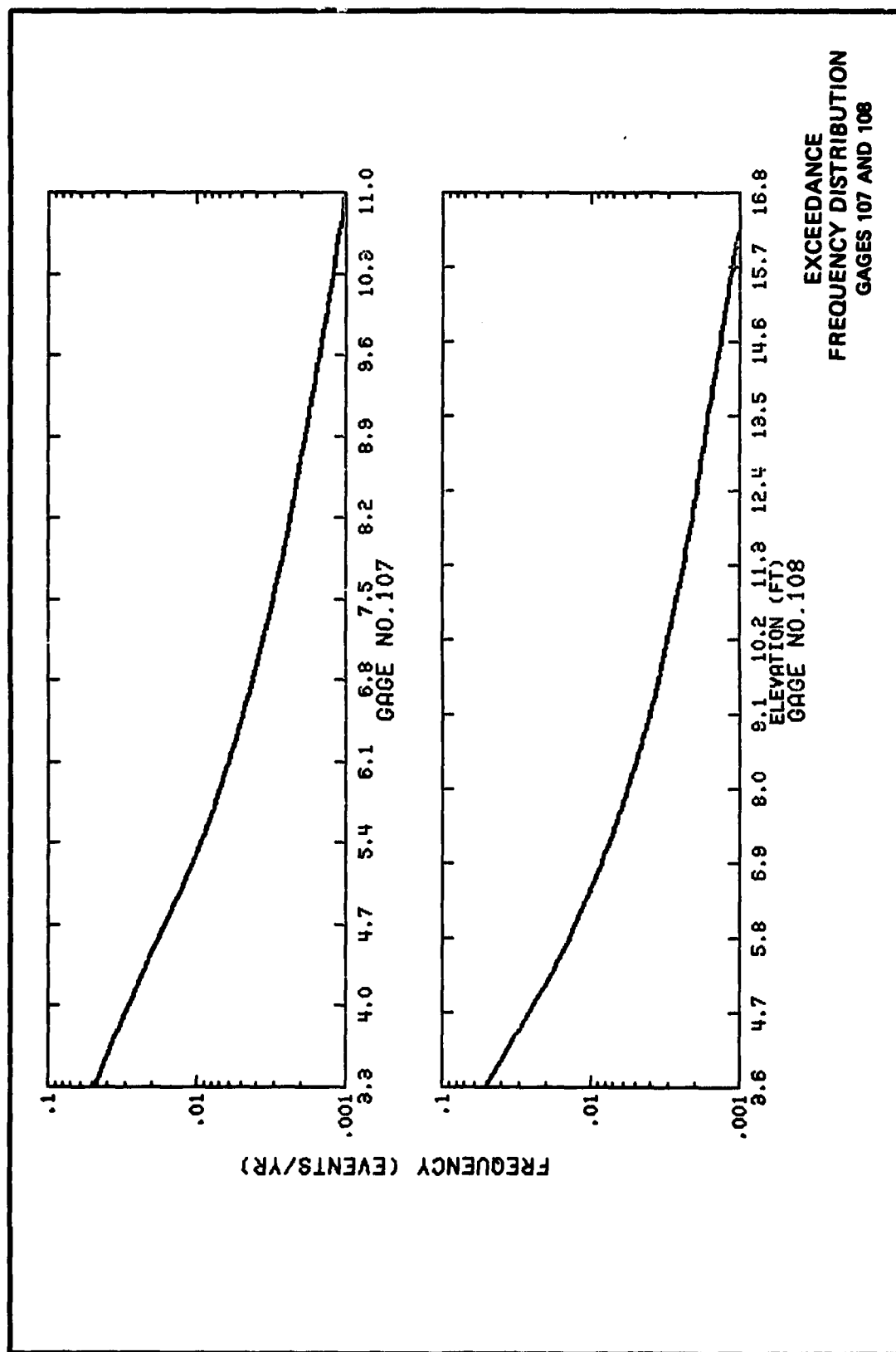


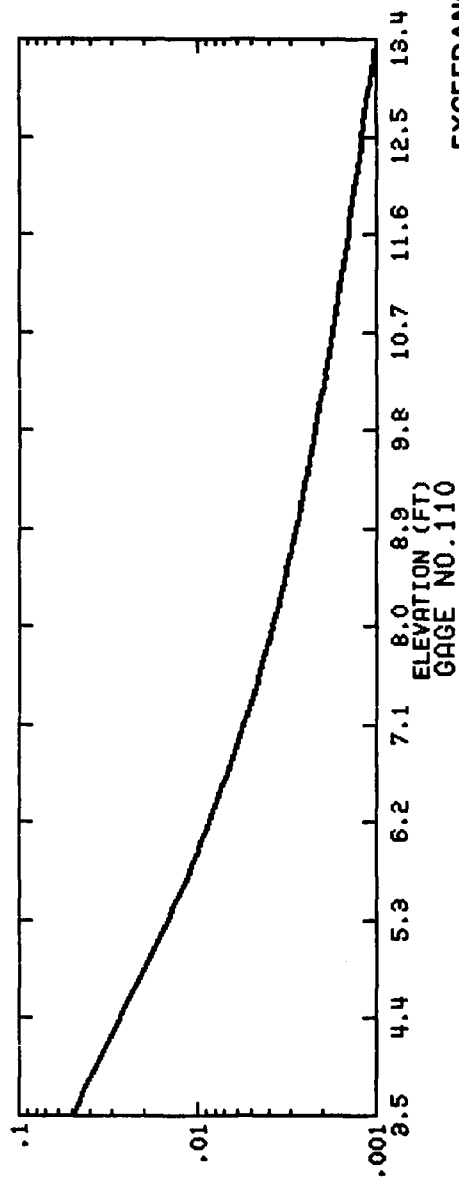
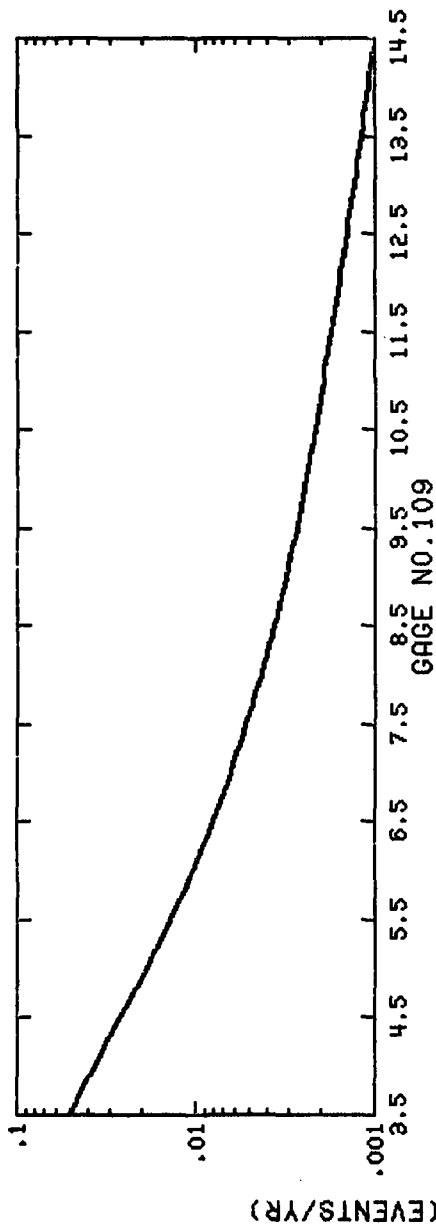




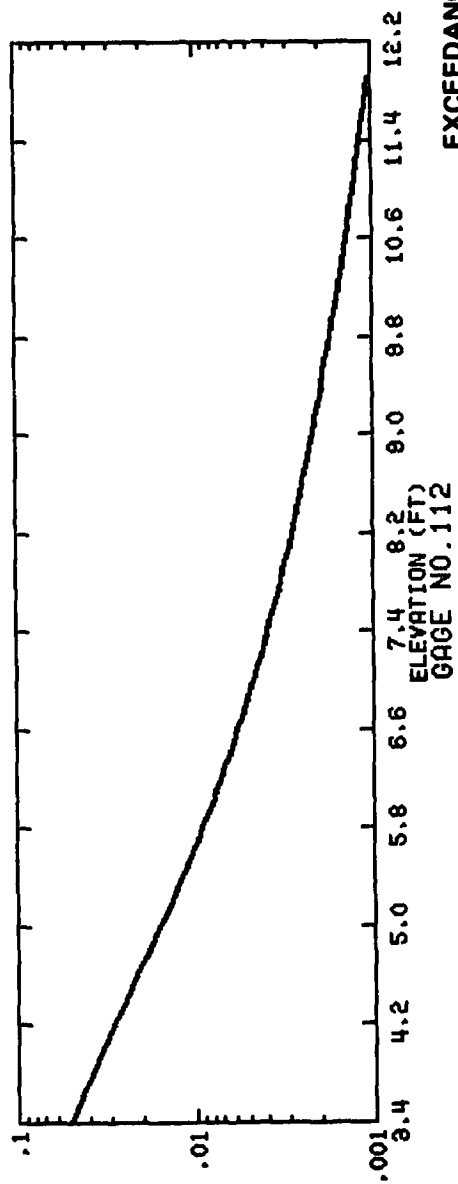
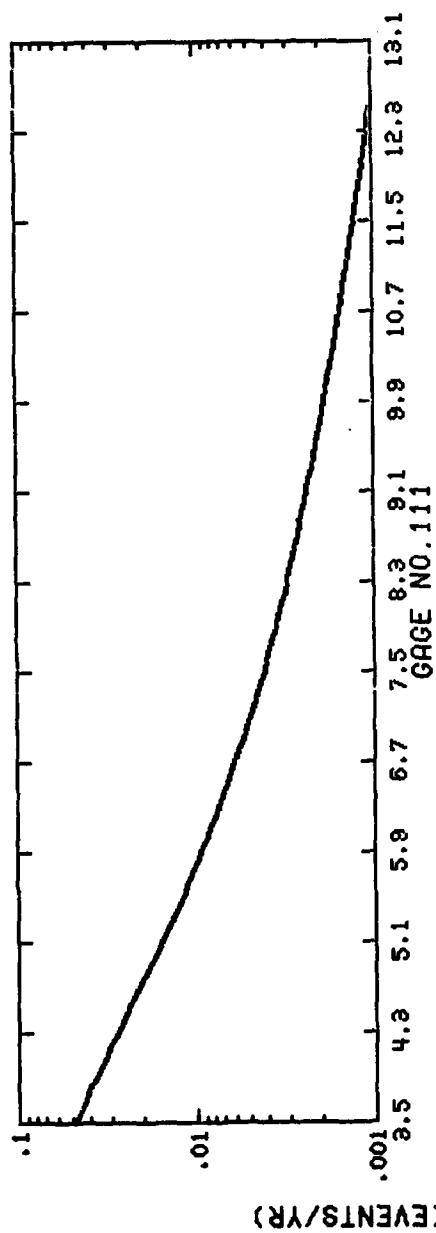




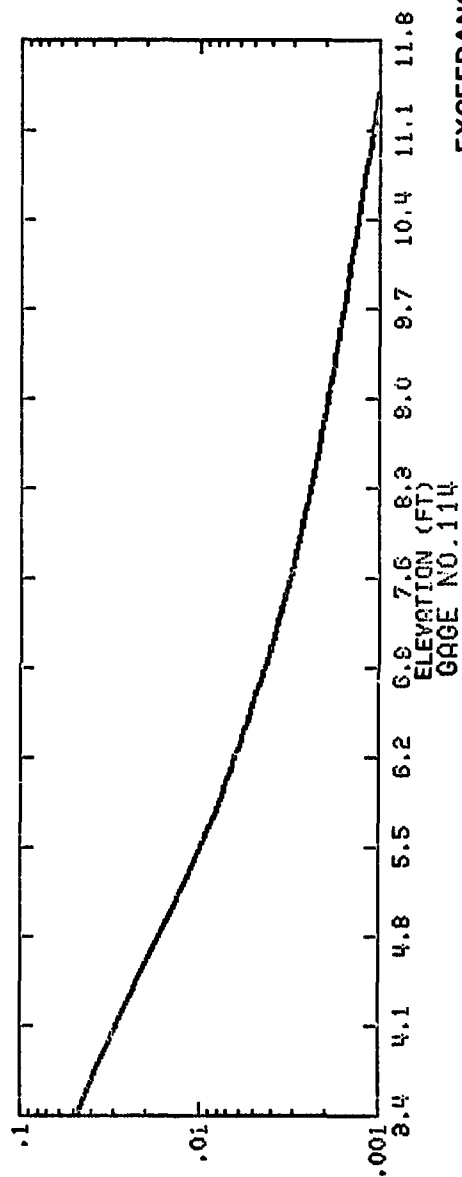
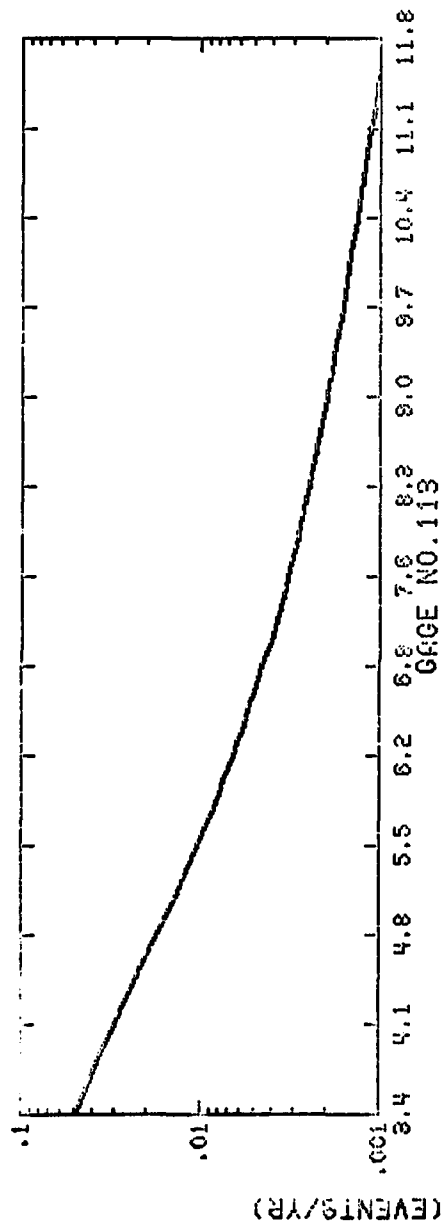




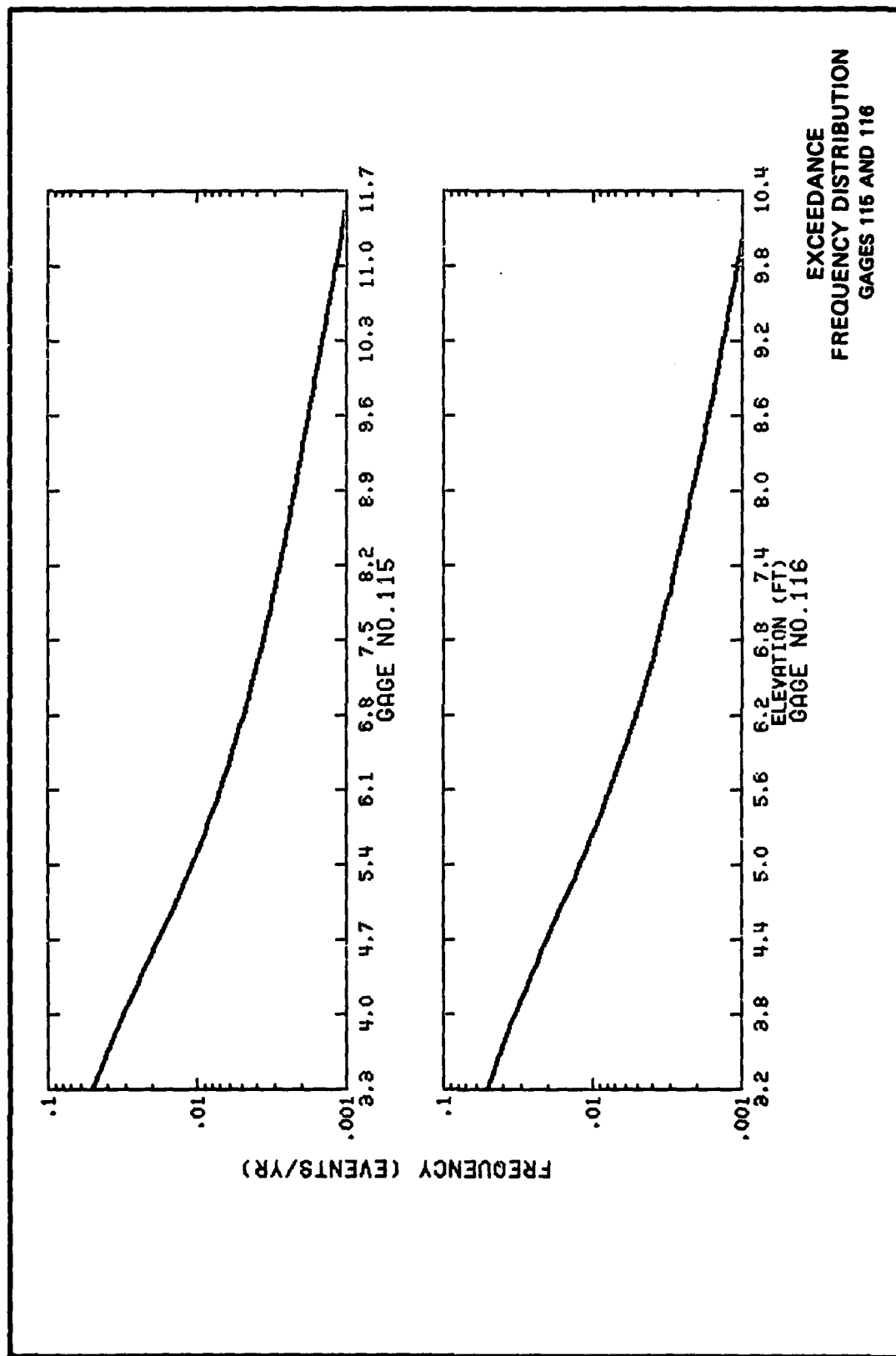
EXCEEDANCE
FREQUENCY DISTRIBUTION
GAGES 109 AND 110

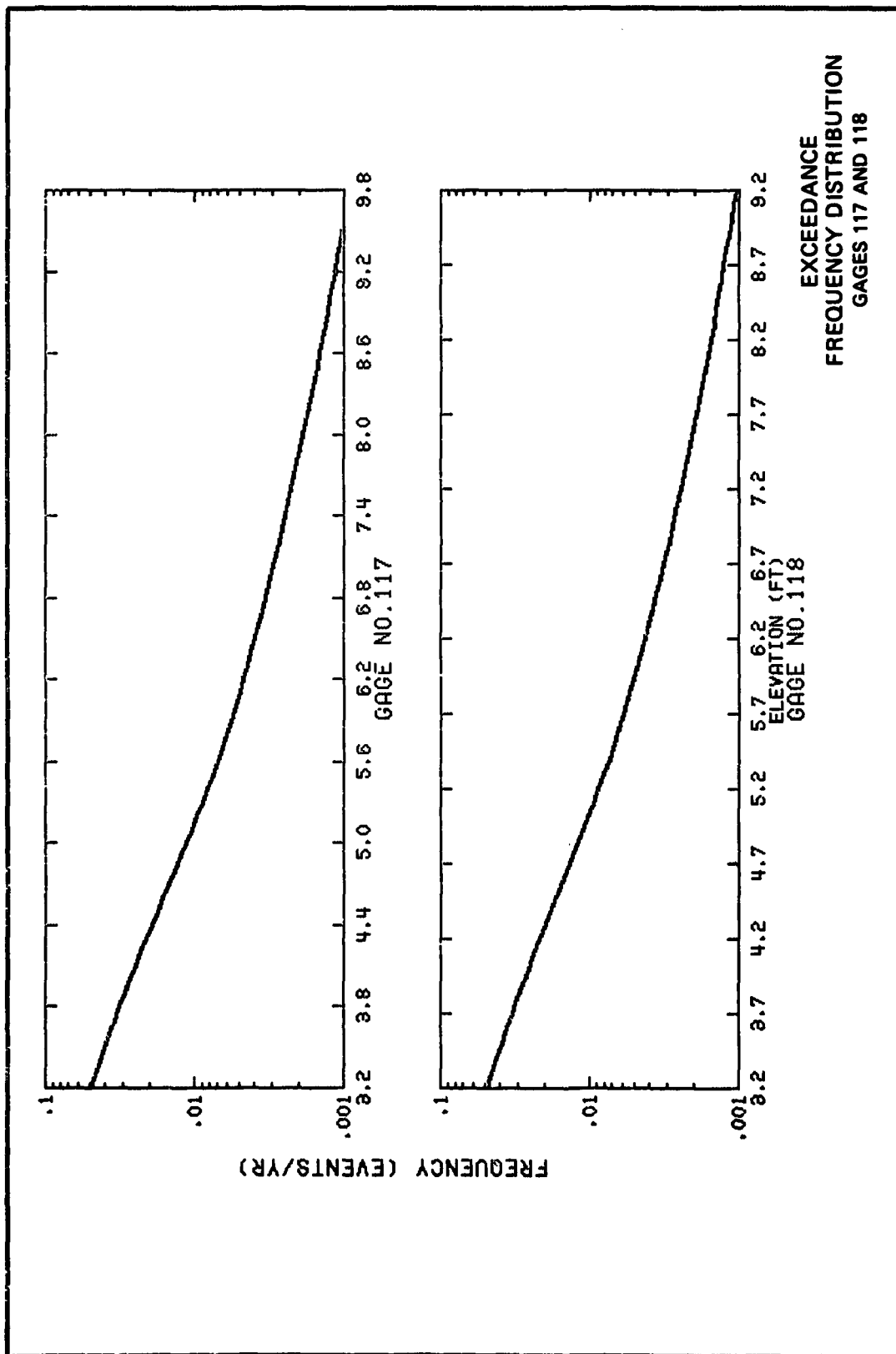


EXCEEDANCE
FREQUENCY DISTRIBUTION
GAGES 111 AND 112



EXCEEDANCE
FREQUENCY DISTRIBUTION
GAGES 113 AND 114





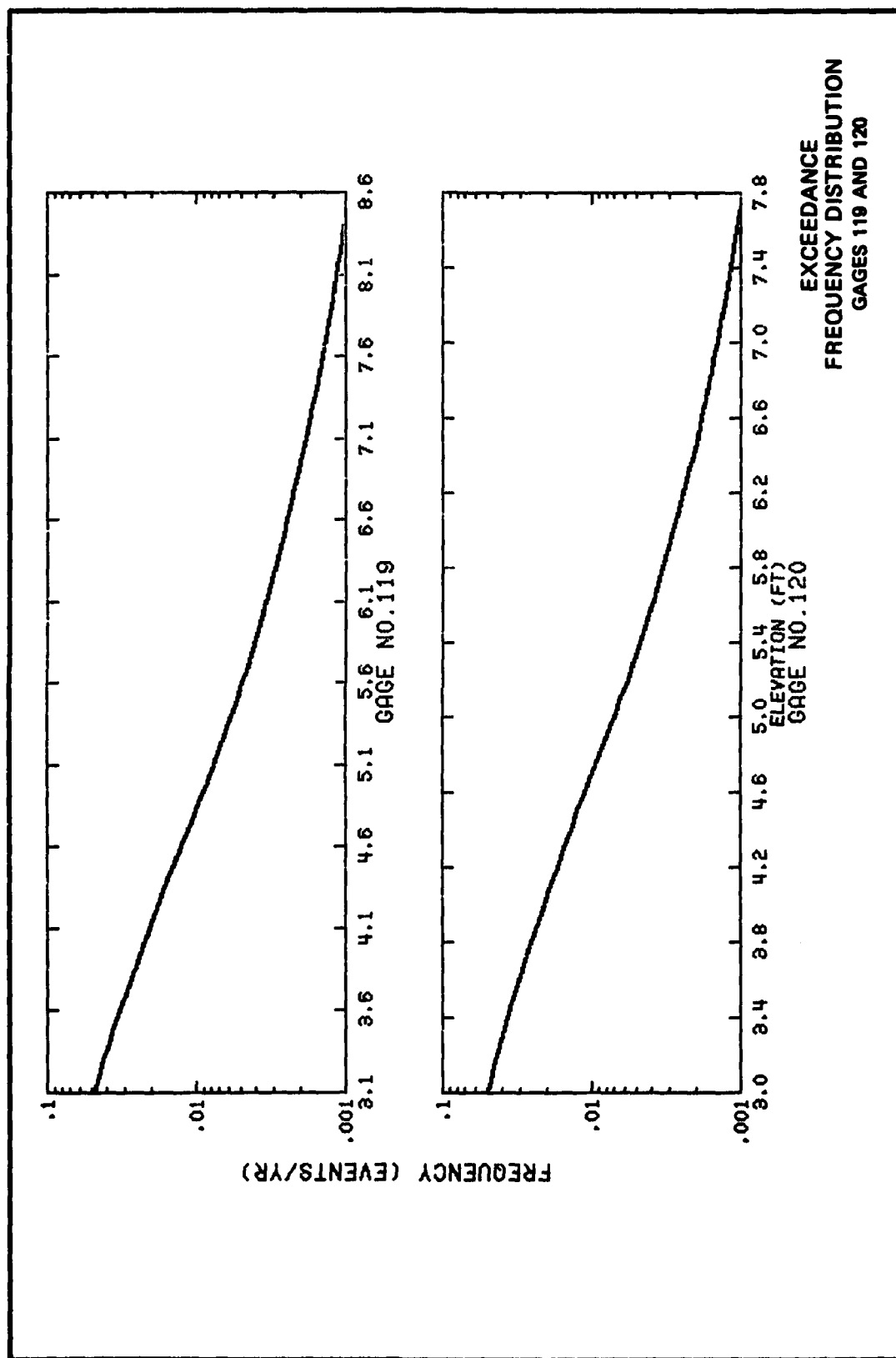
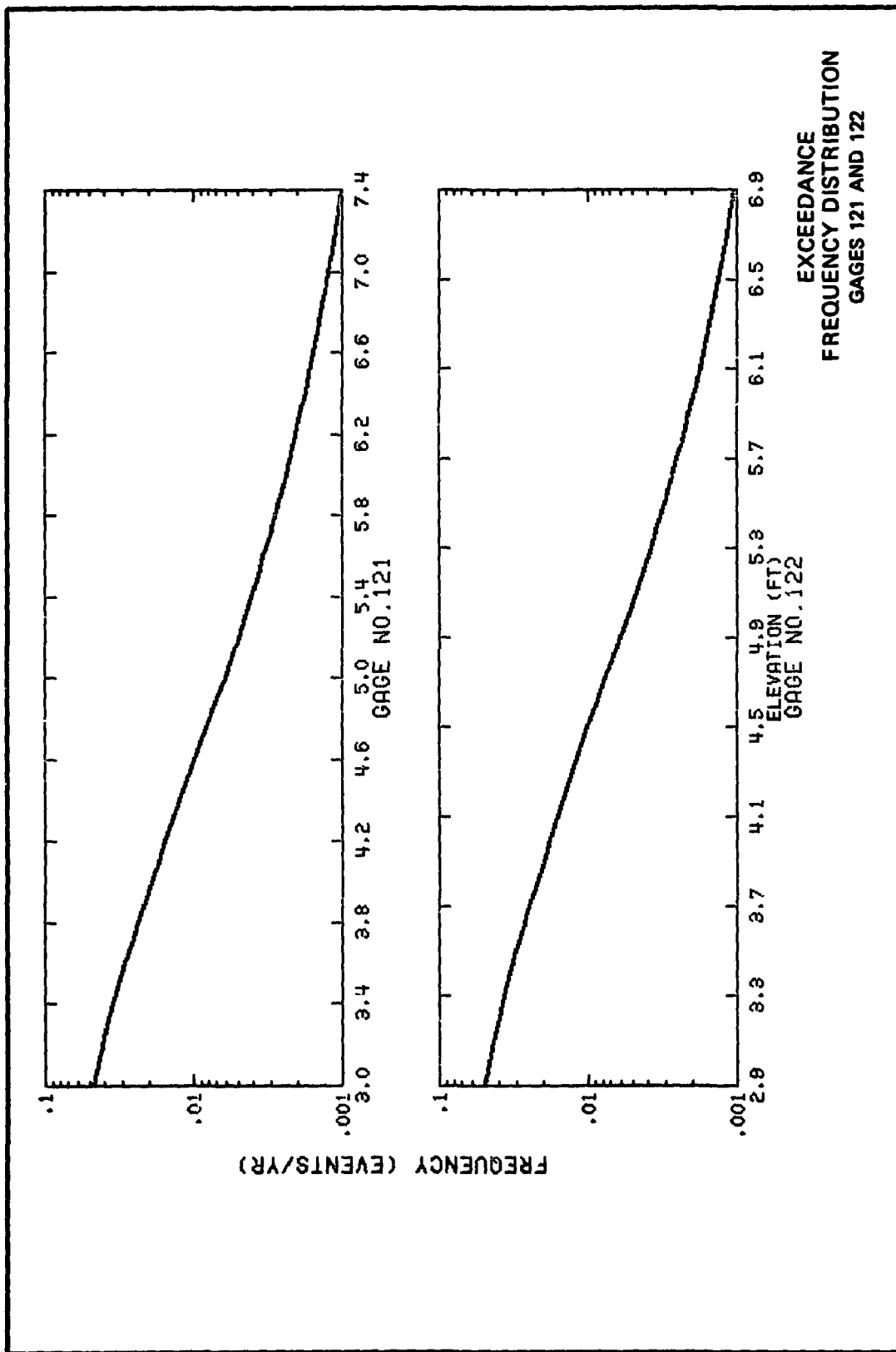


PLATE 60



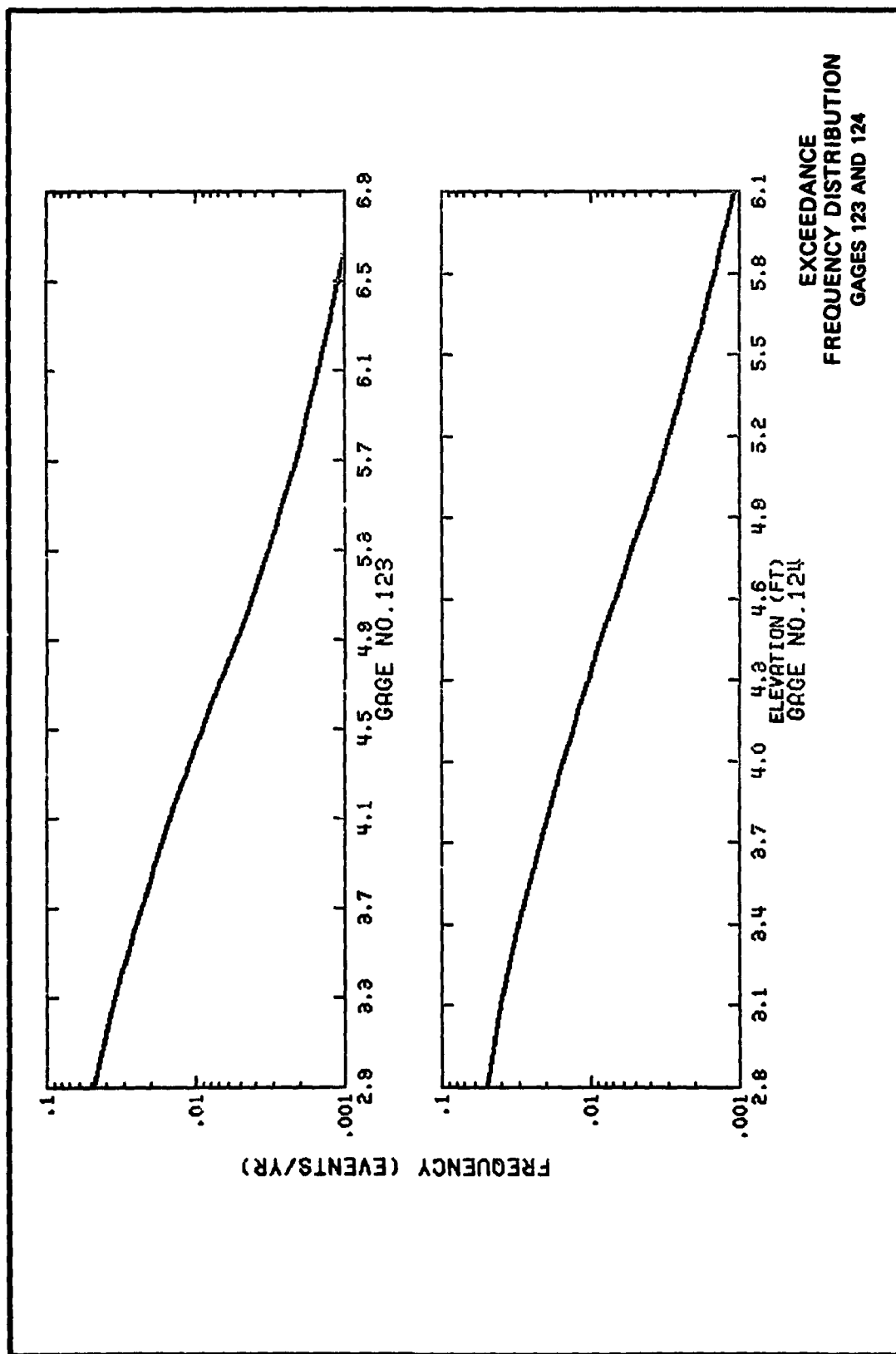
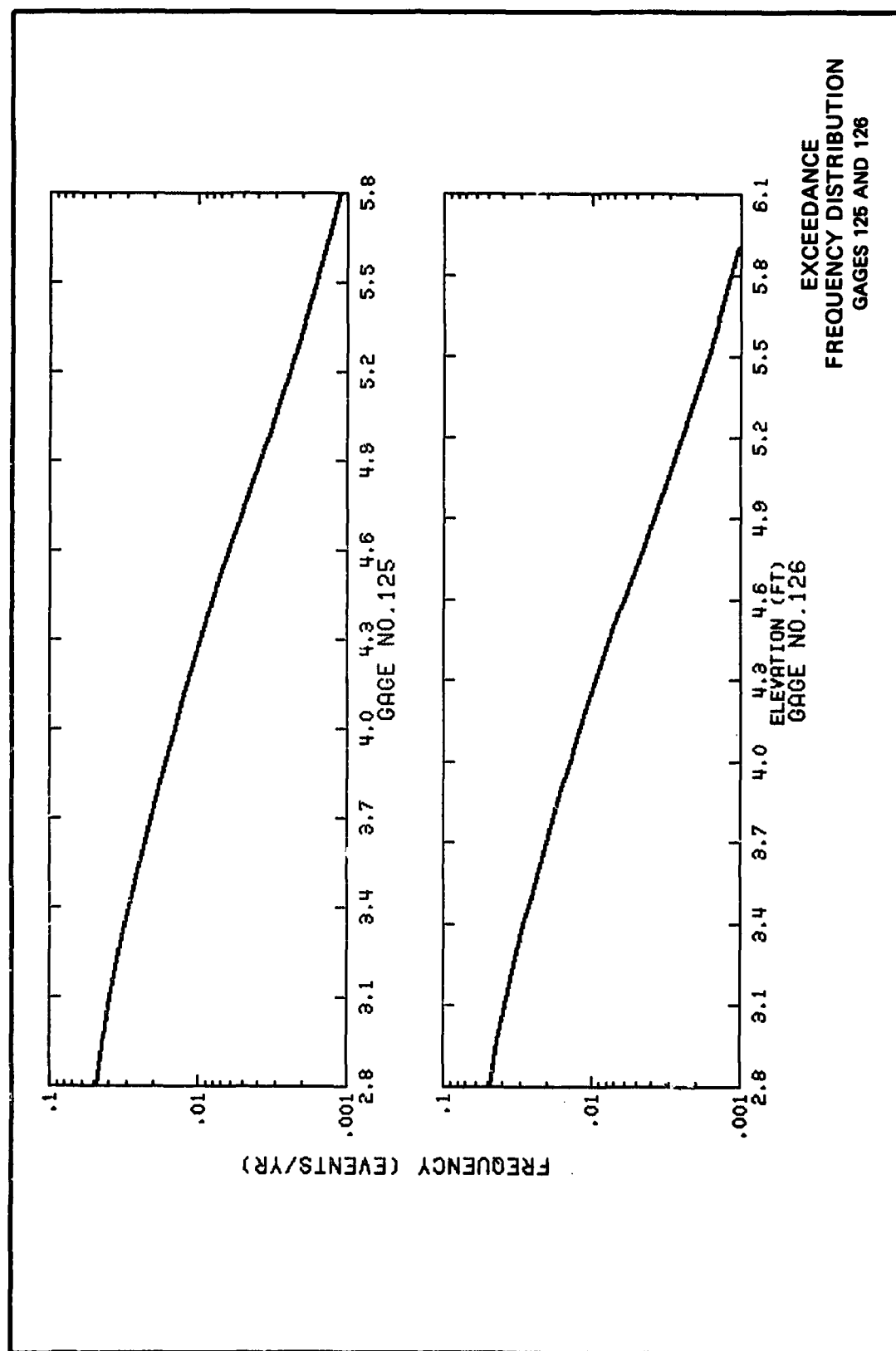


PLATE 62



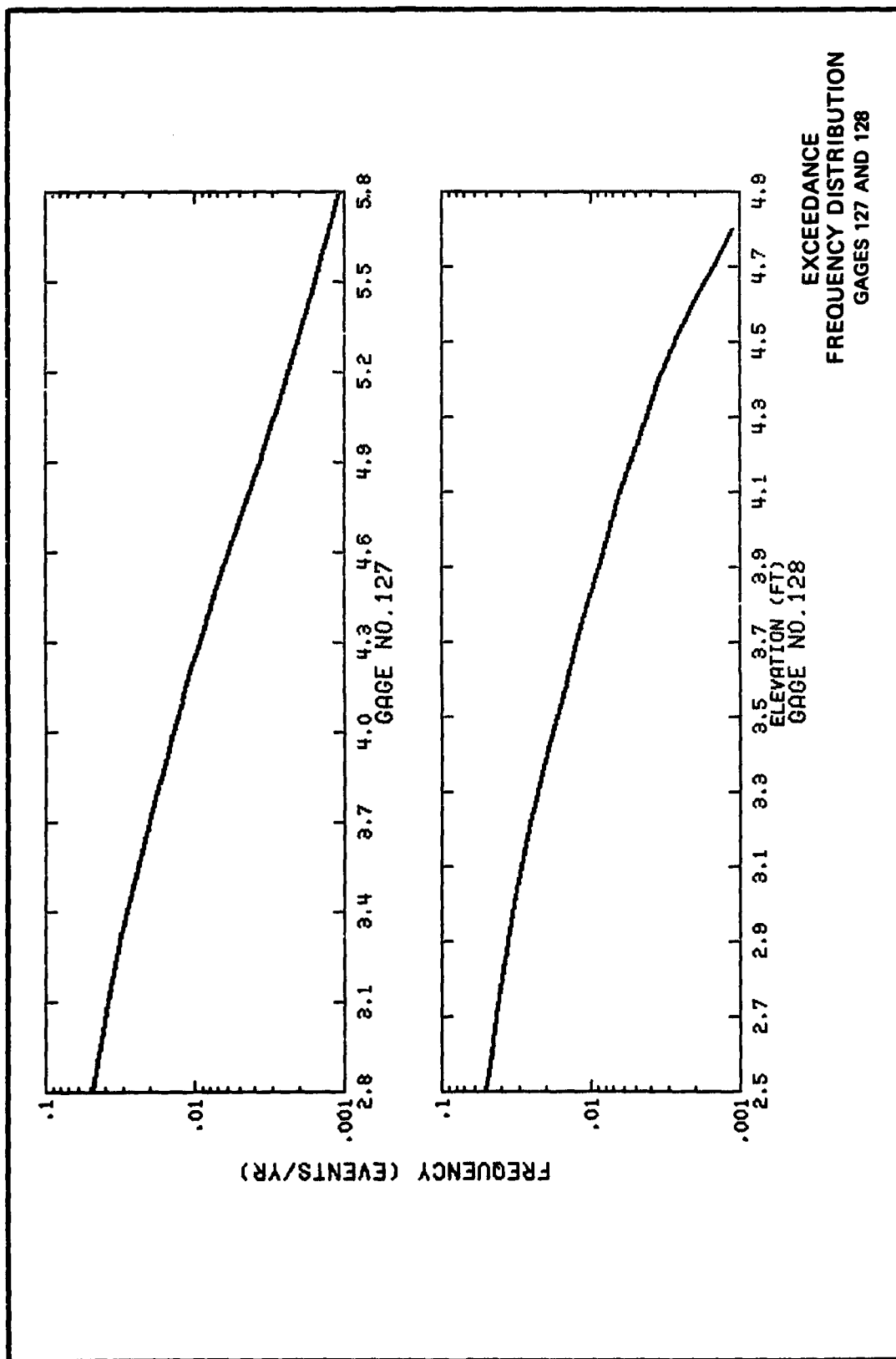
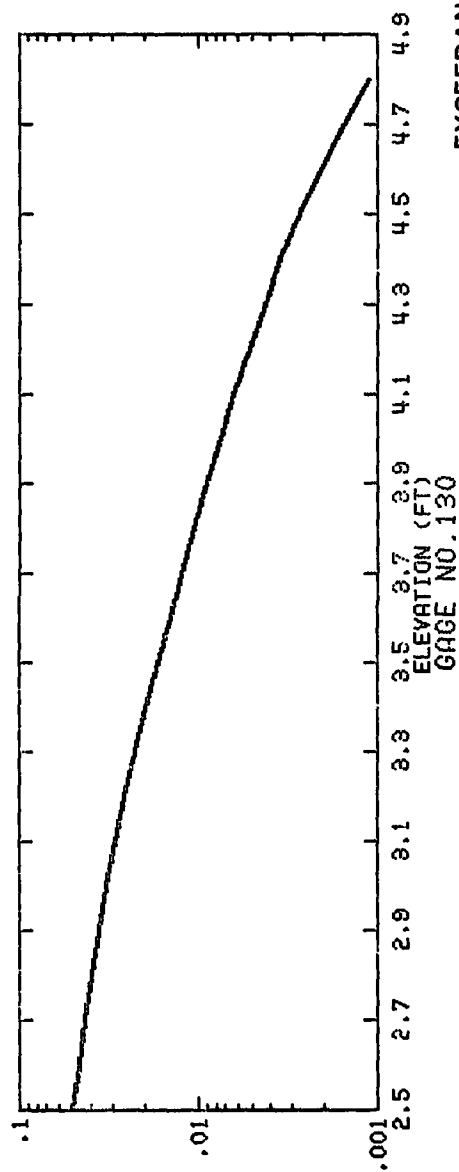
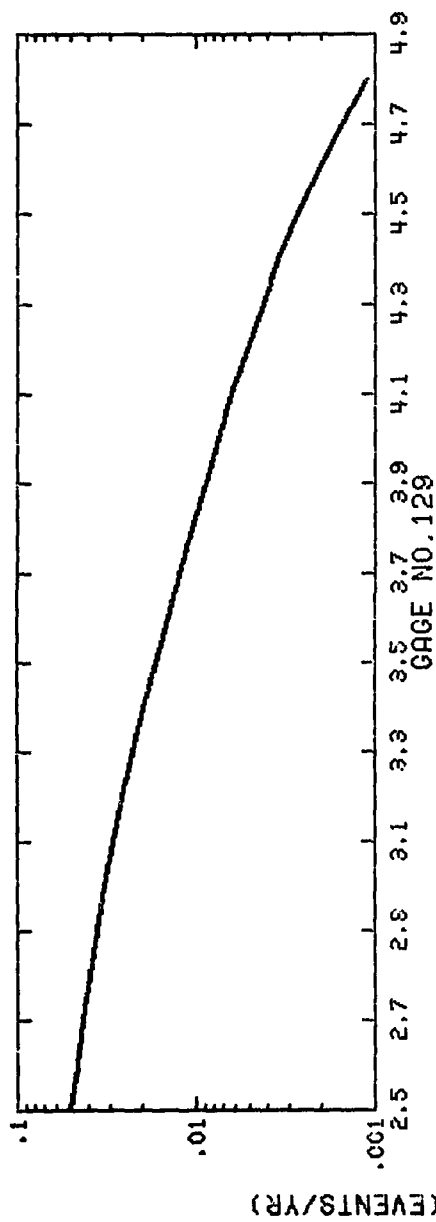
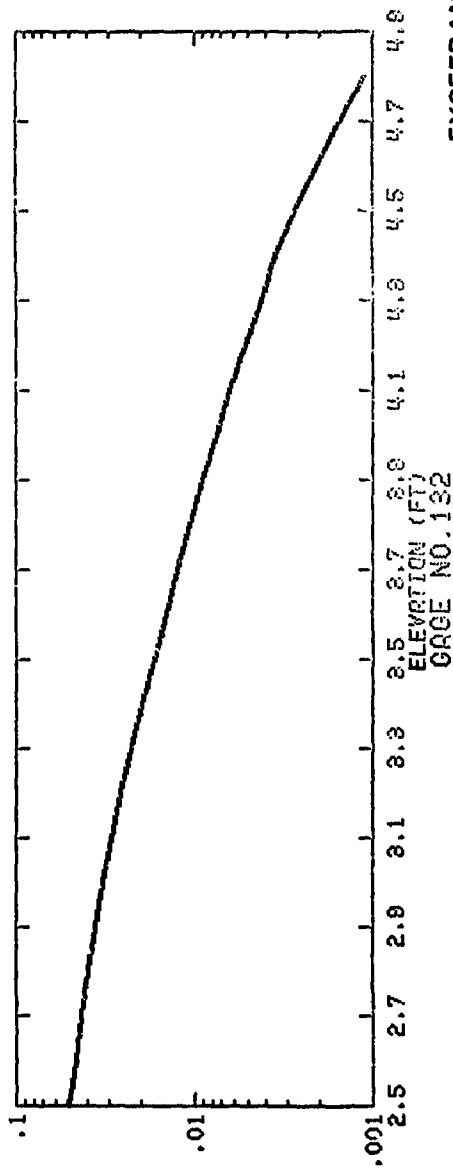
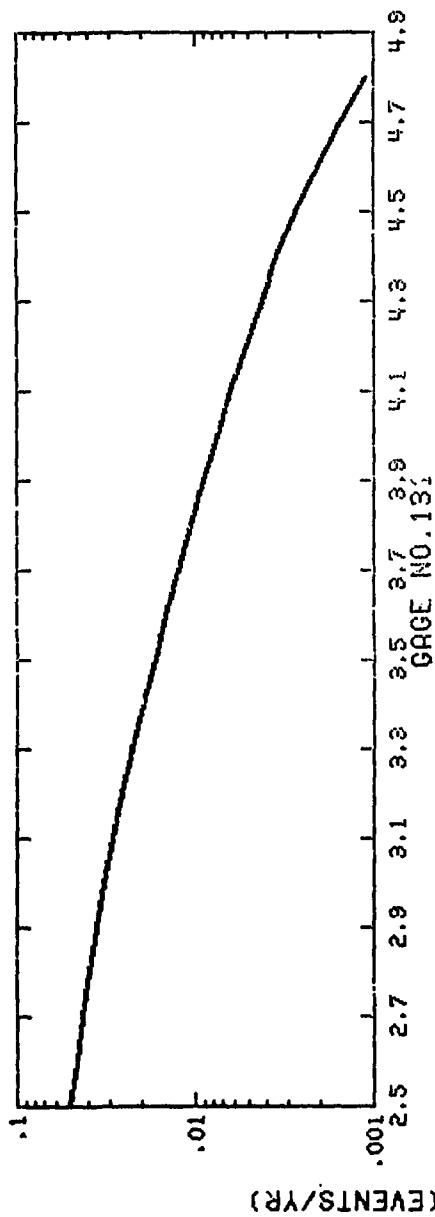


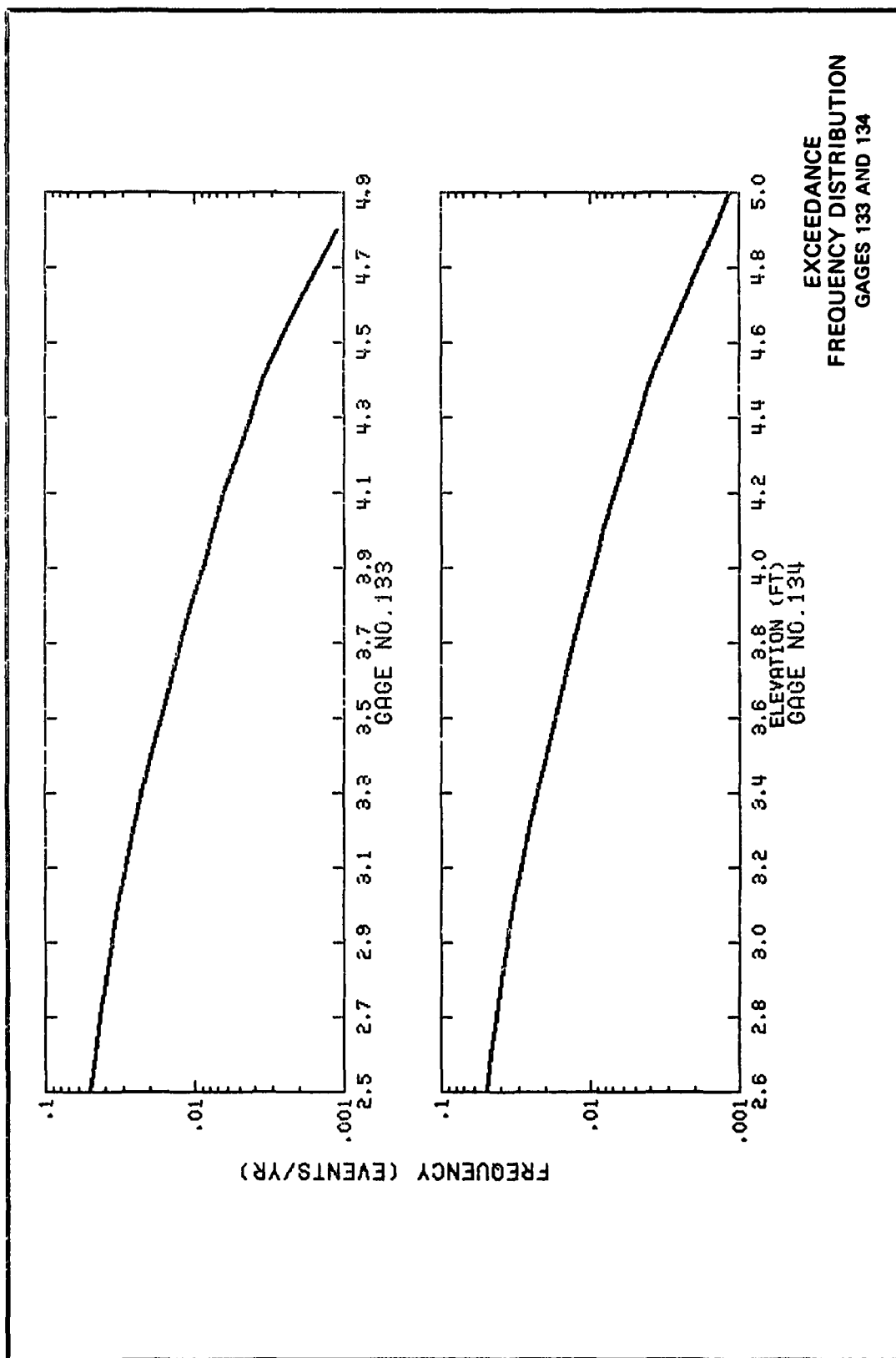
PLATE 64

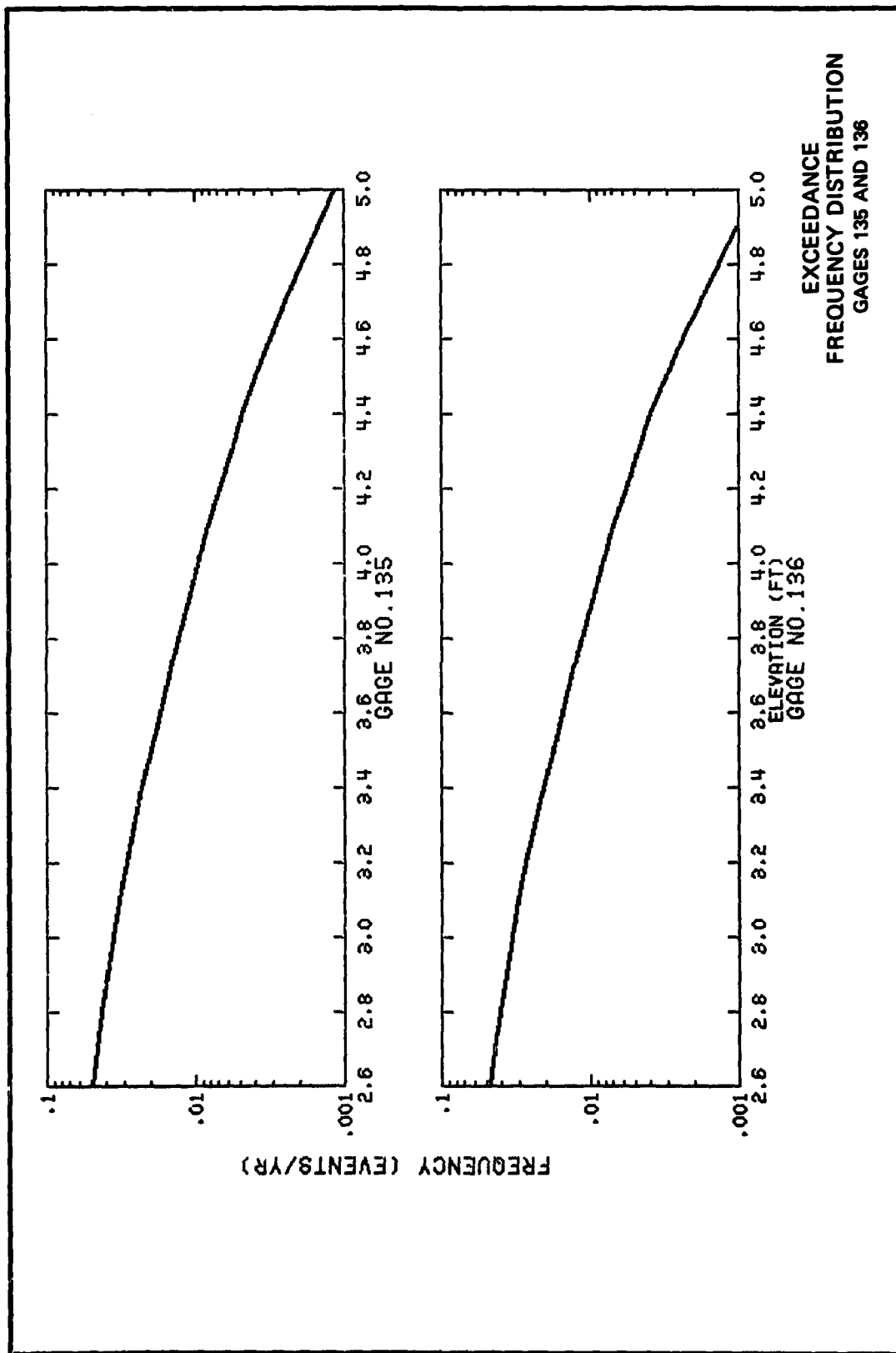


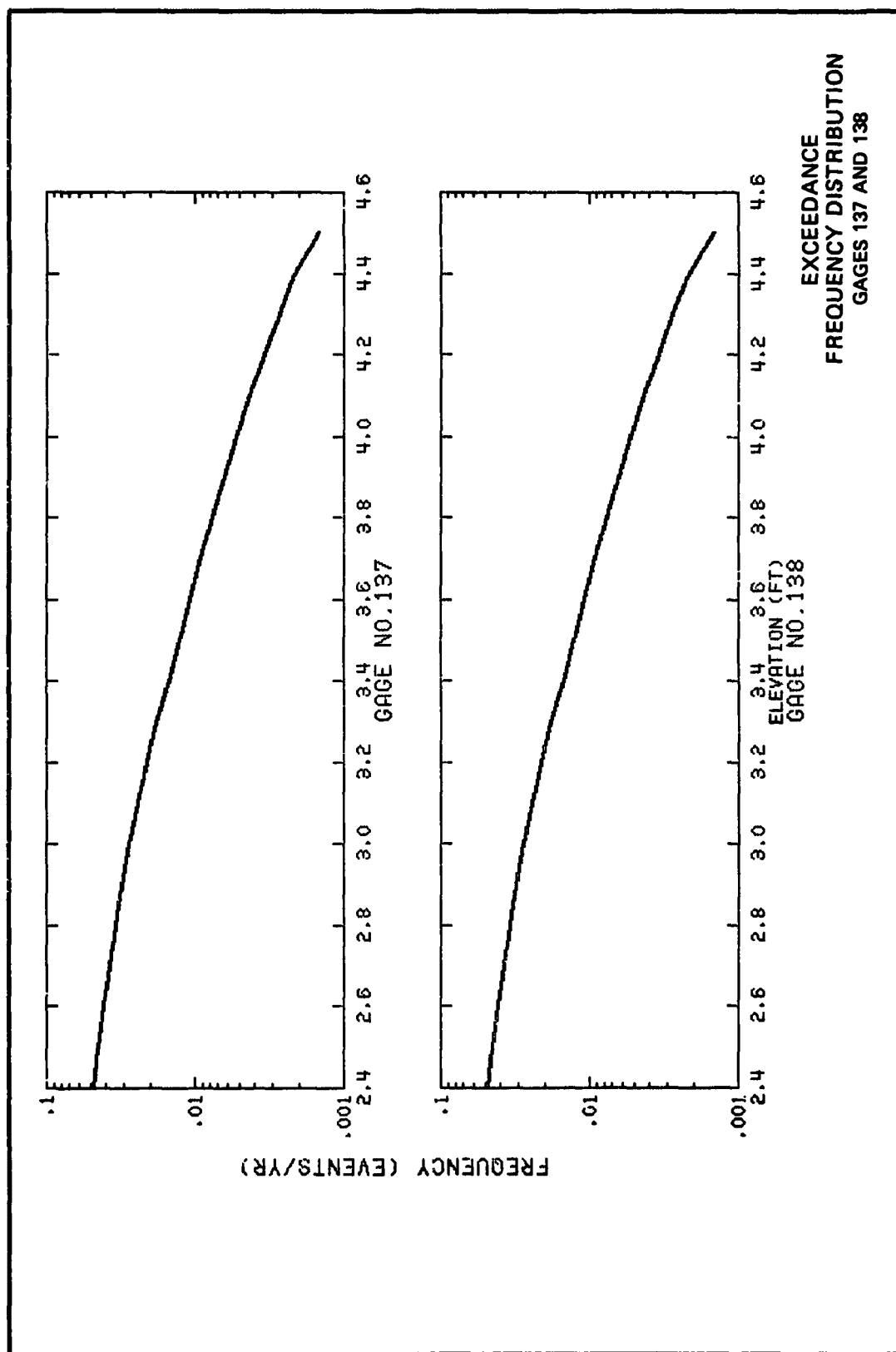
EXCEEDANCE
FREQUENCY DISTRIBUTION
GAGES 129 AND 130

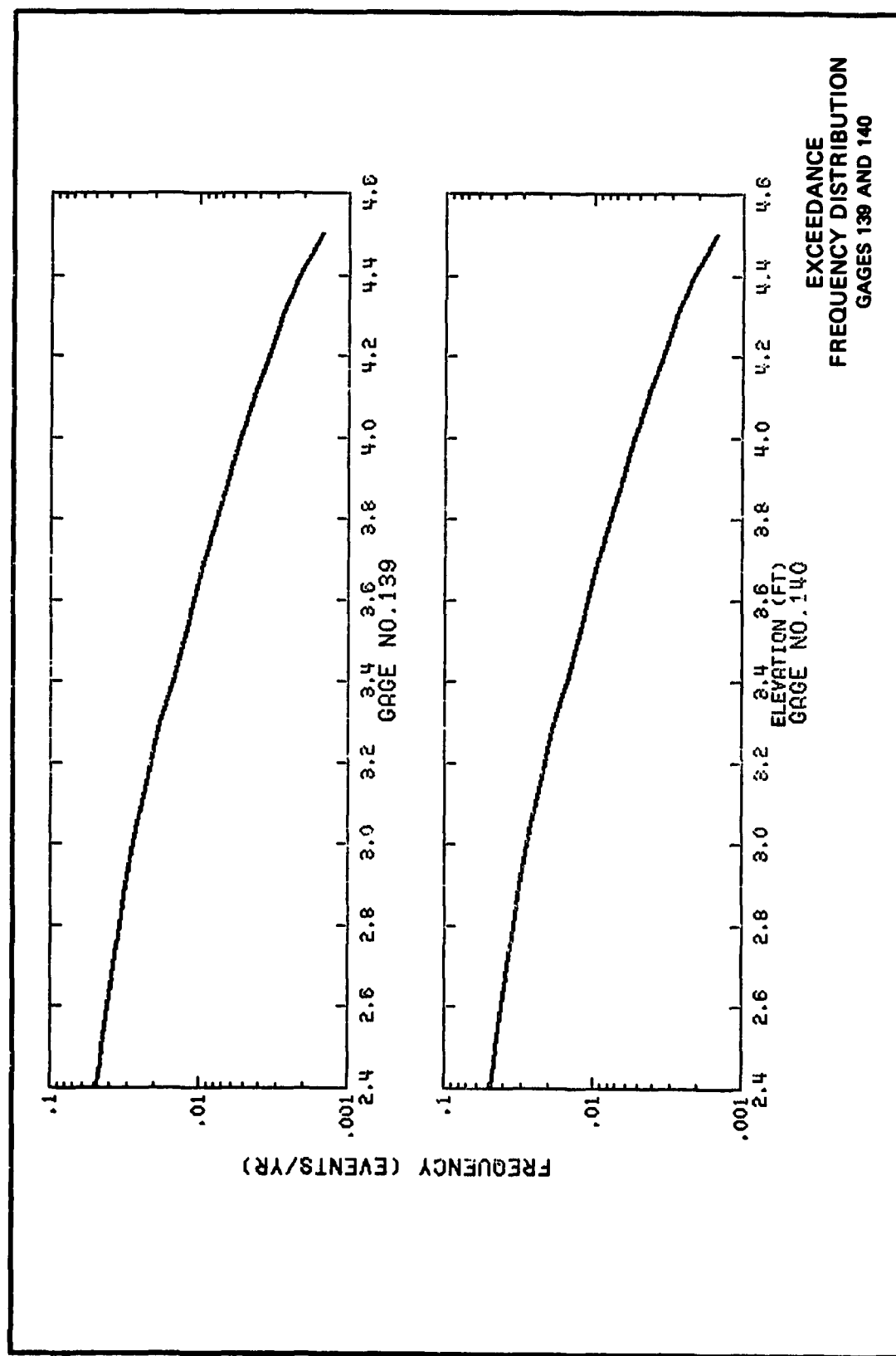


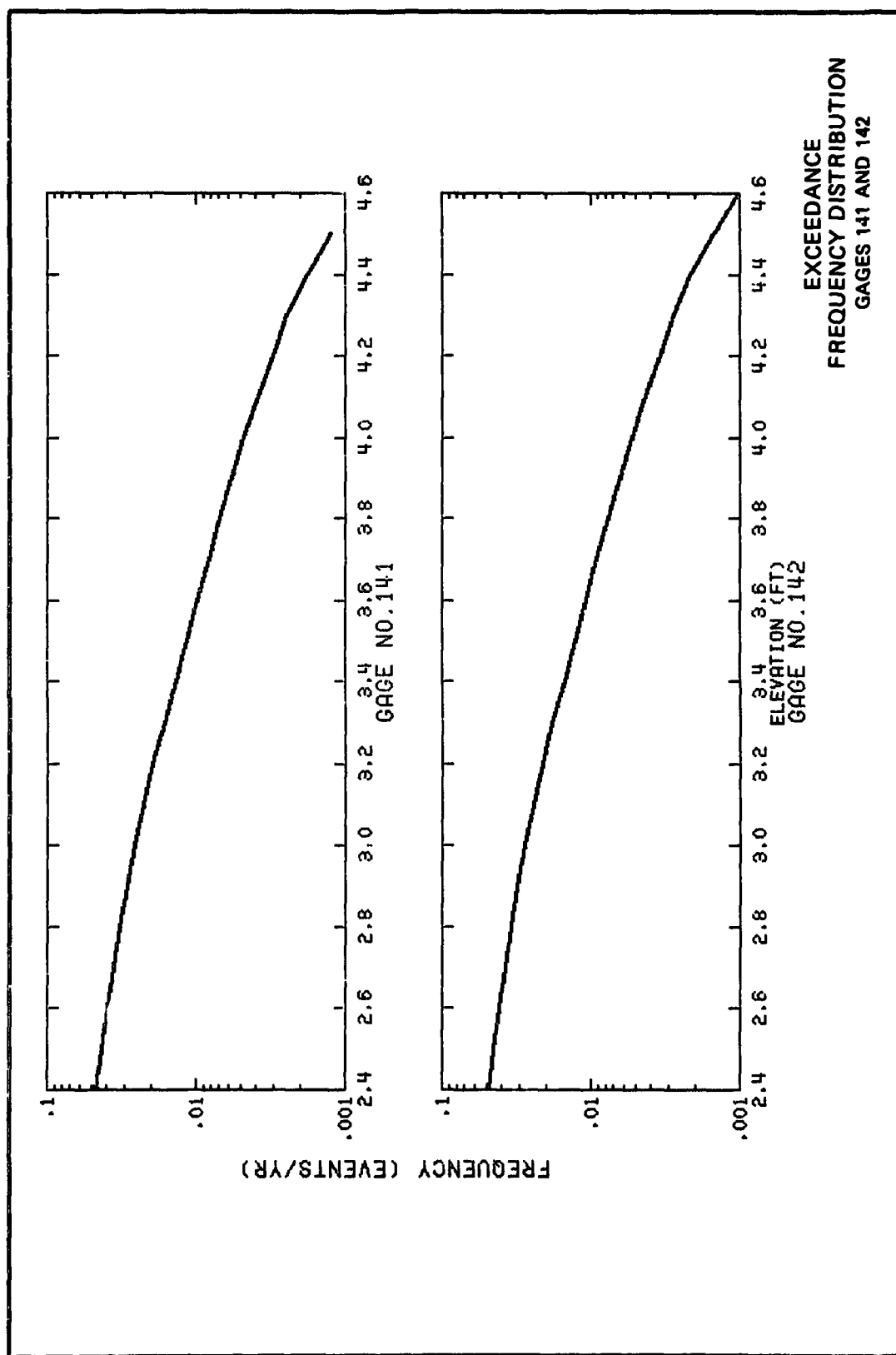
EXCEEDANCE
FREQUENCY DISTRIBUTION
GAGES 131 AND 132











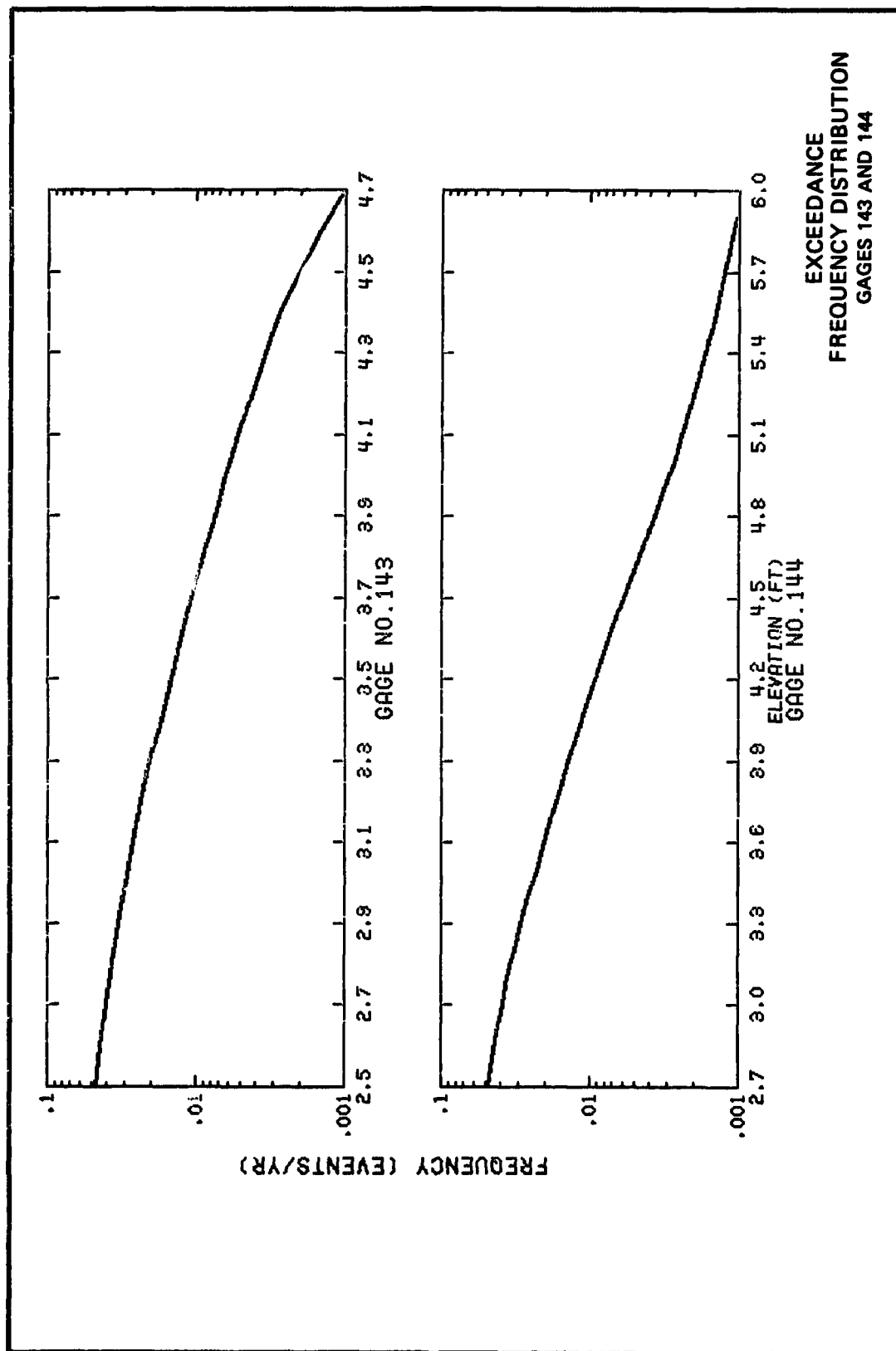
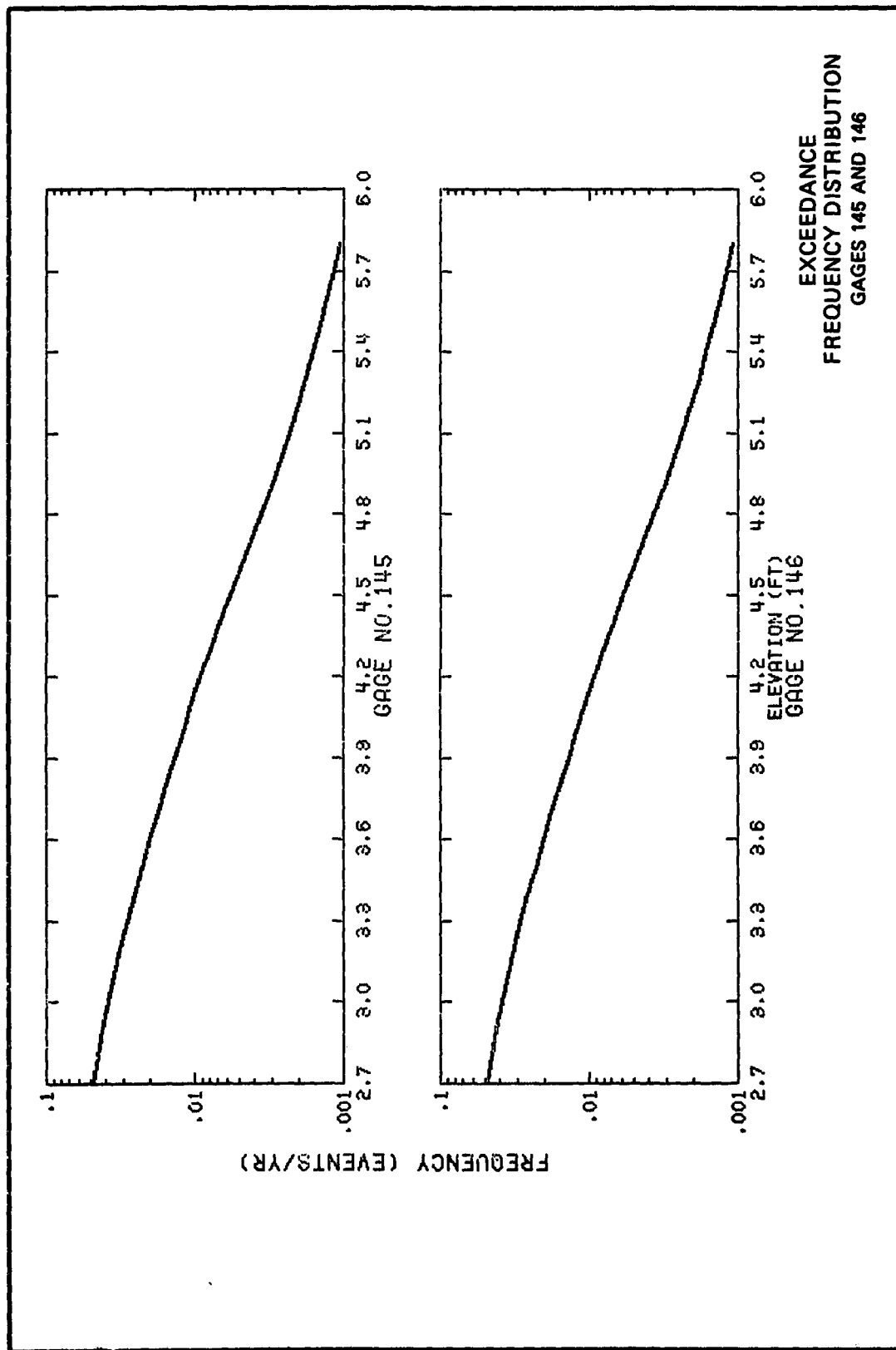
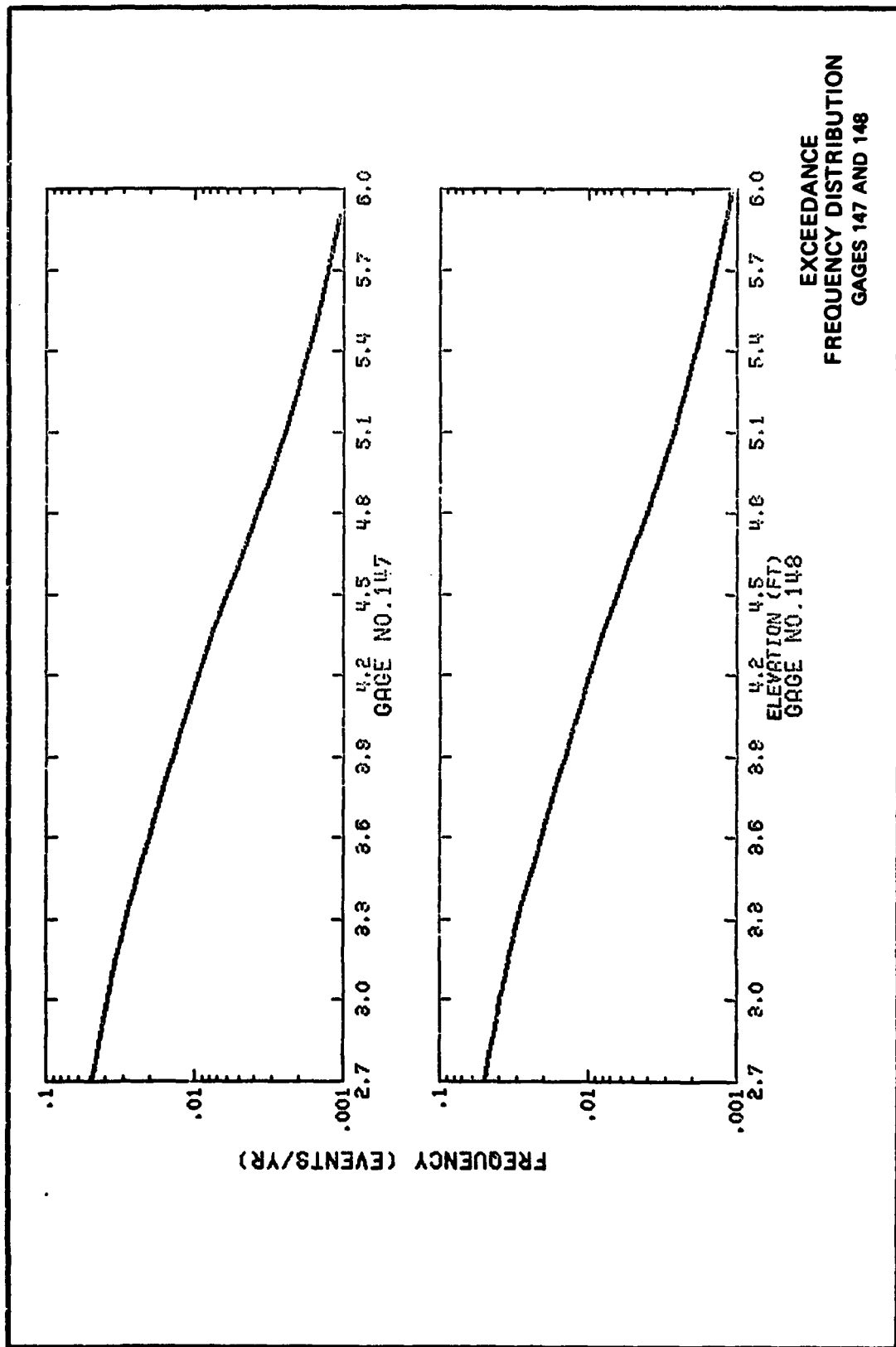
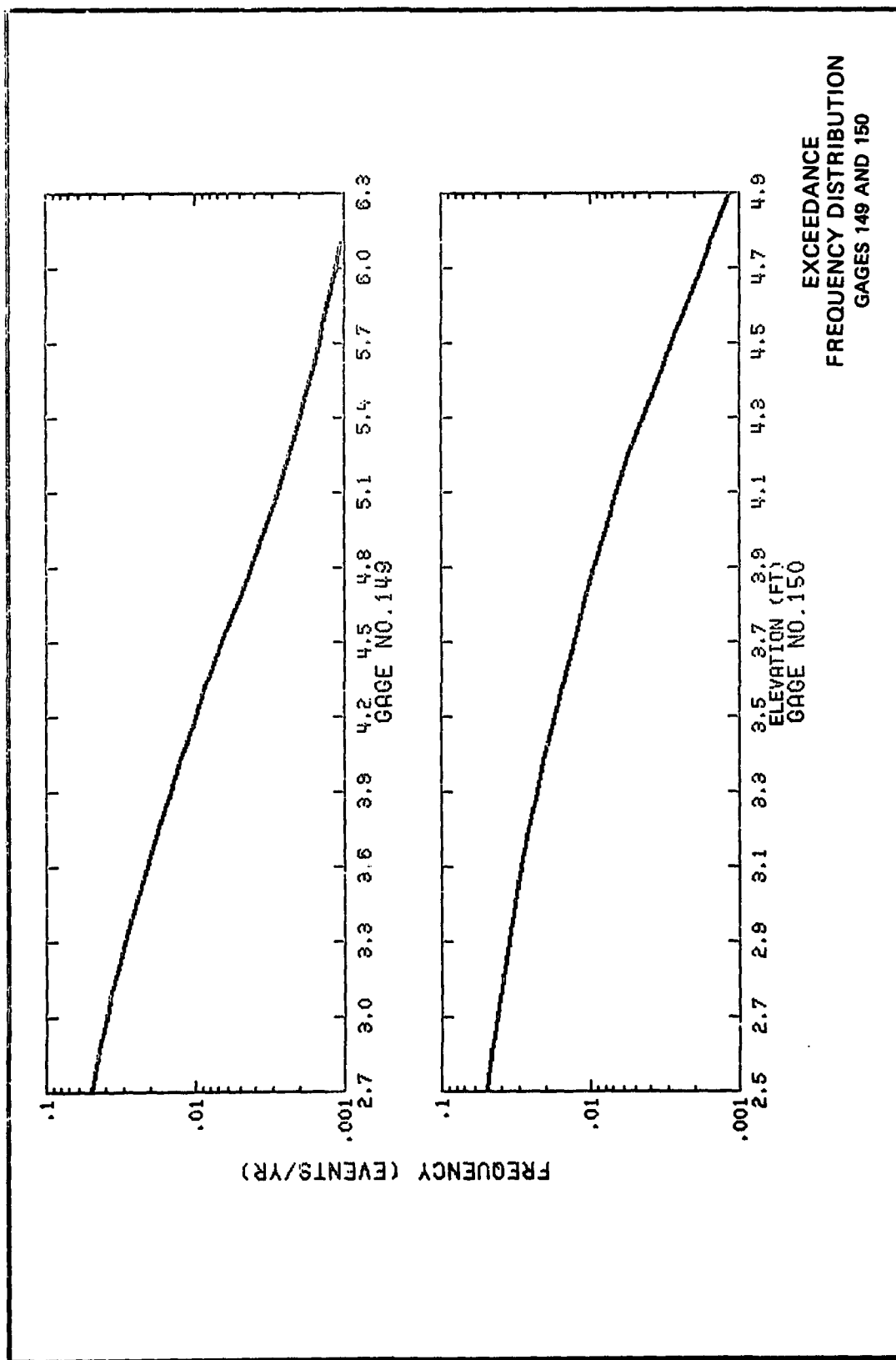
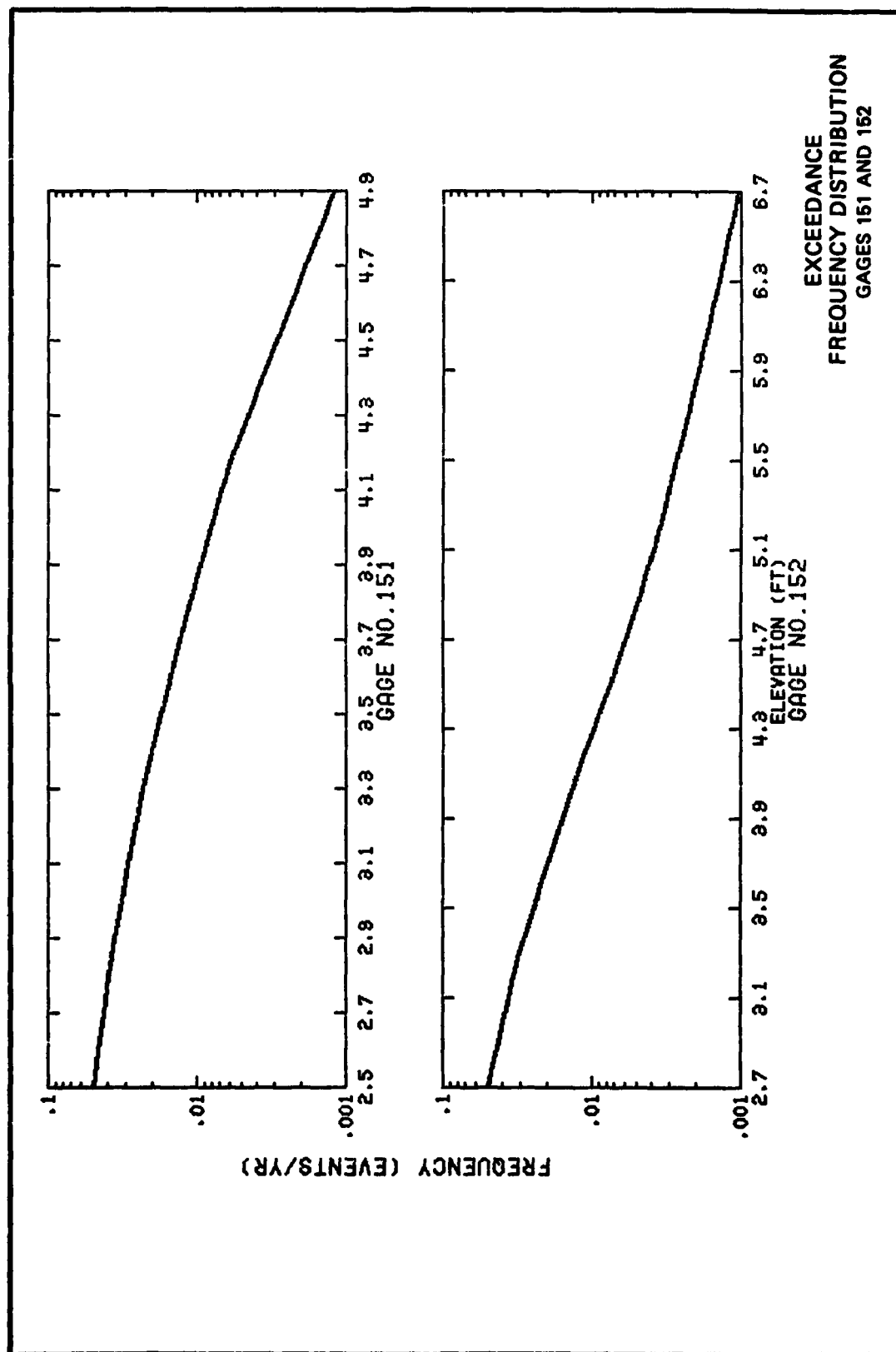


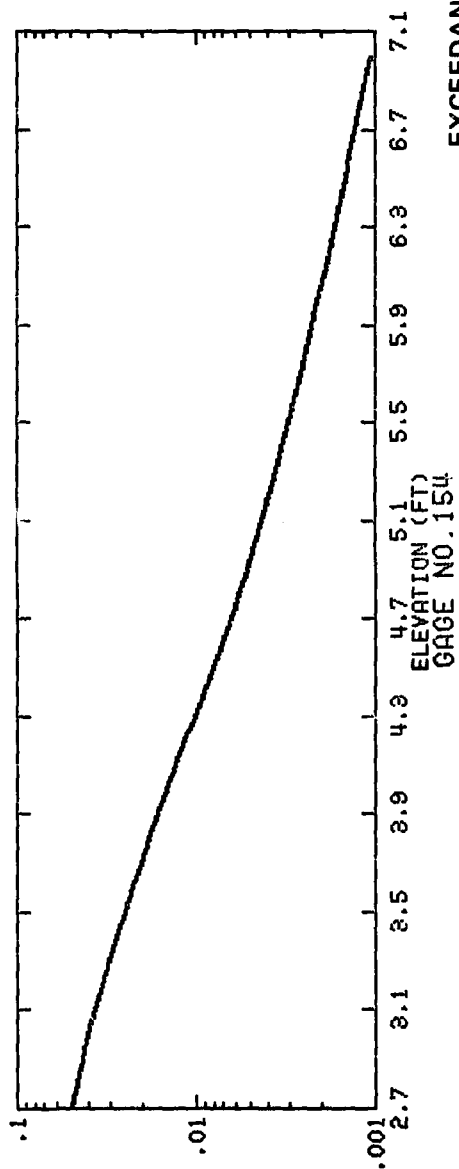
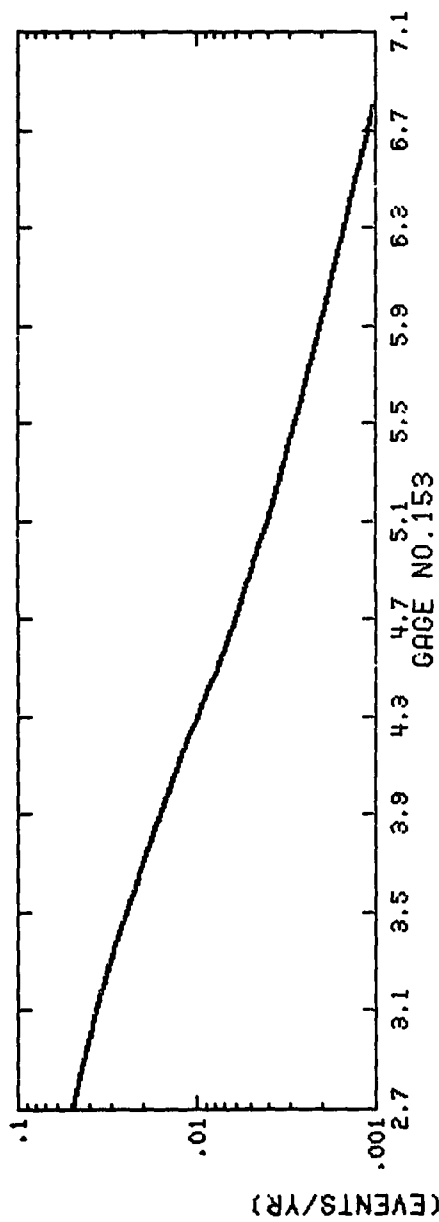
PLATE 72



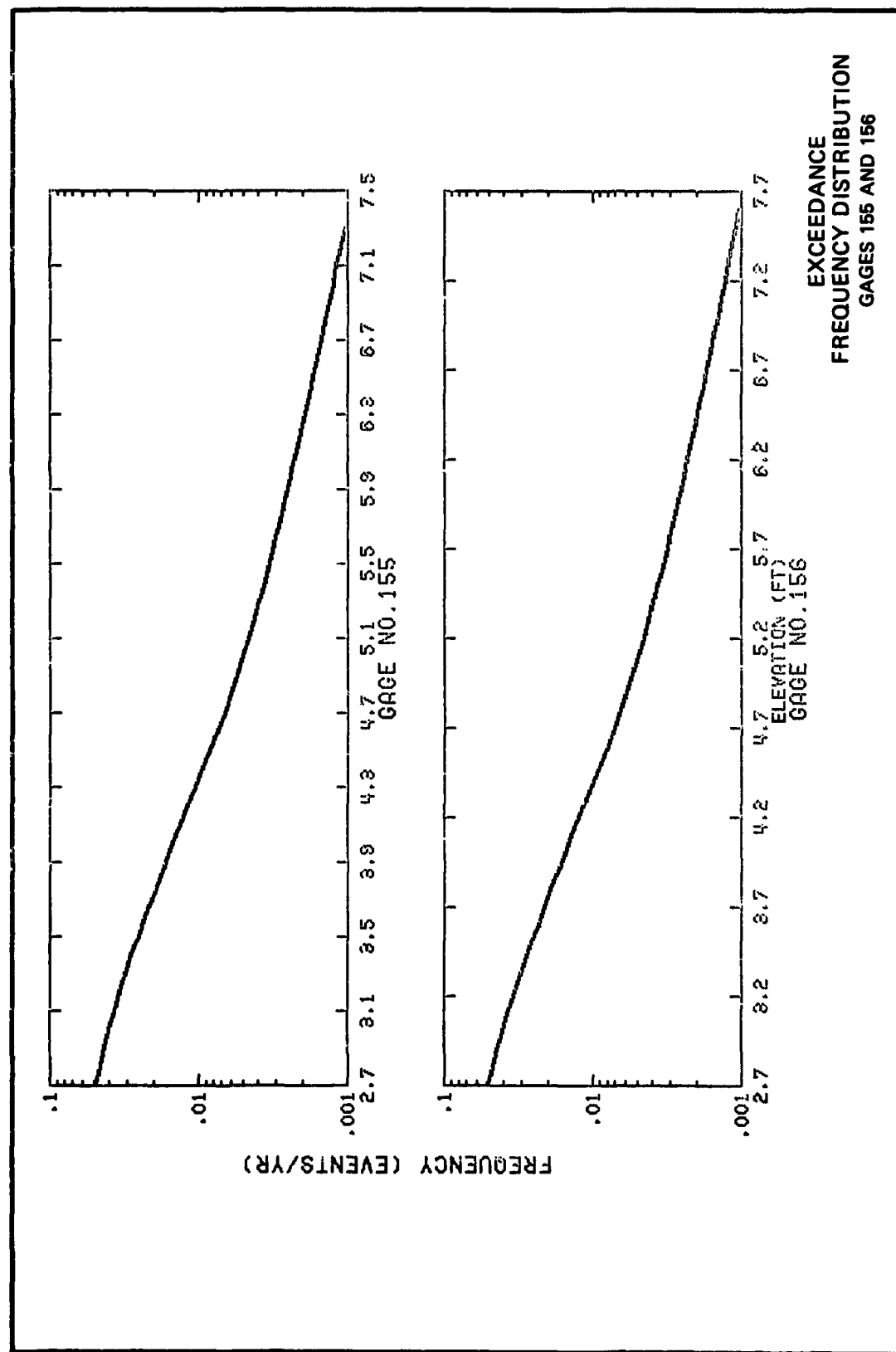


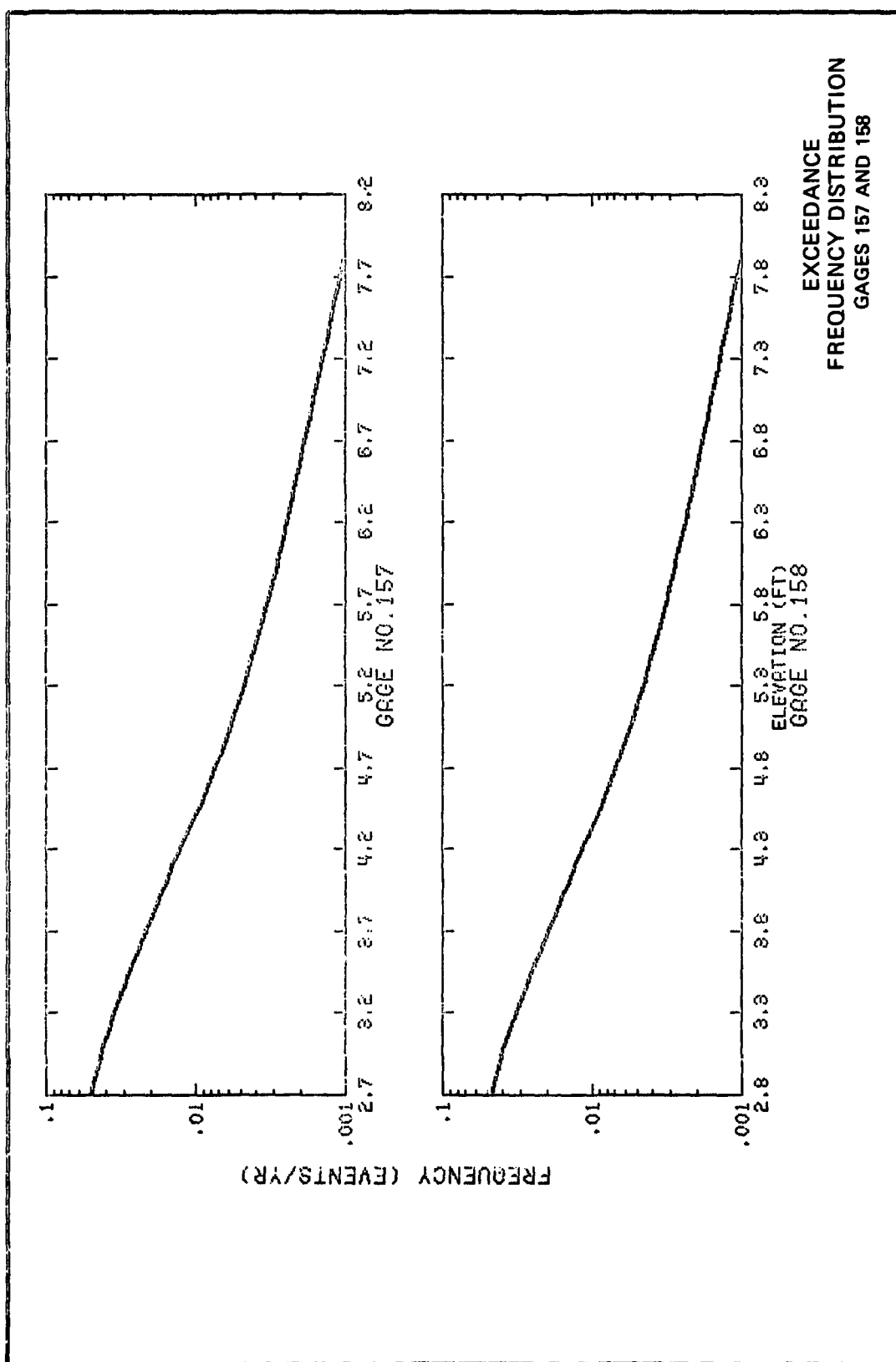






EXCEEDANCE
FREQUENCY DISTRIBUTION
GAGES 153 AND 154





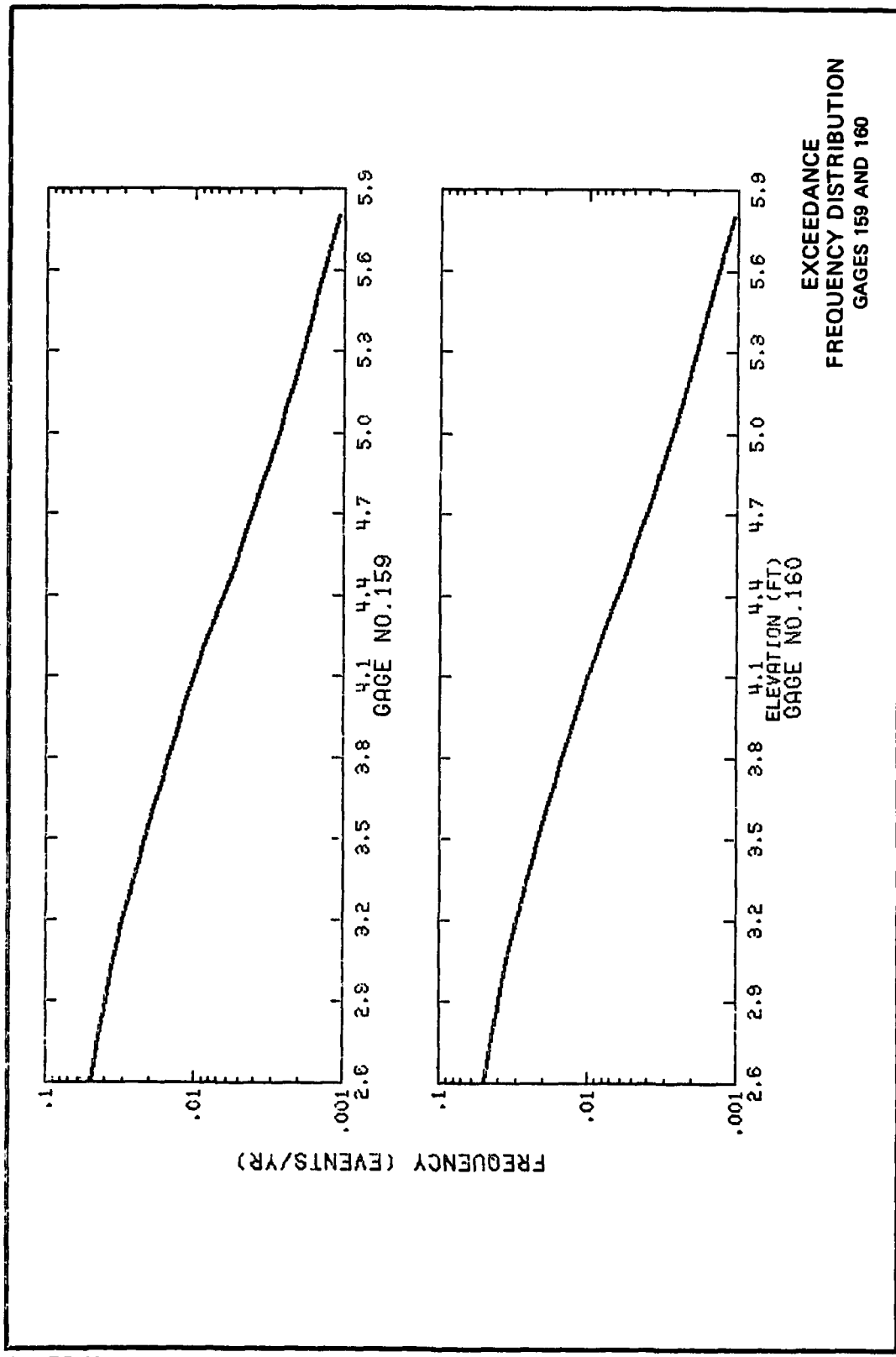
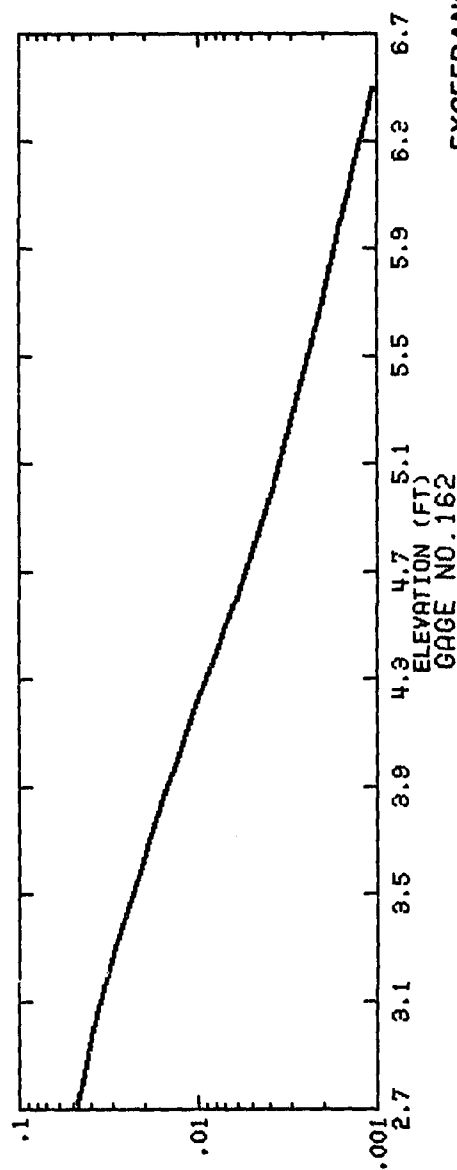
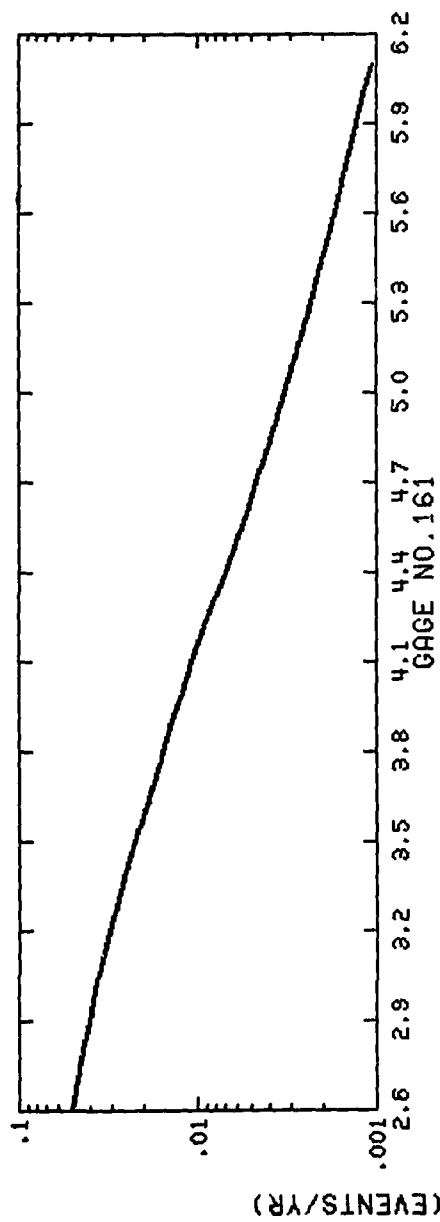
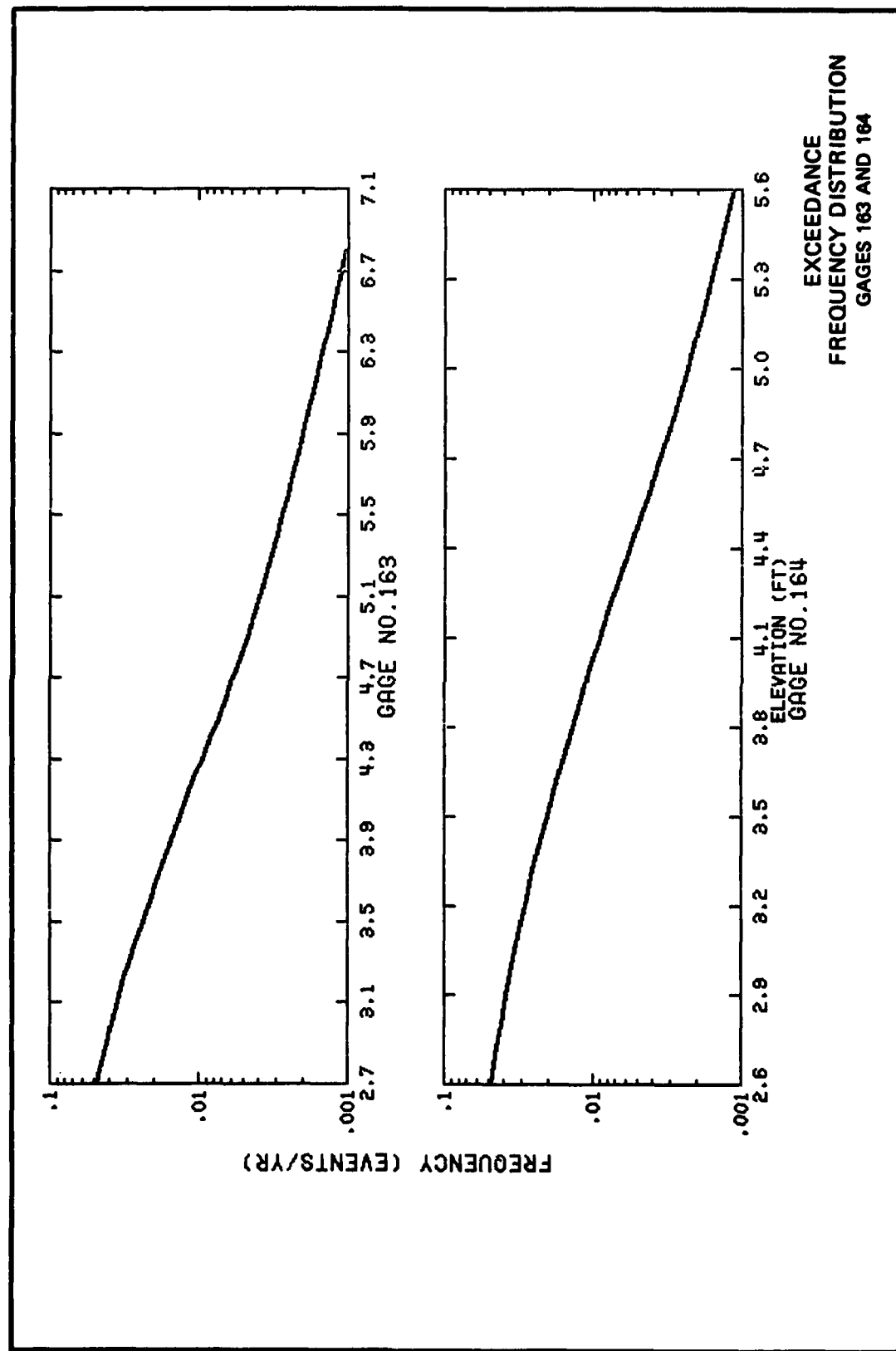
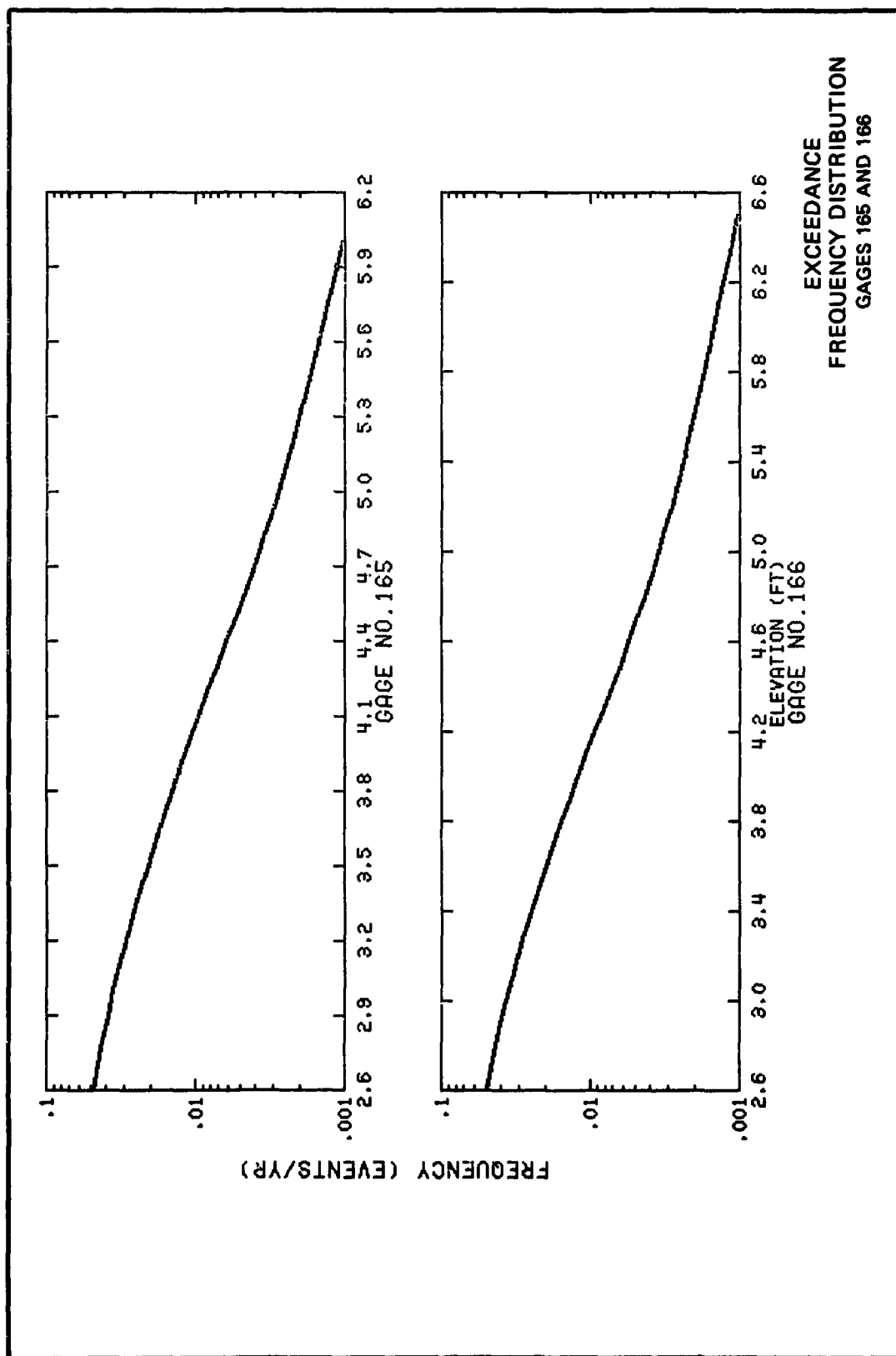


PLATE 80

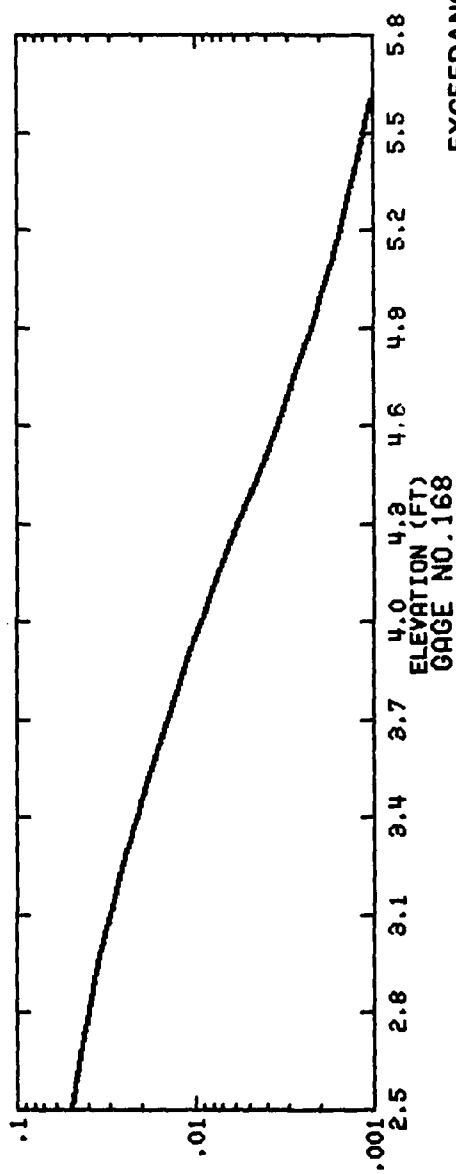
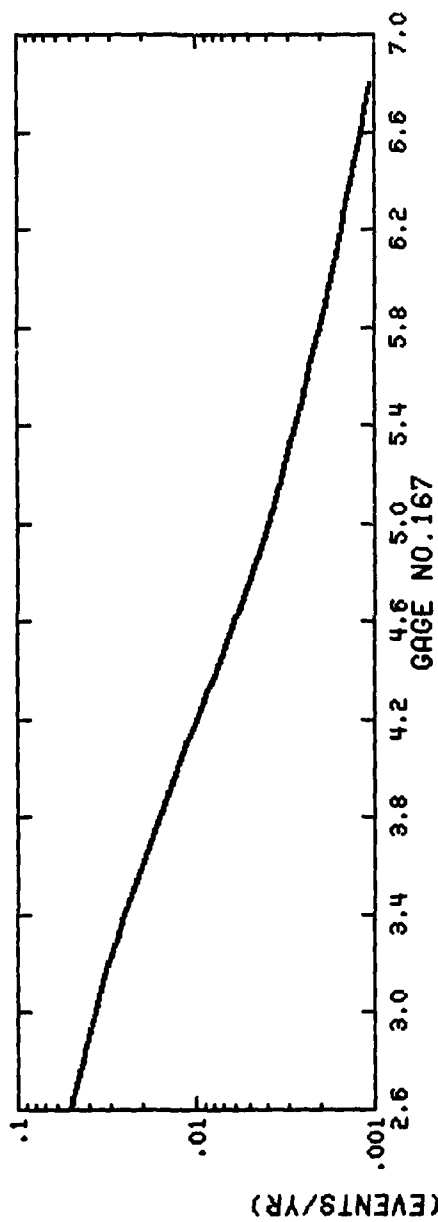


EXCEEDANCE
FREQUENCY DISTRIBUTION
GAGES 161 AND 162

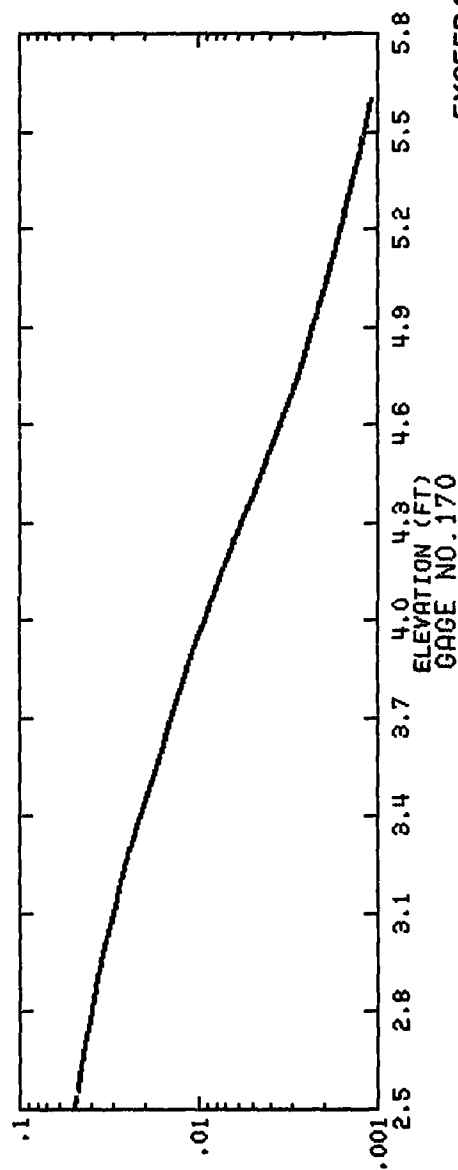
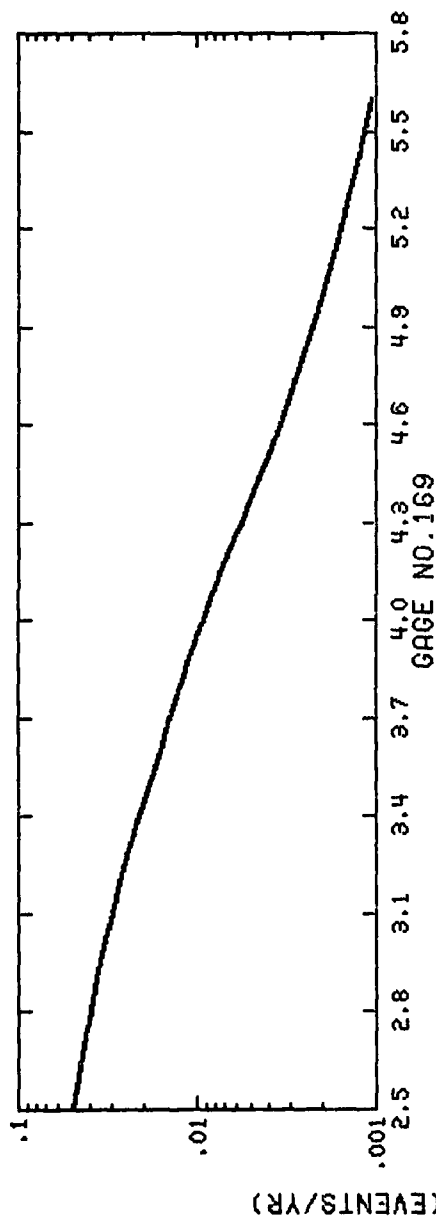




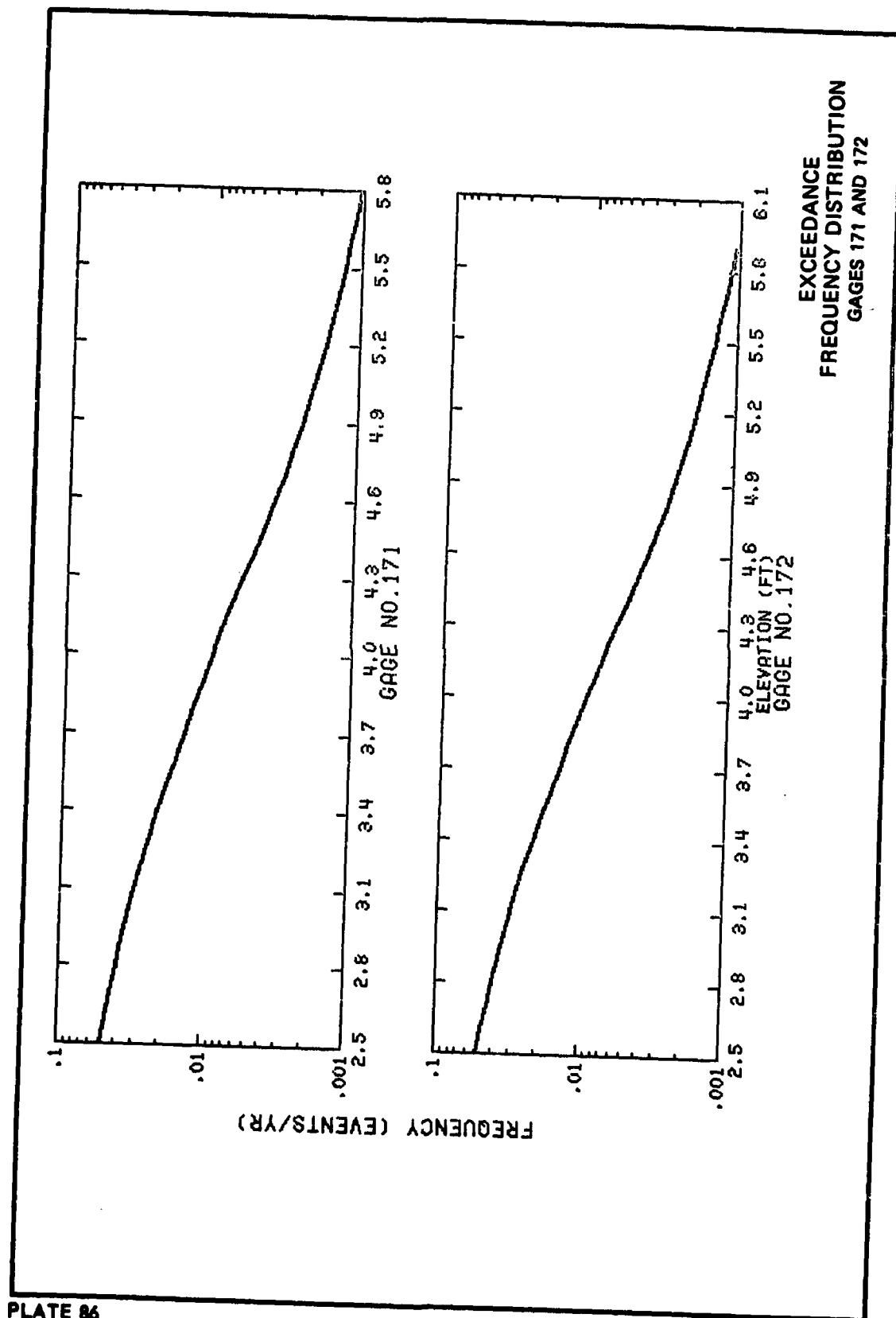
EXCEEDANCE
FREQUENCY DISTRIBUTION
GAGES 165 AND 166

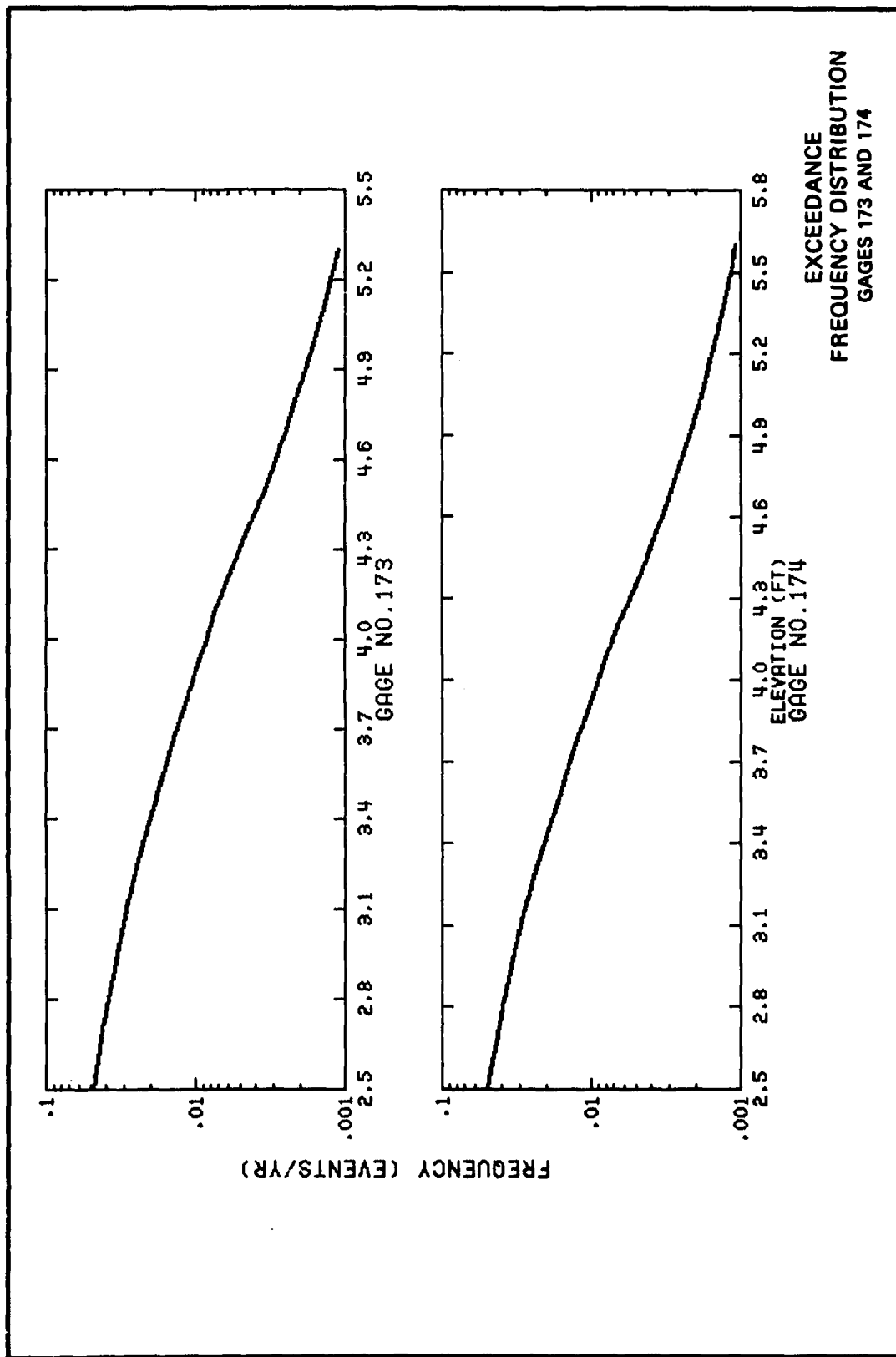


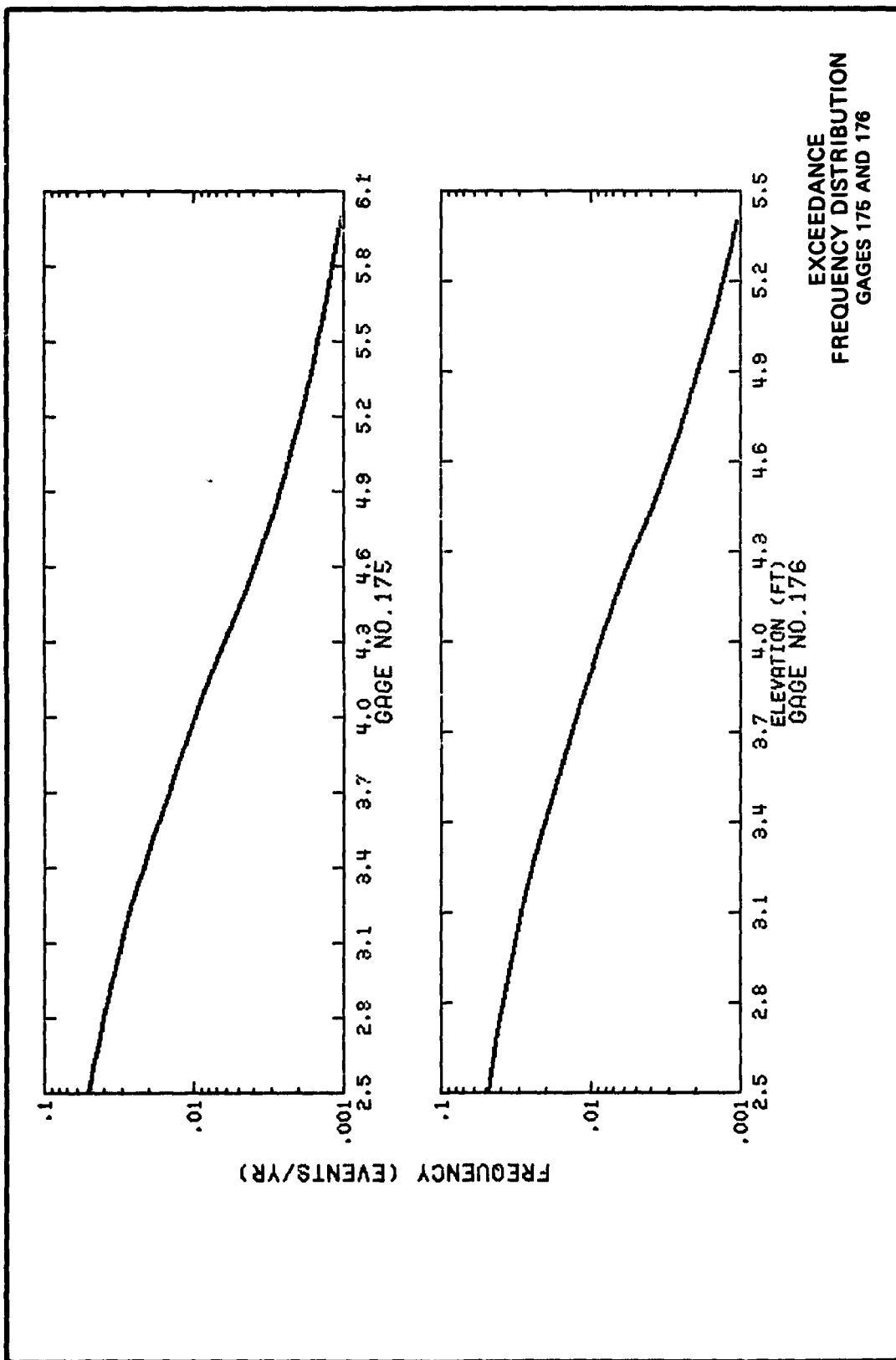
EXCEEDANCE
FREQUENCY DISTRIBUTION
GAGES 167 AND 168

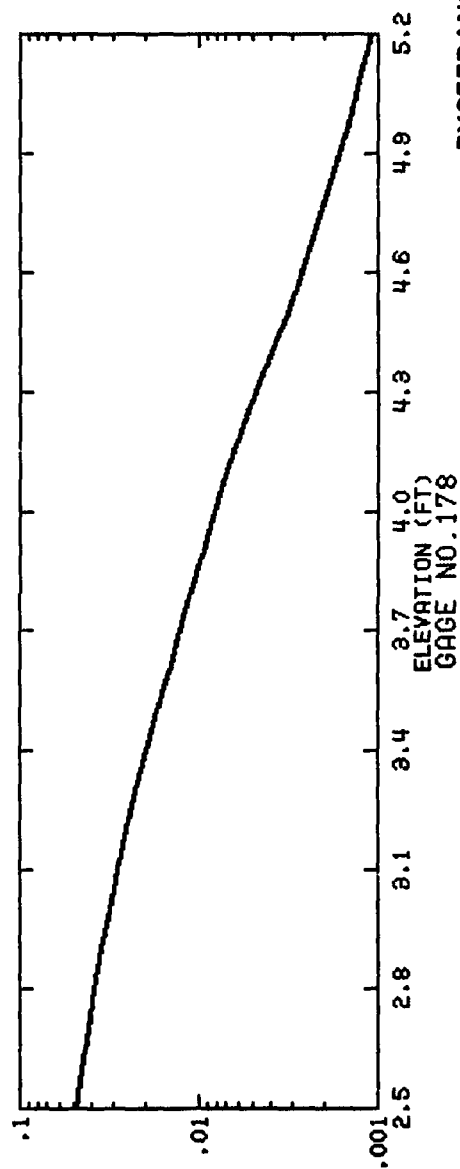
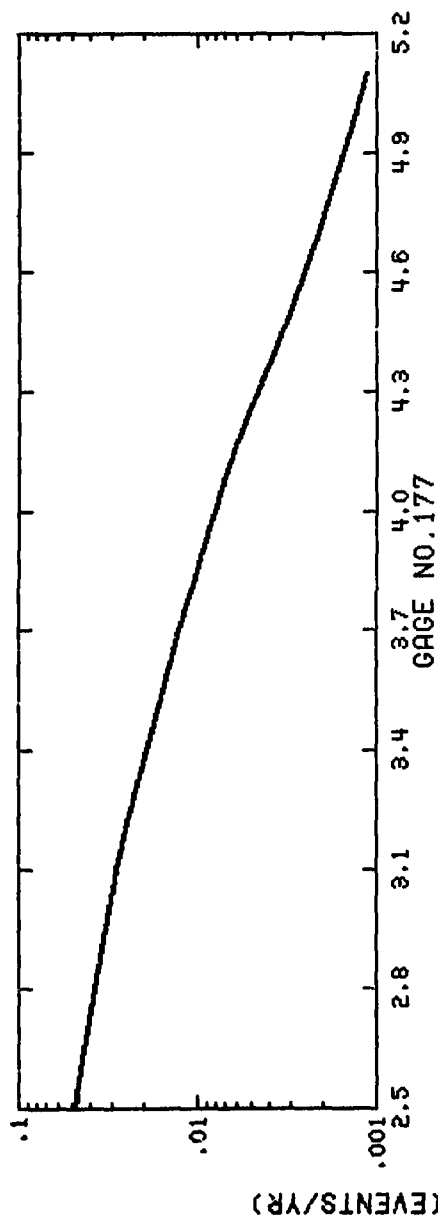


EXCEEDANCE
FREQUENCY DISTRIBUTION
GAGES 169 AND 170

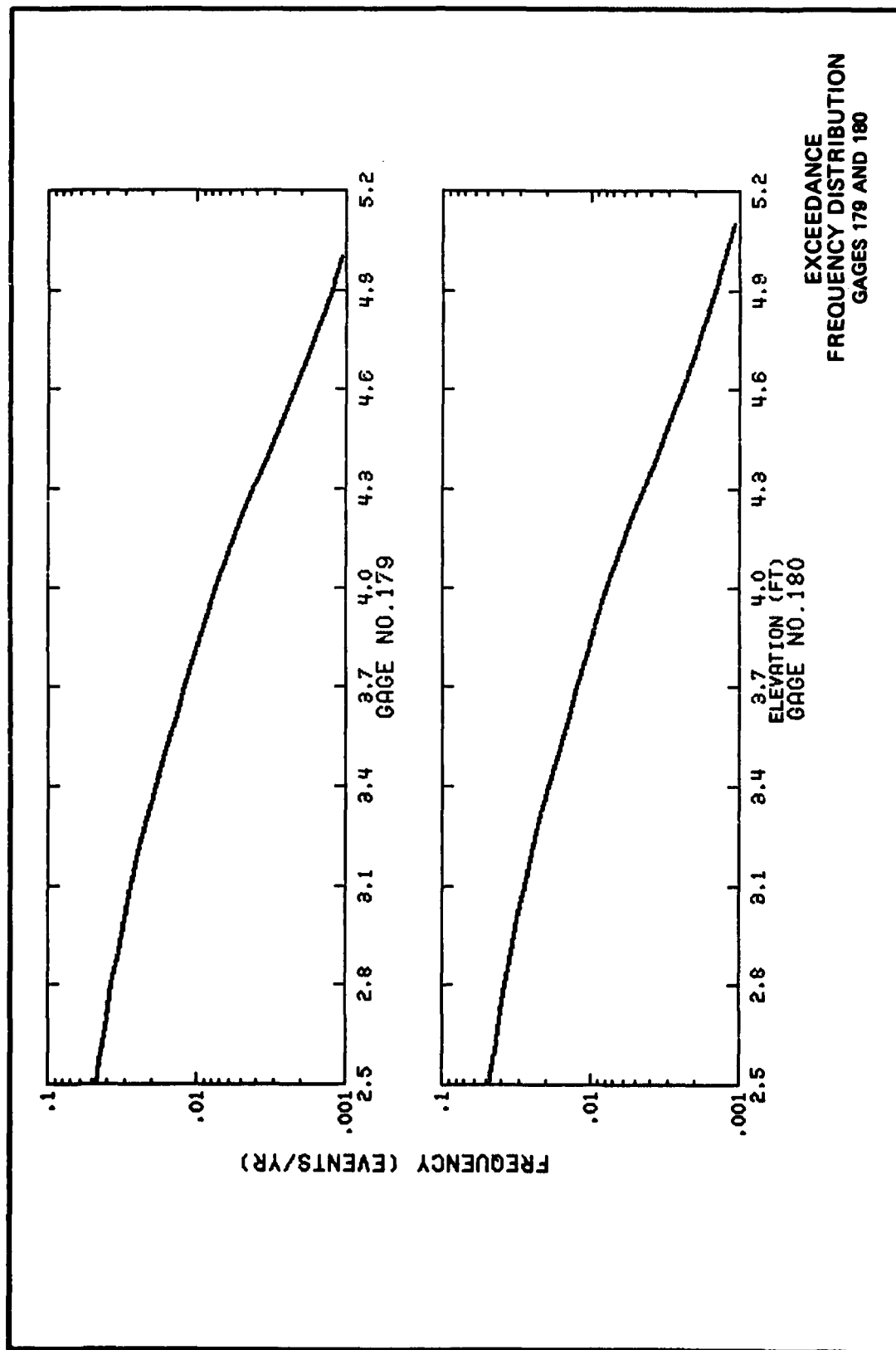


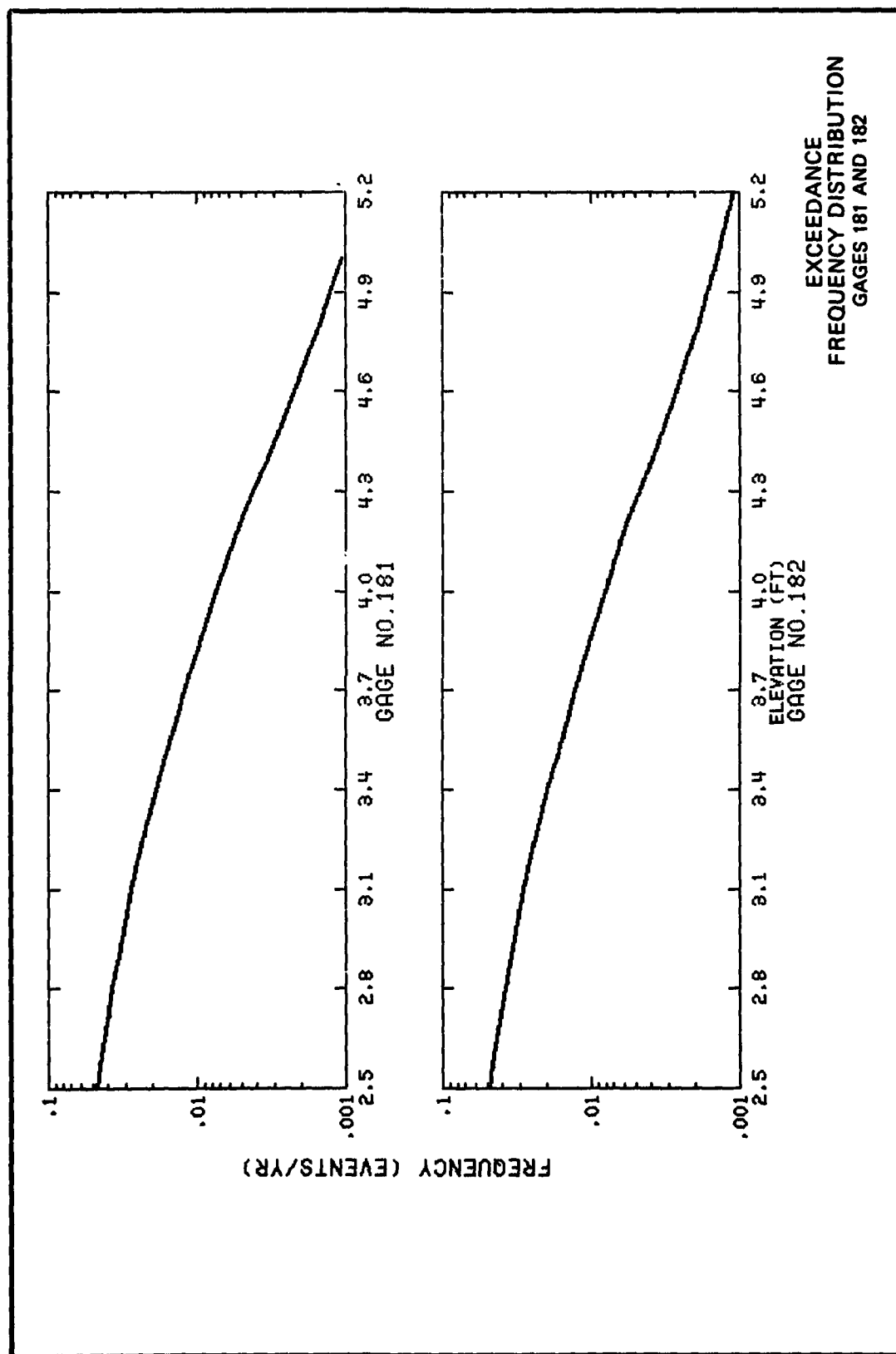


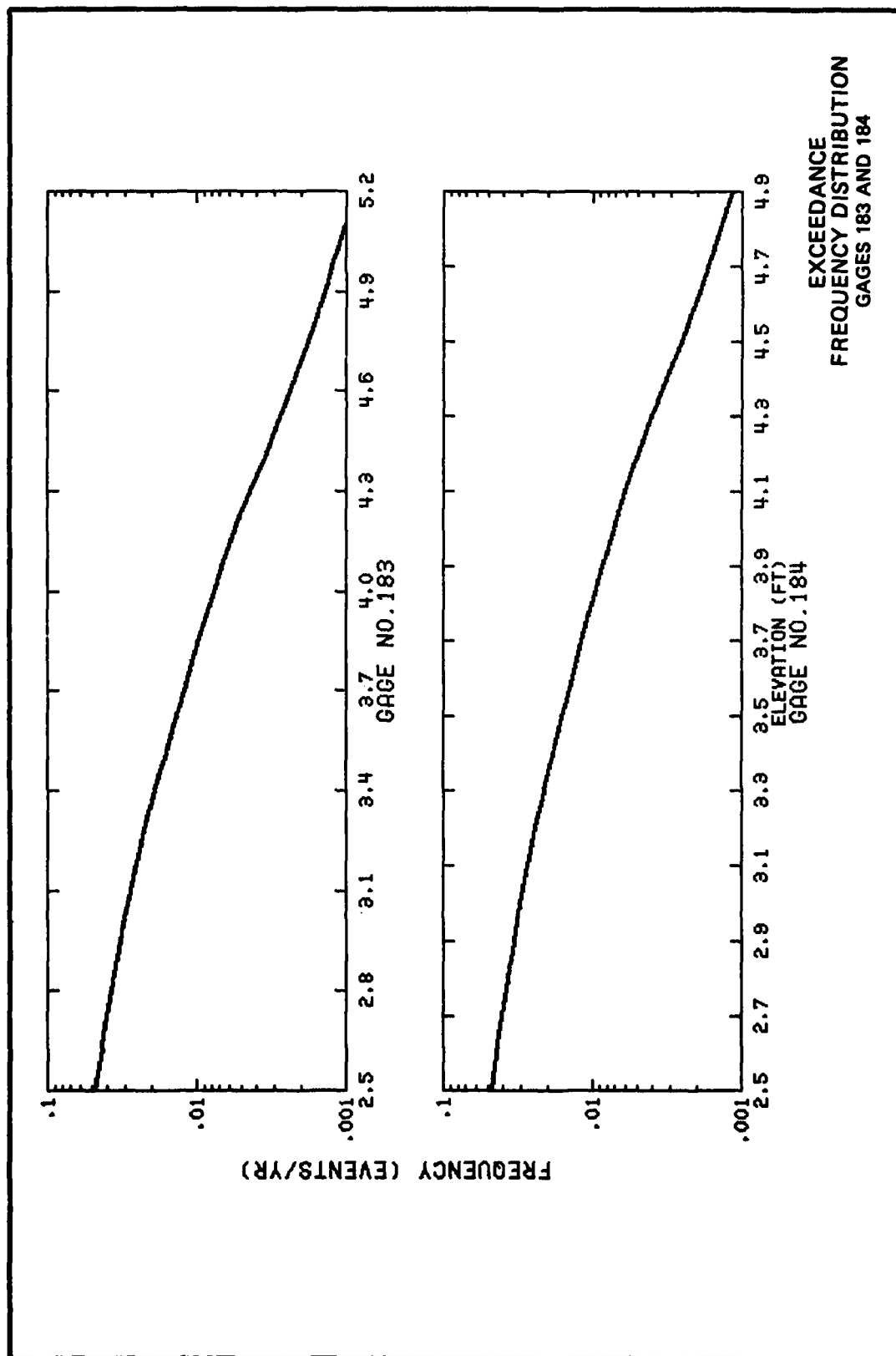


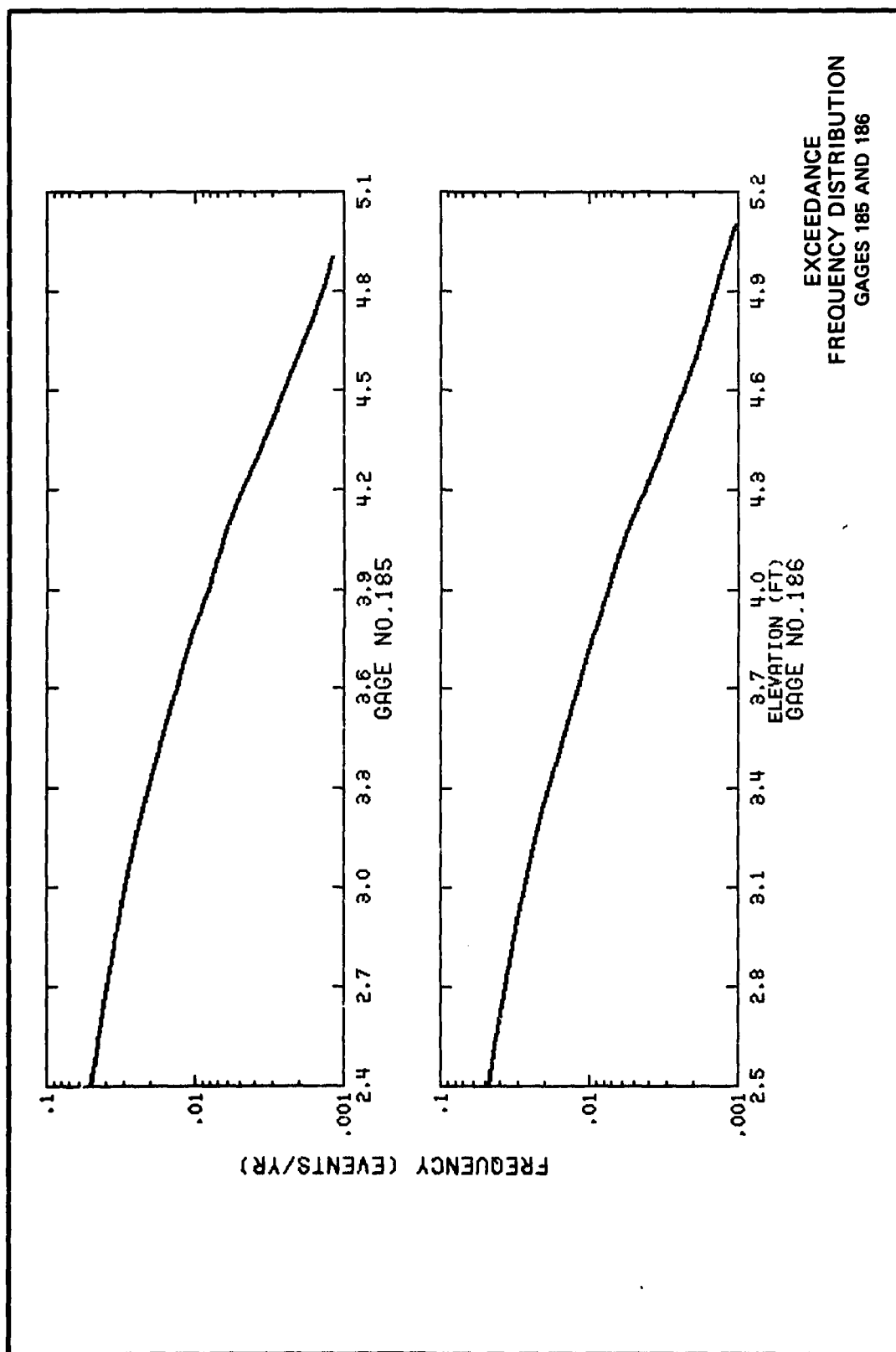


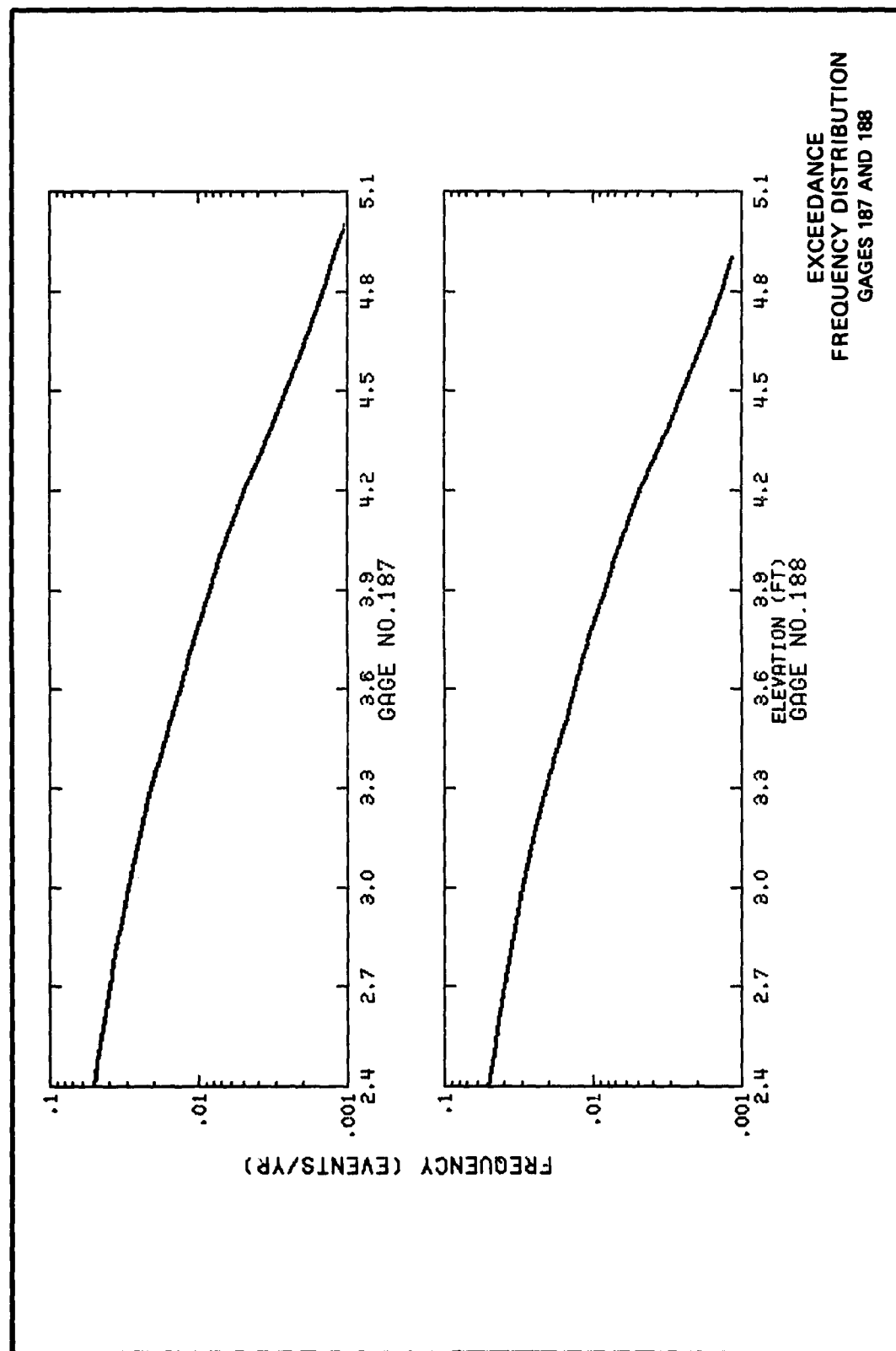
EXCEEDANCE
FREQUENCY DISTRIBUTION
GAGES 177 AND 178

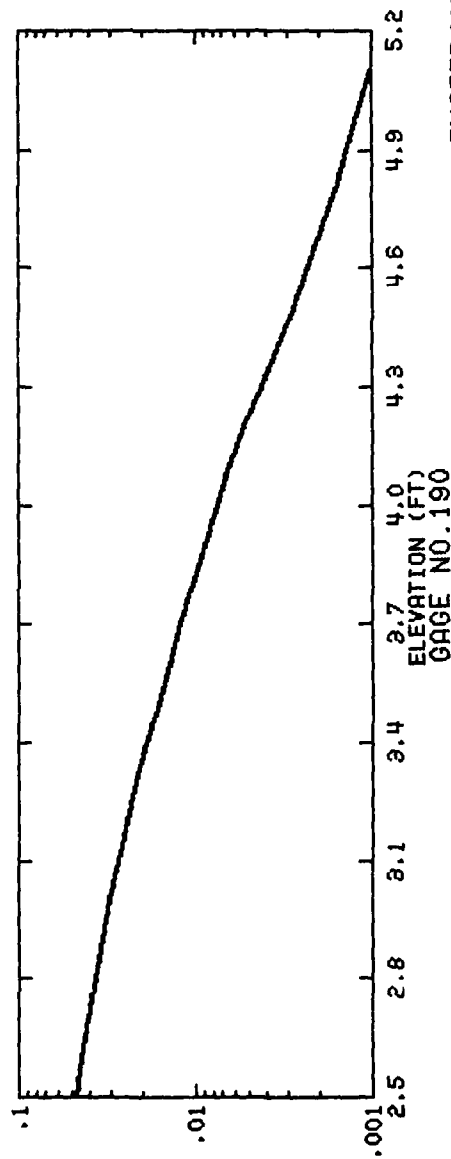
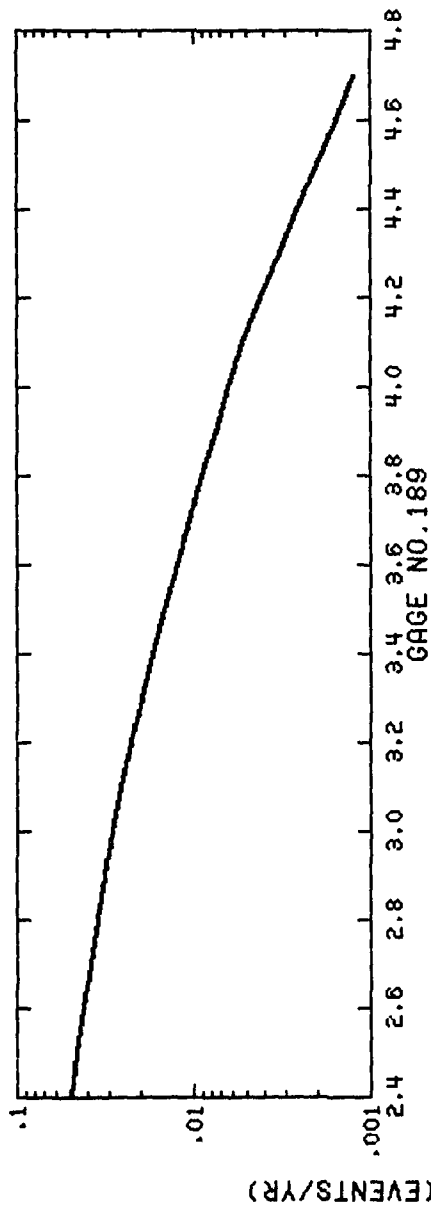




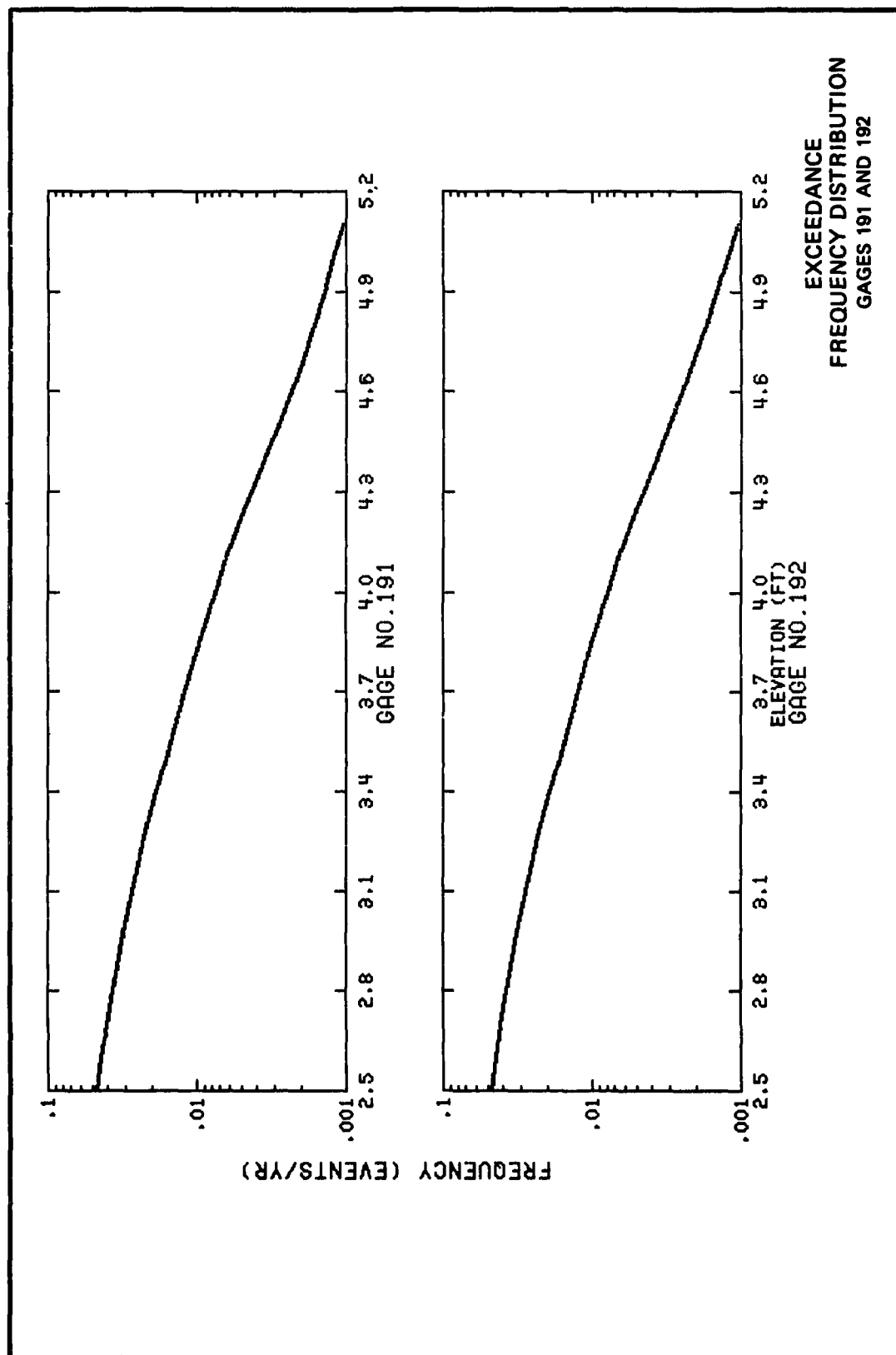








EXCEEDANCE
FREQUENCY DISTRIBUTION
GAGES 188 AND 190



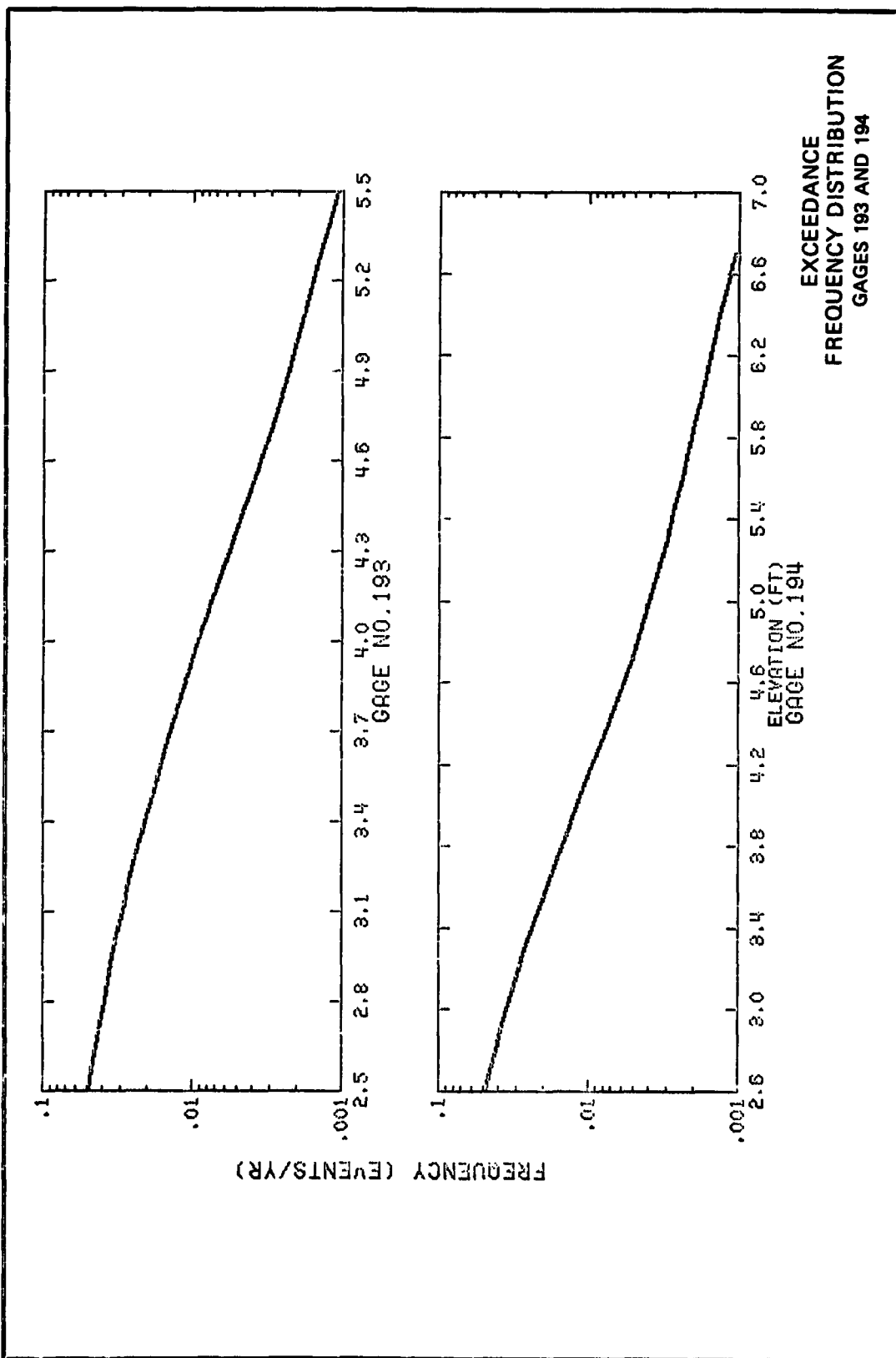
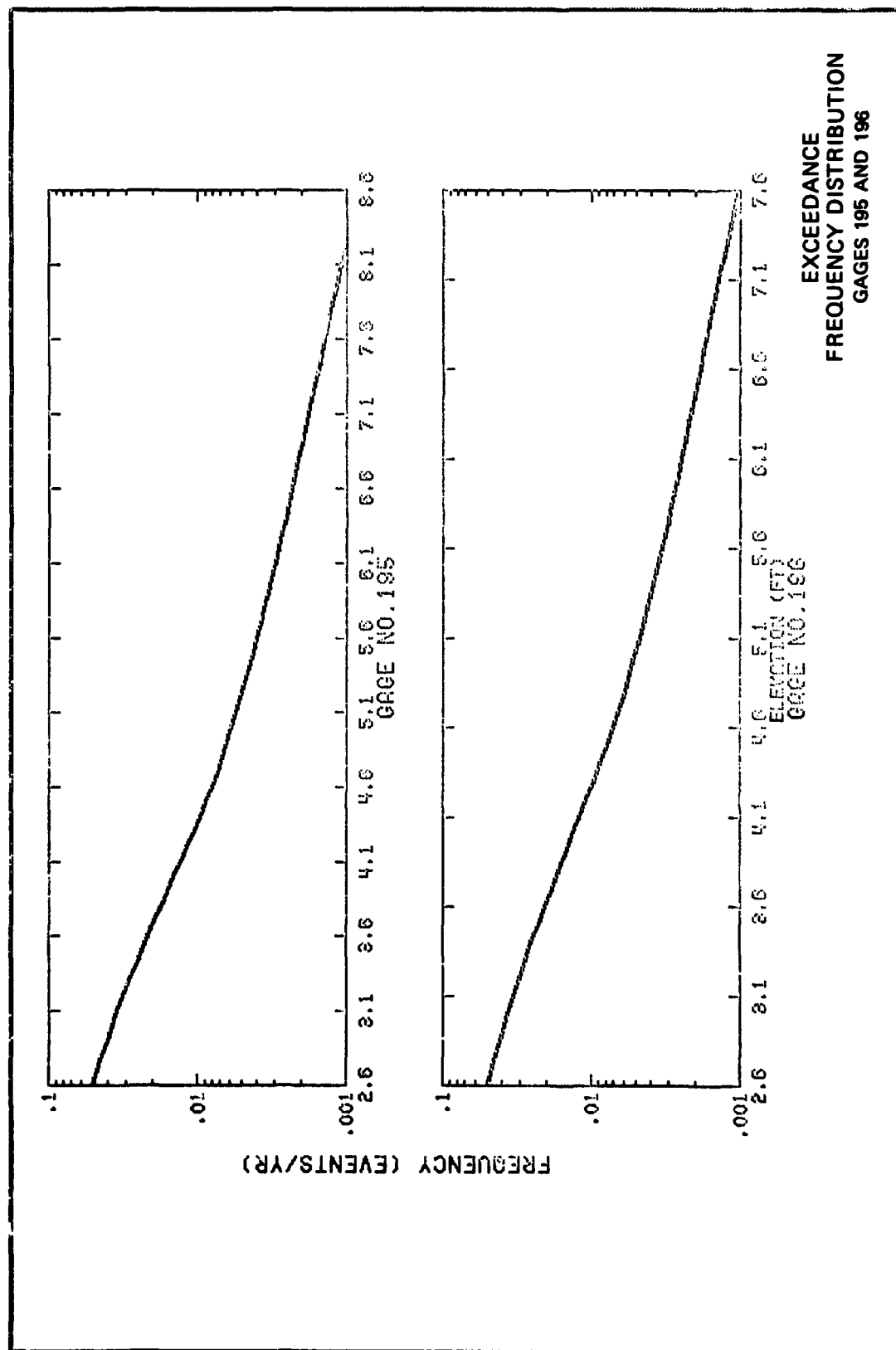
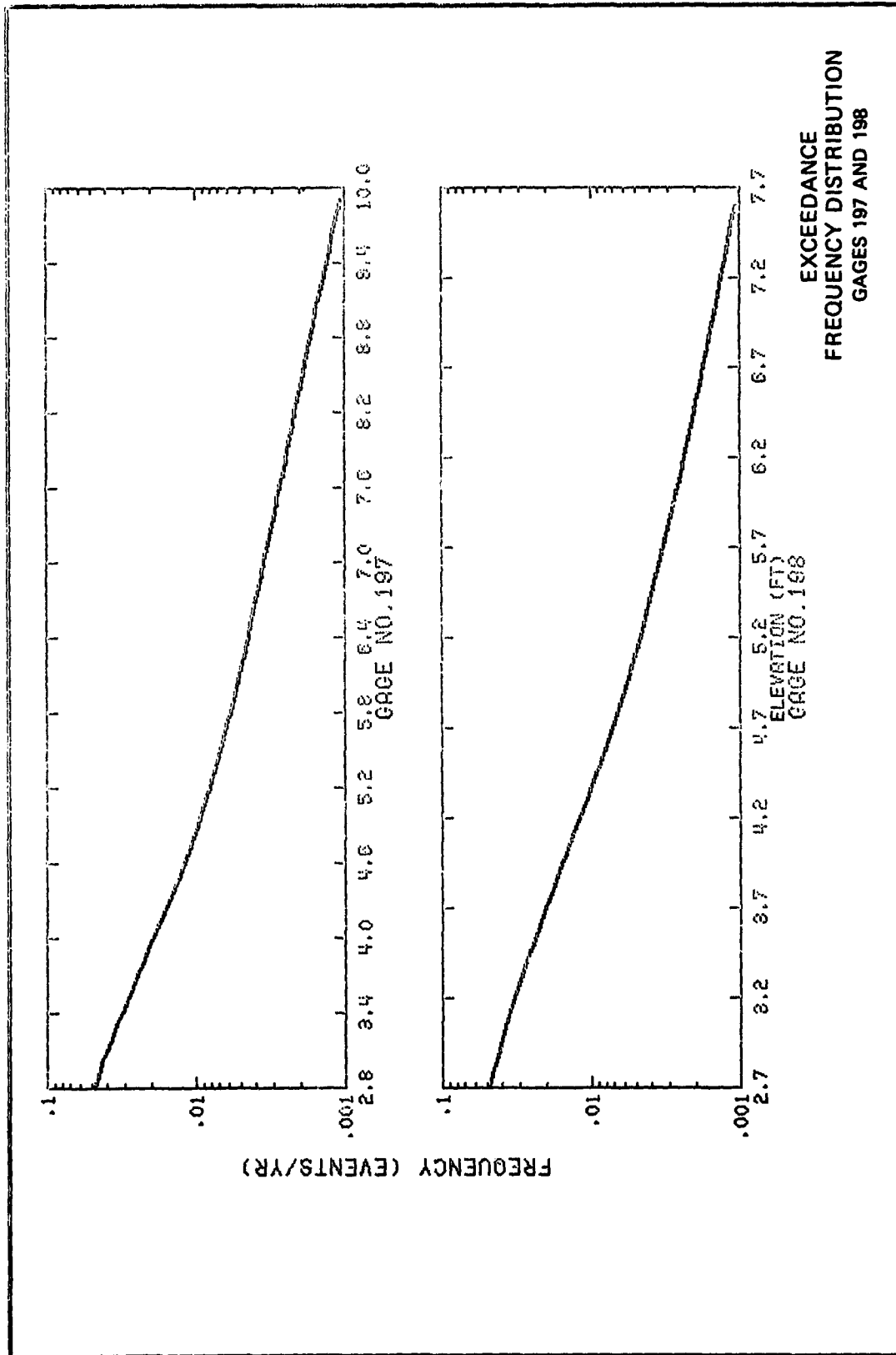
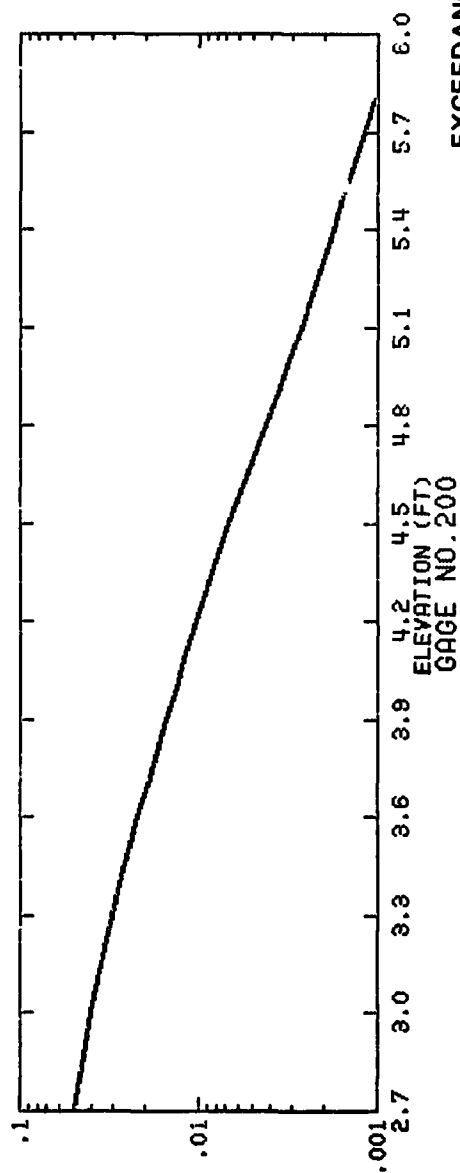
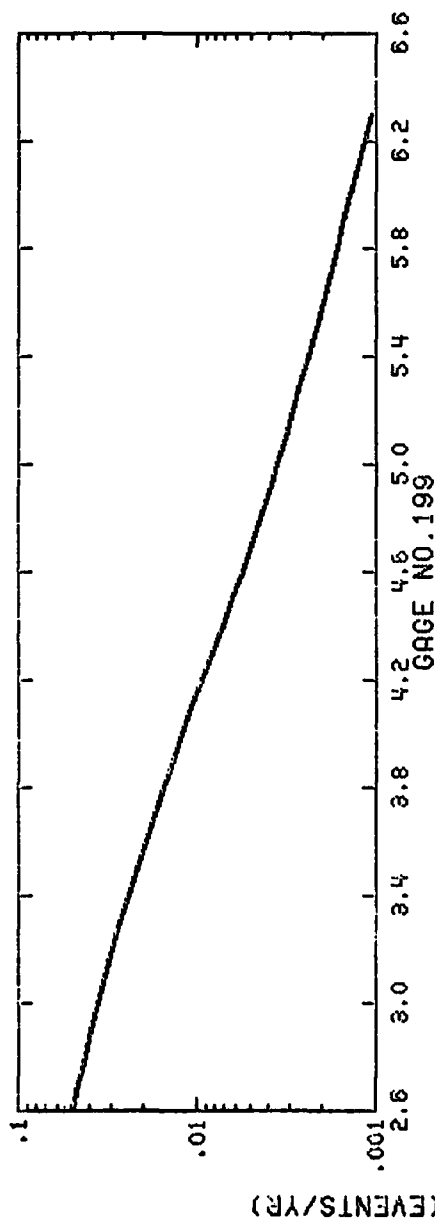


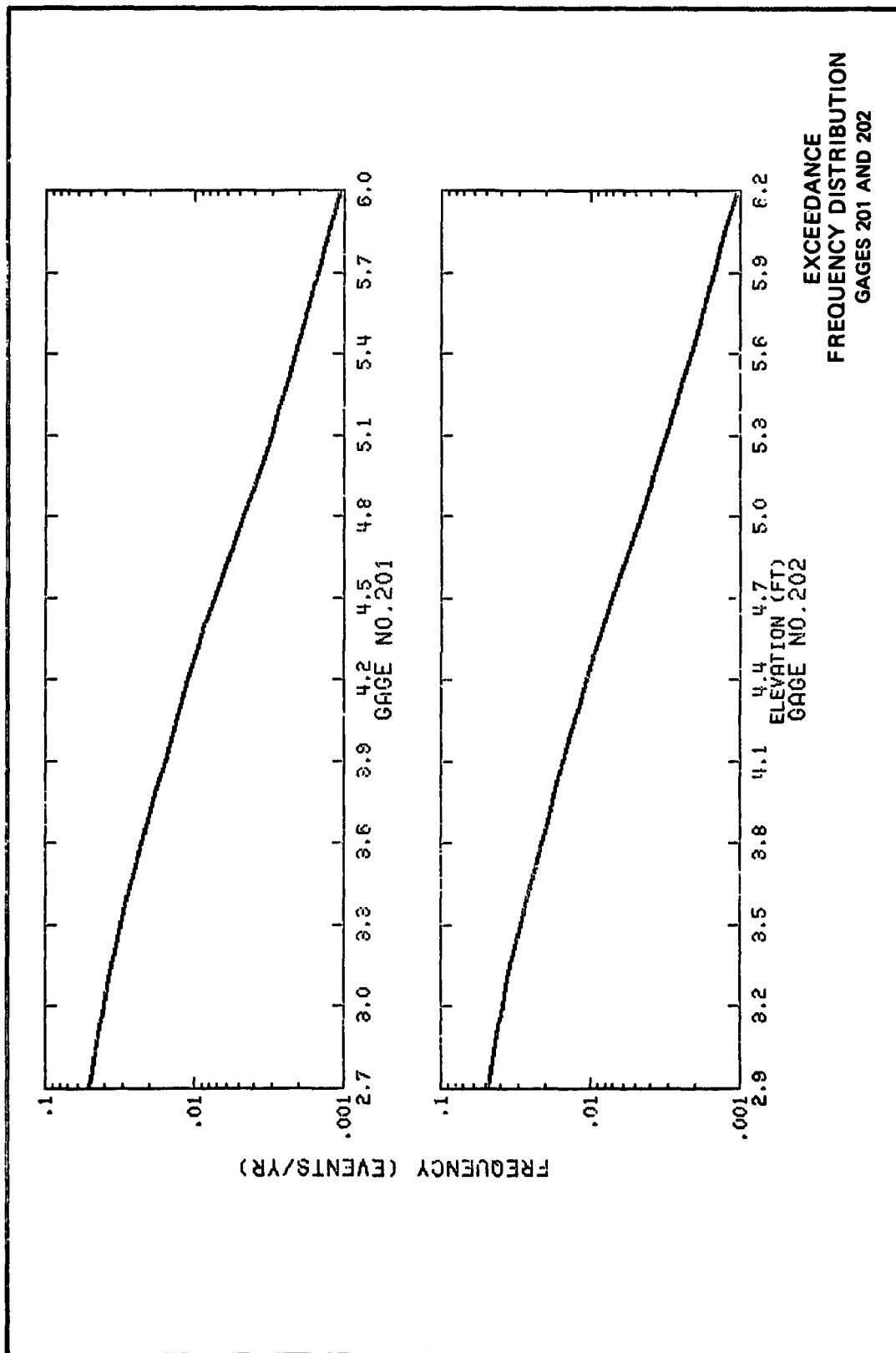
PLATE 97

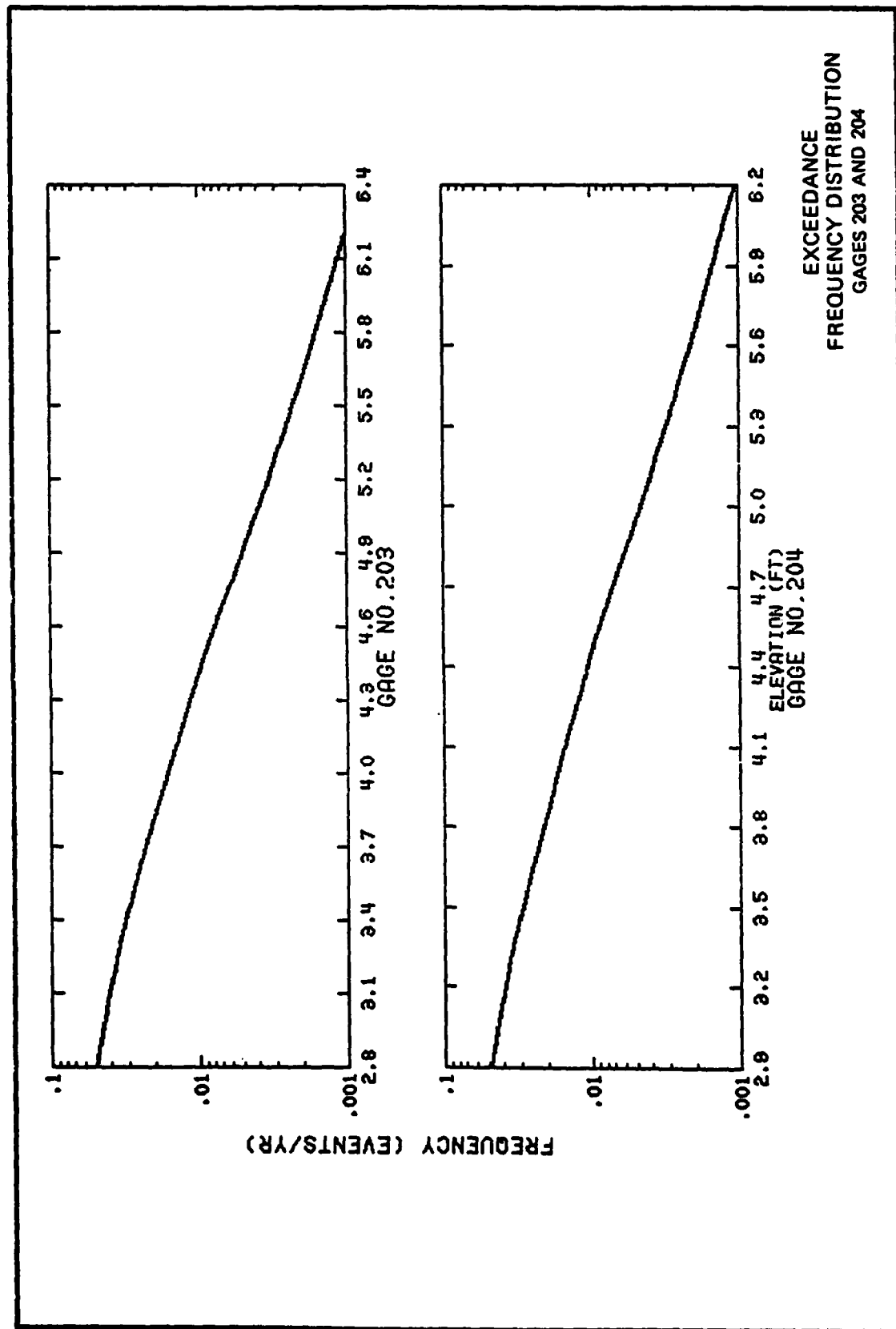


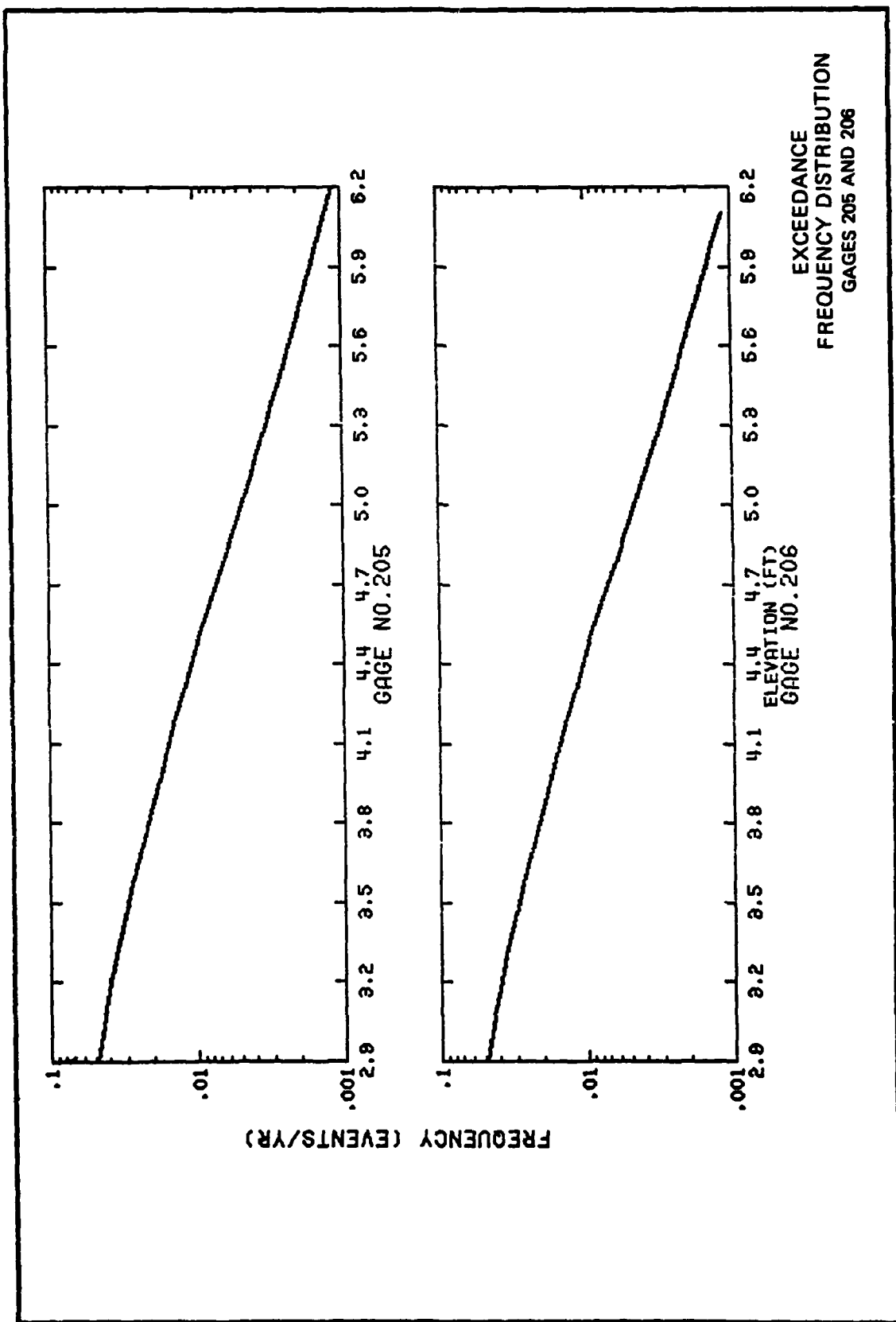


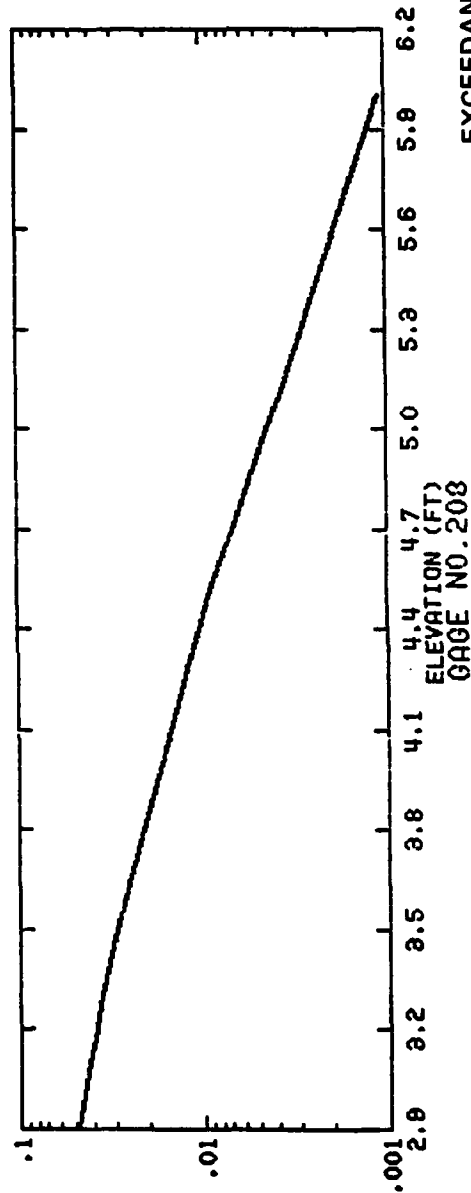
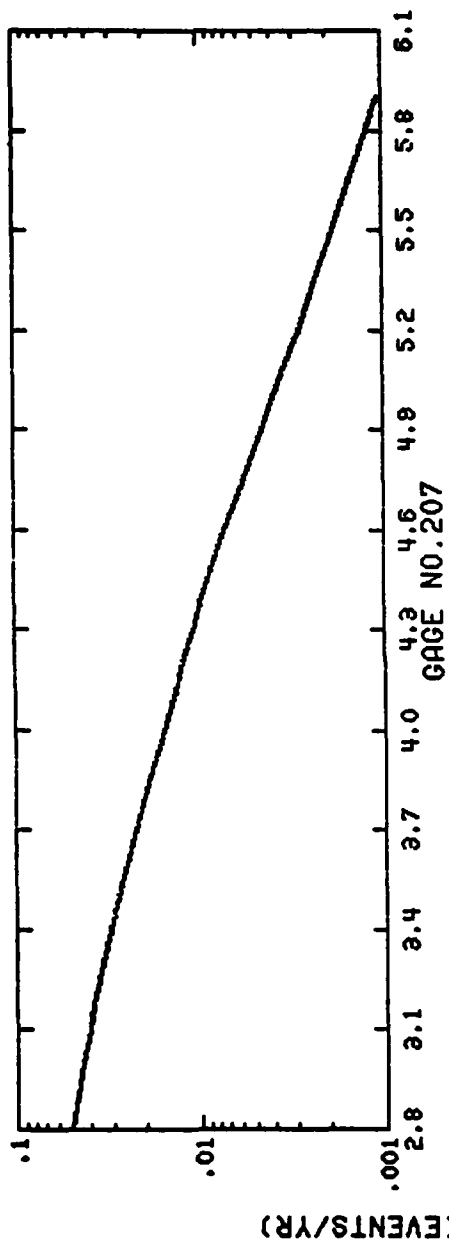


EXCEEDANCE
FREQUENCY DISTRIBUTION
GAGES 199 AND 200

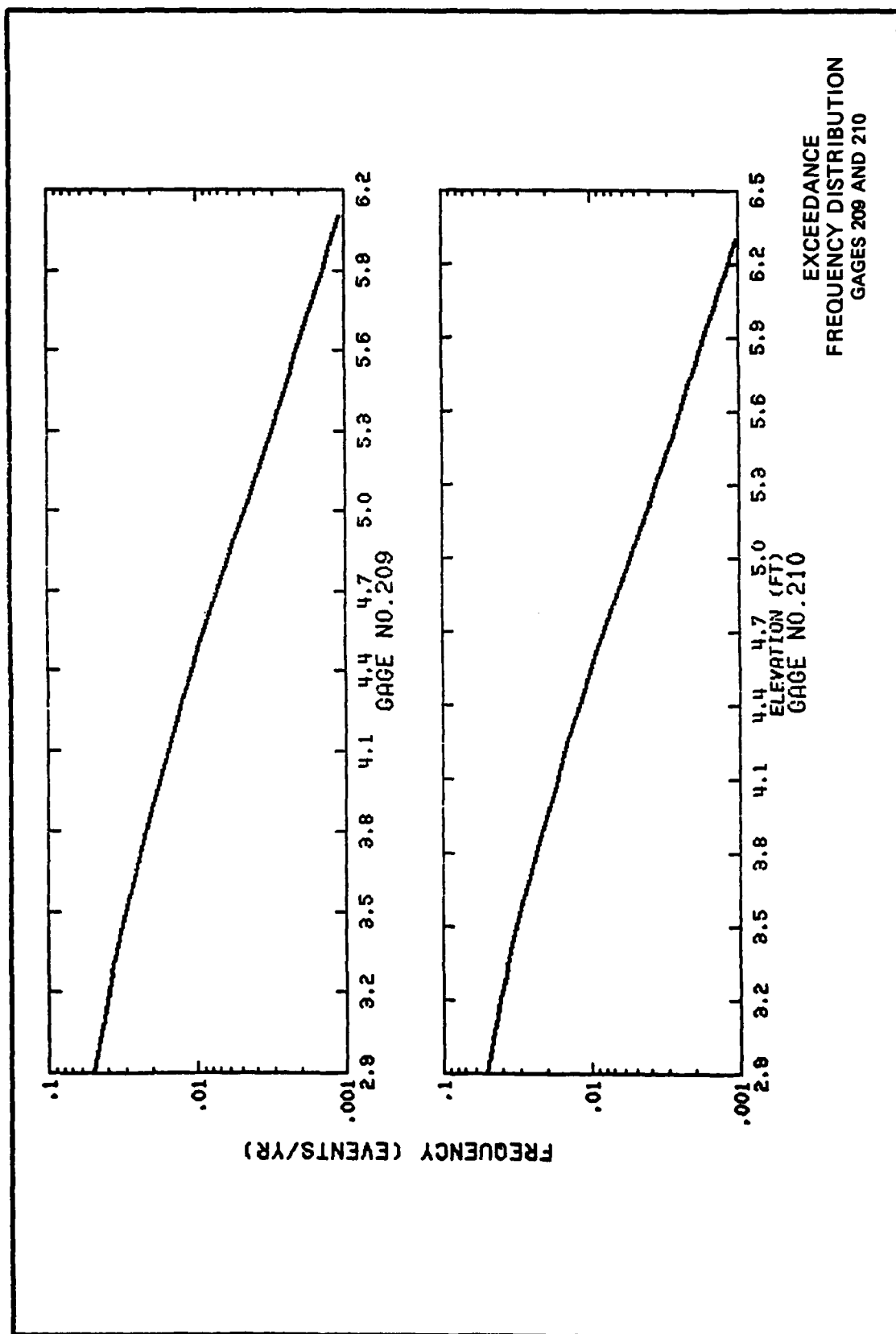


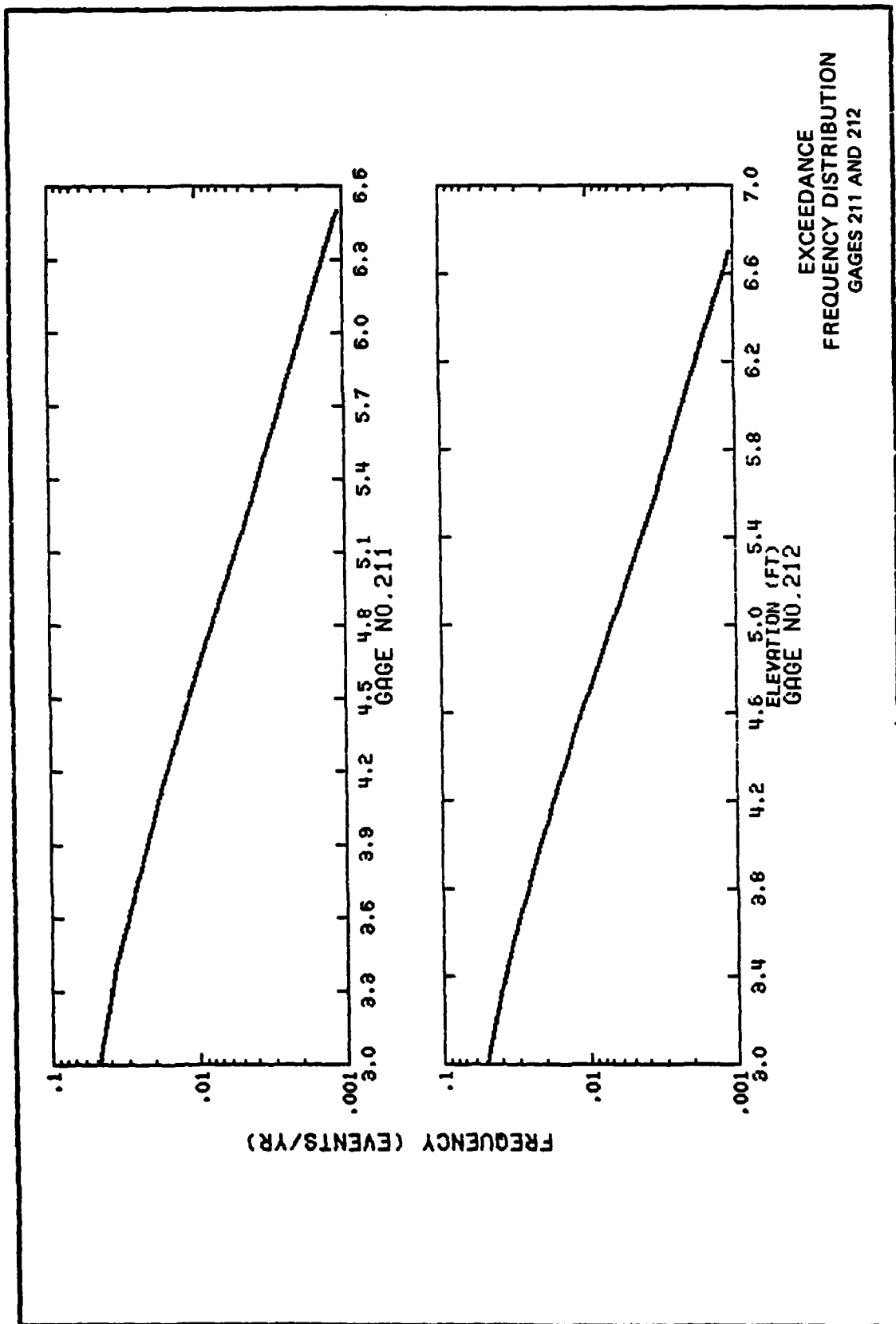


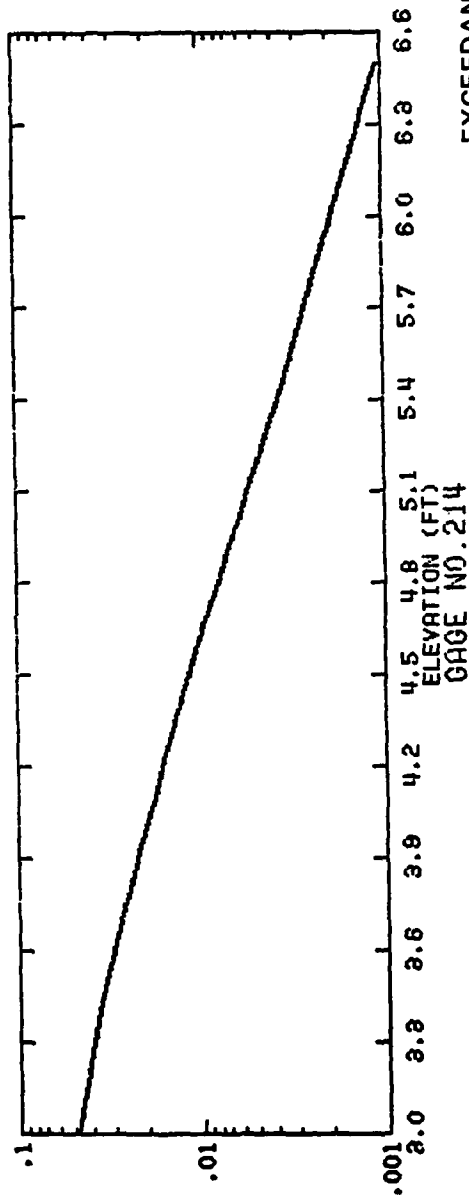
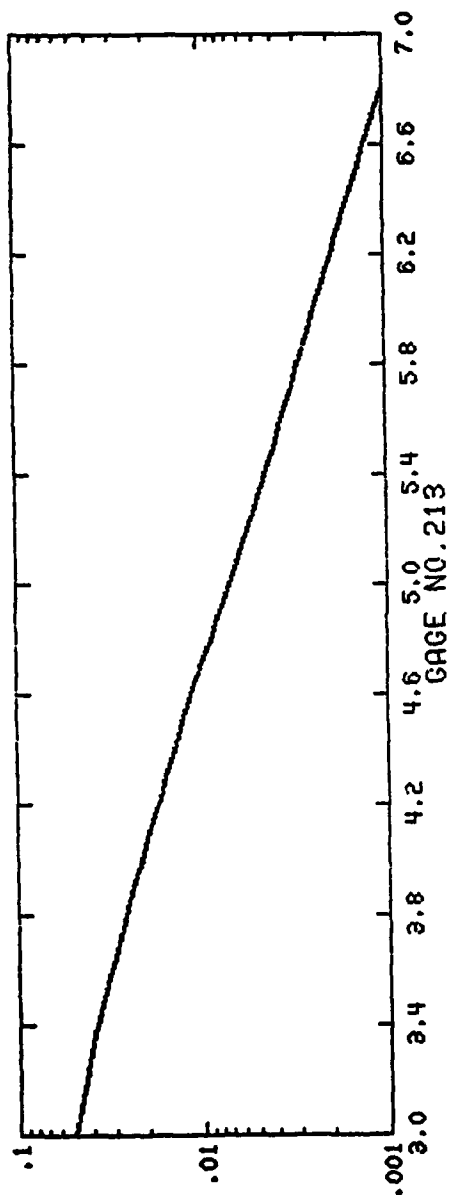




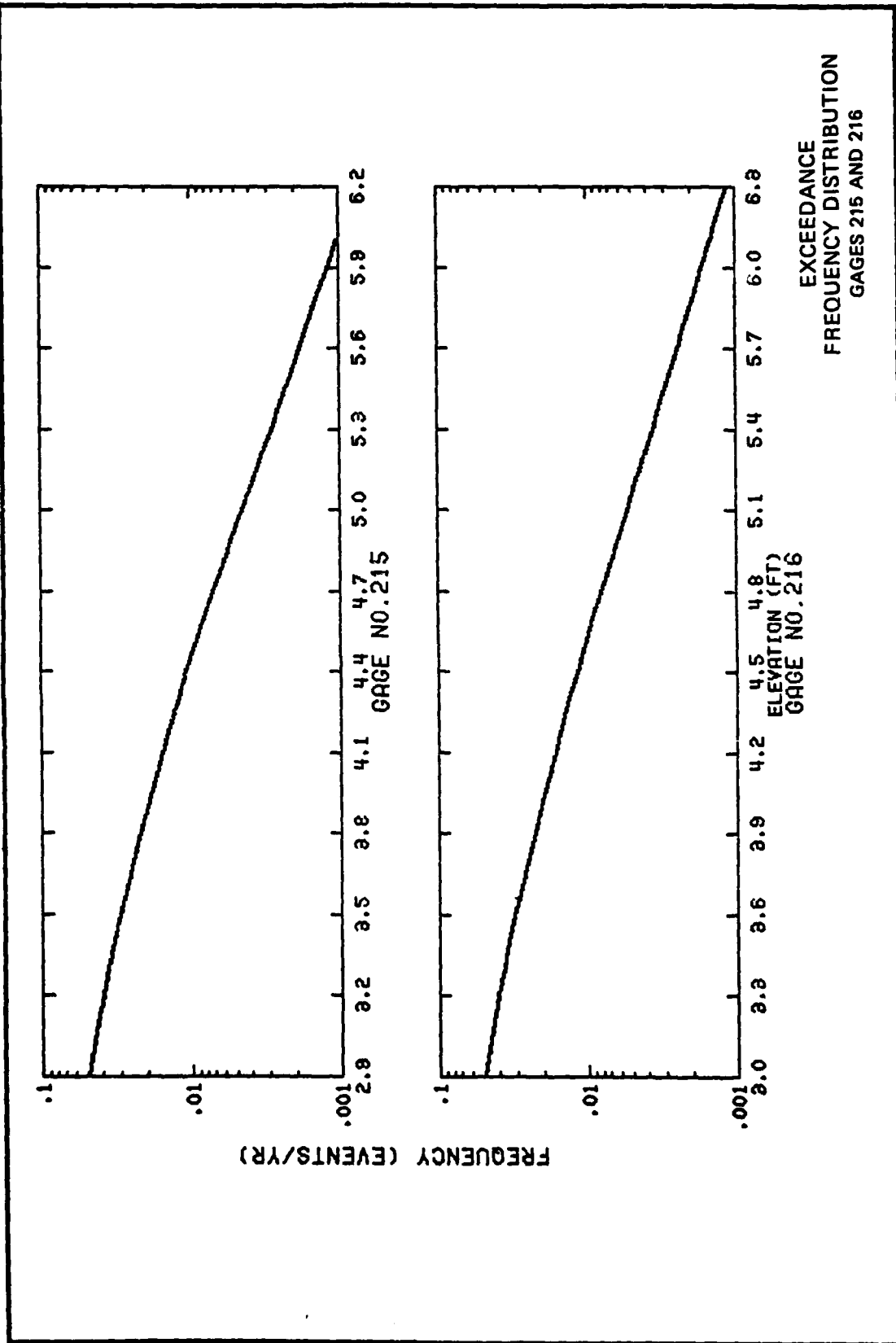
EXCEEDANCE
FREQUENCY DISTRIBUTION
GAGES 207 AND 208

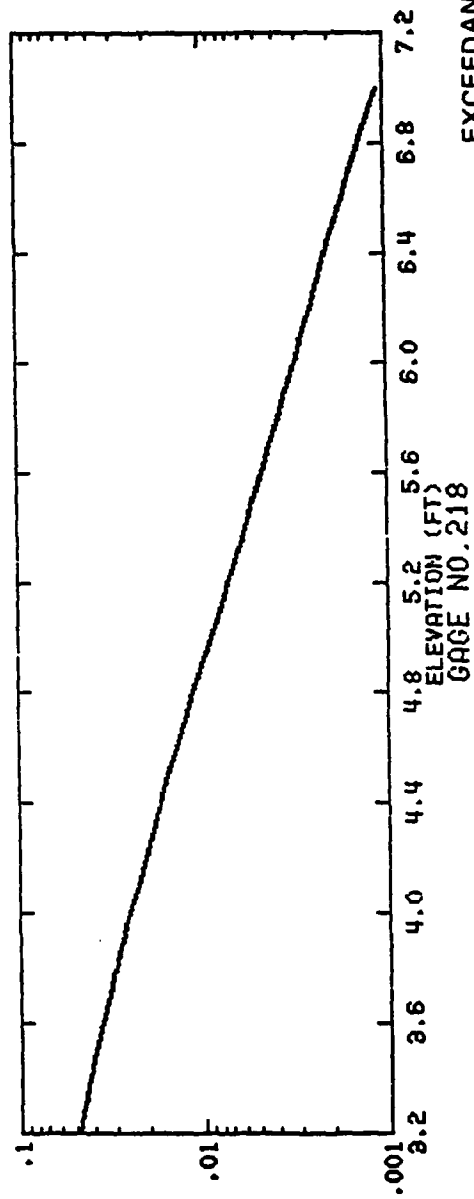
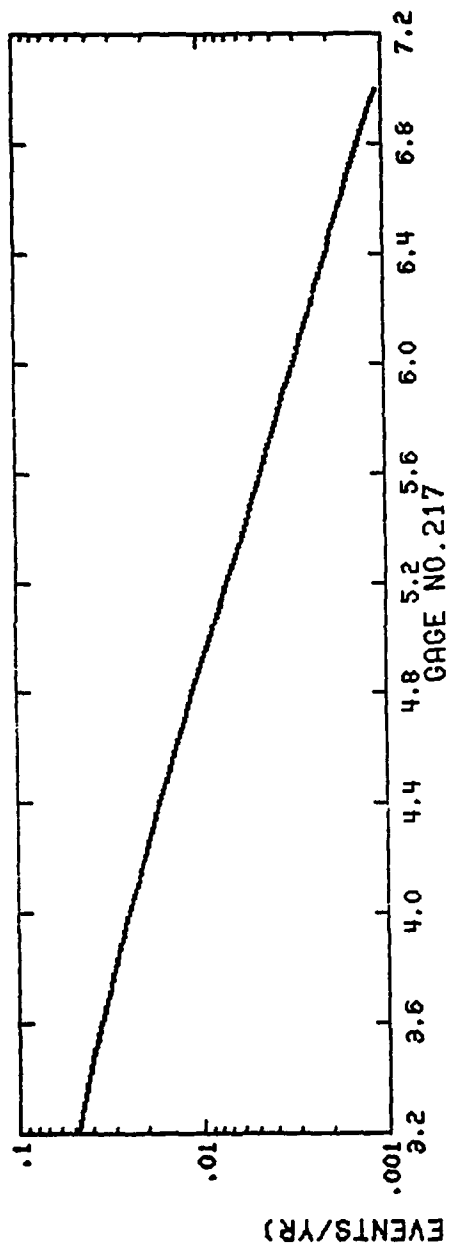




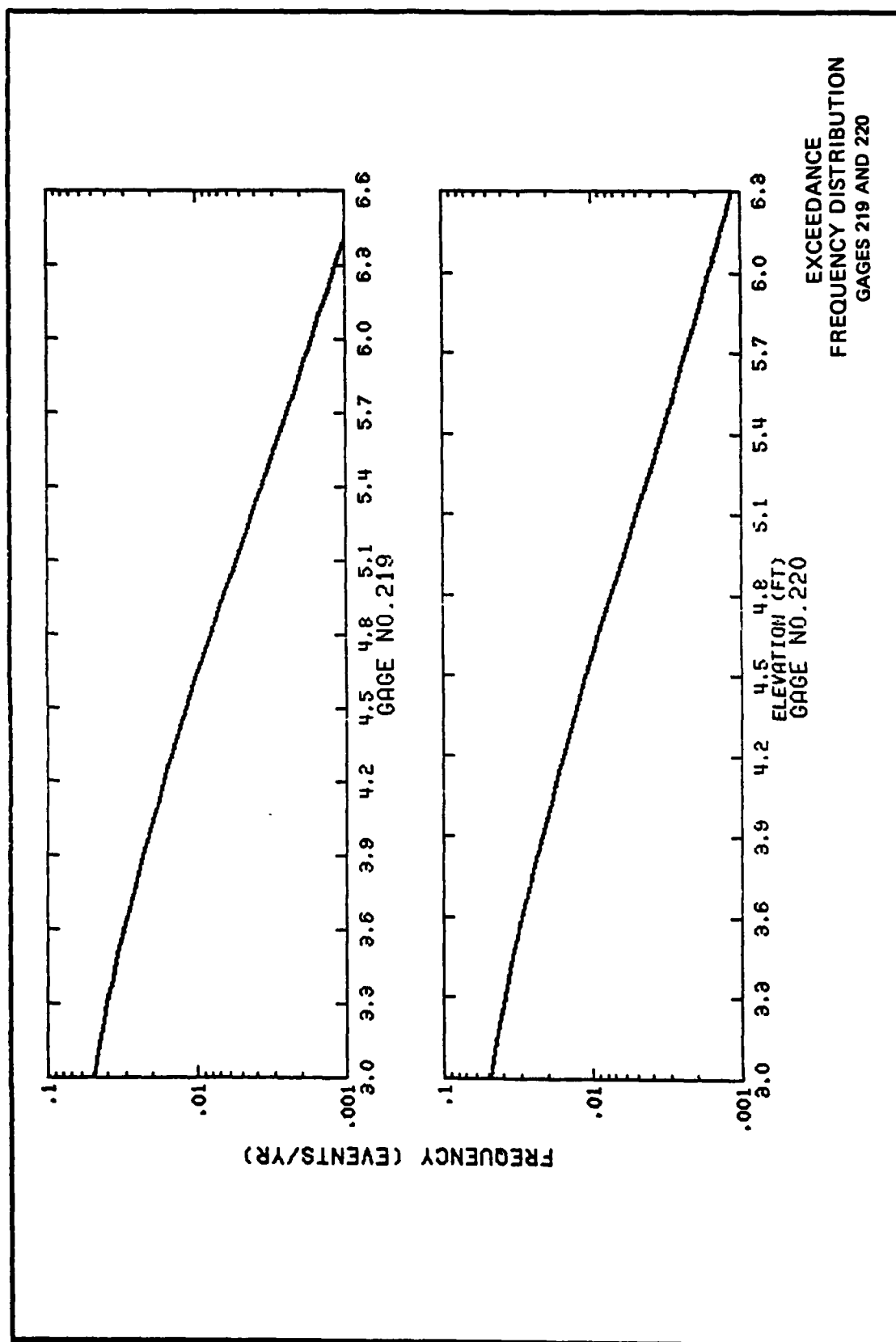


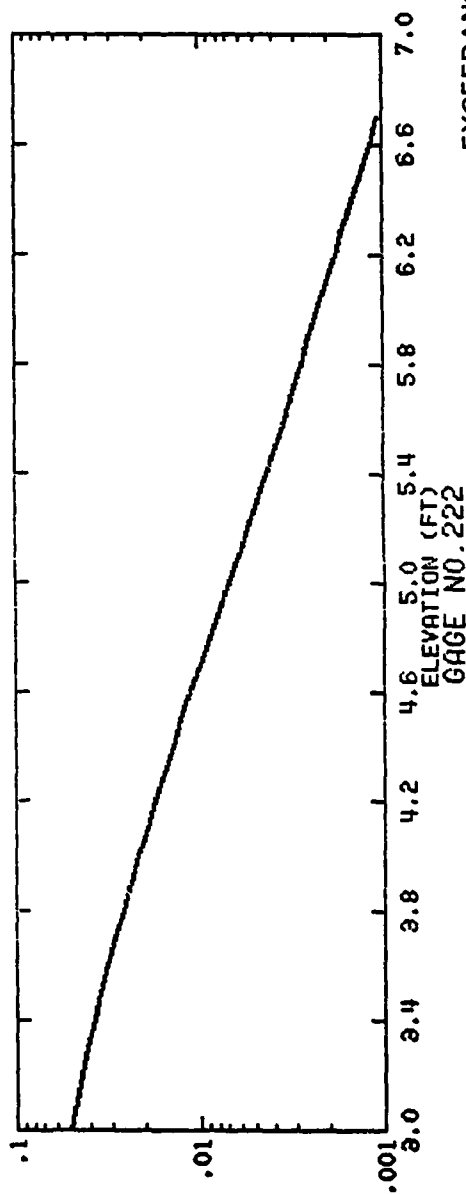
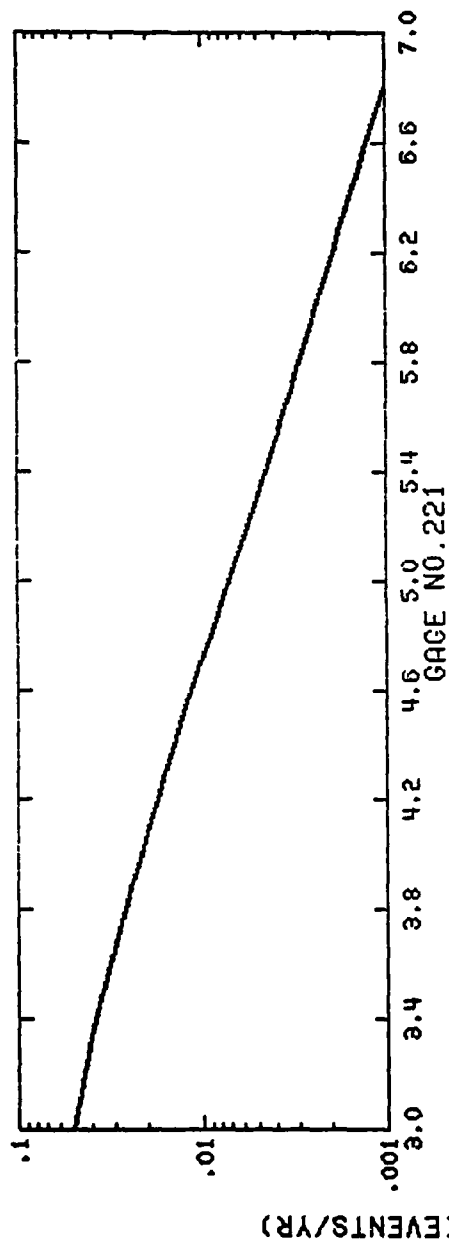
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GAGES 213 AND 214



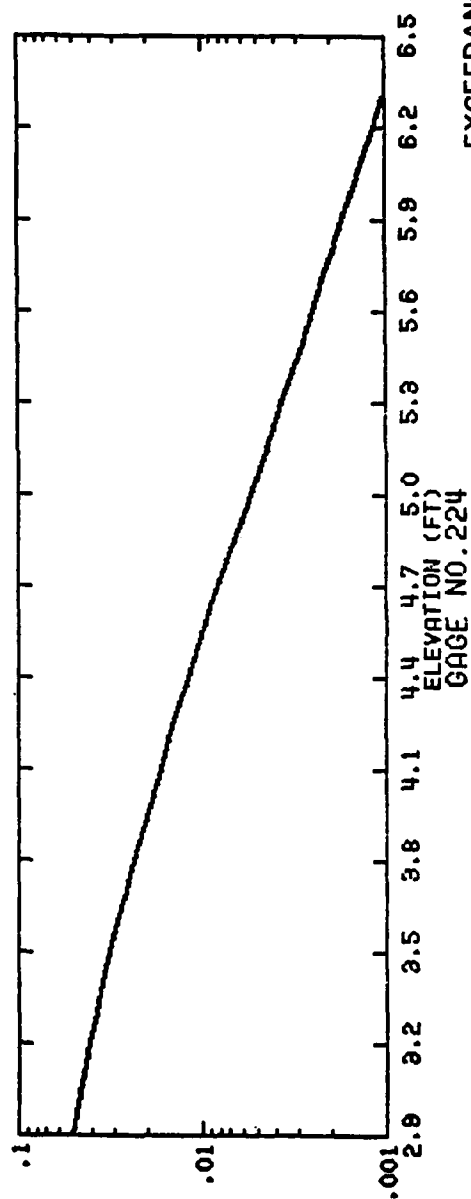
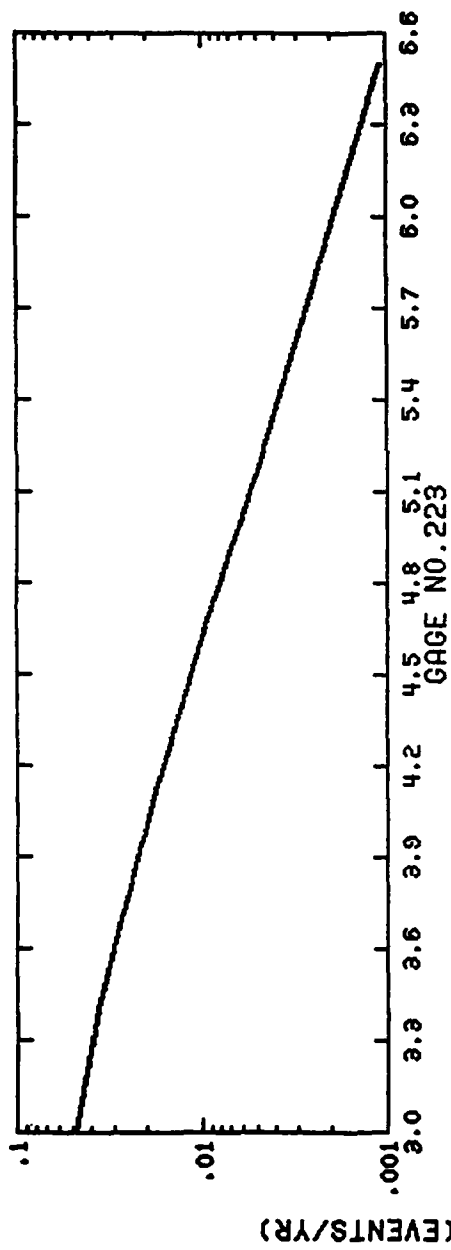


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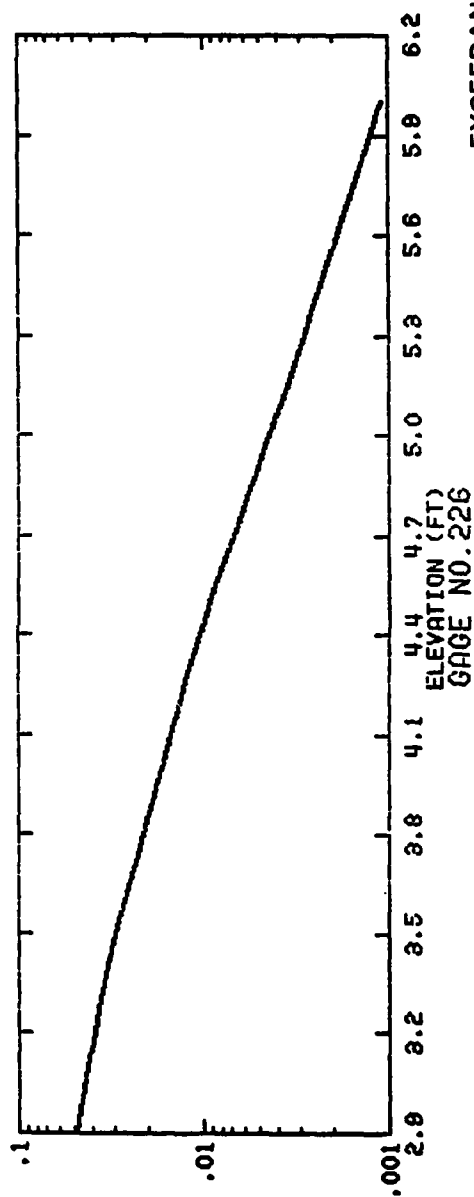
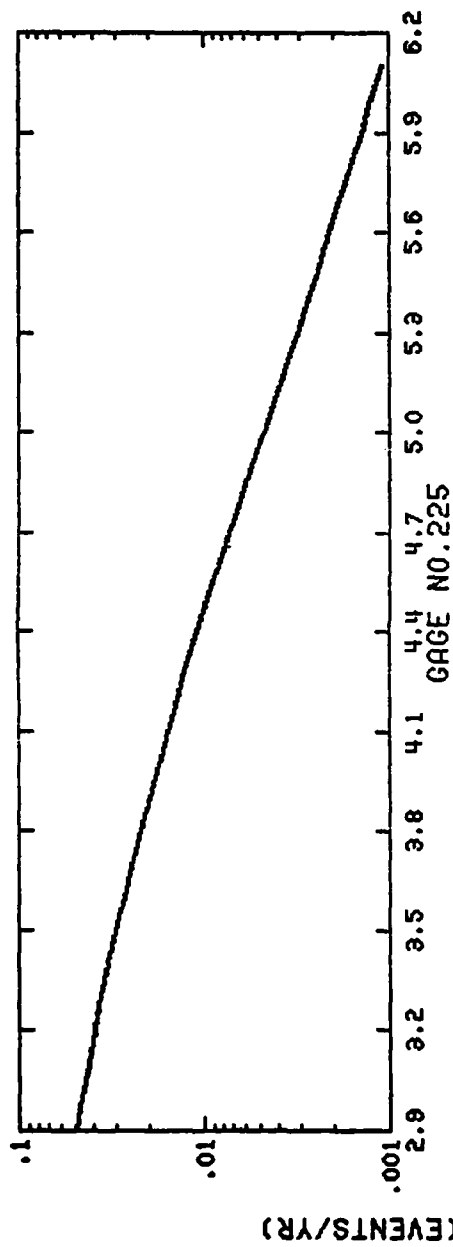




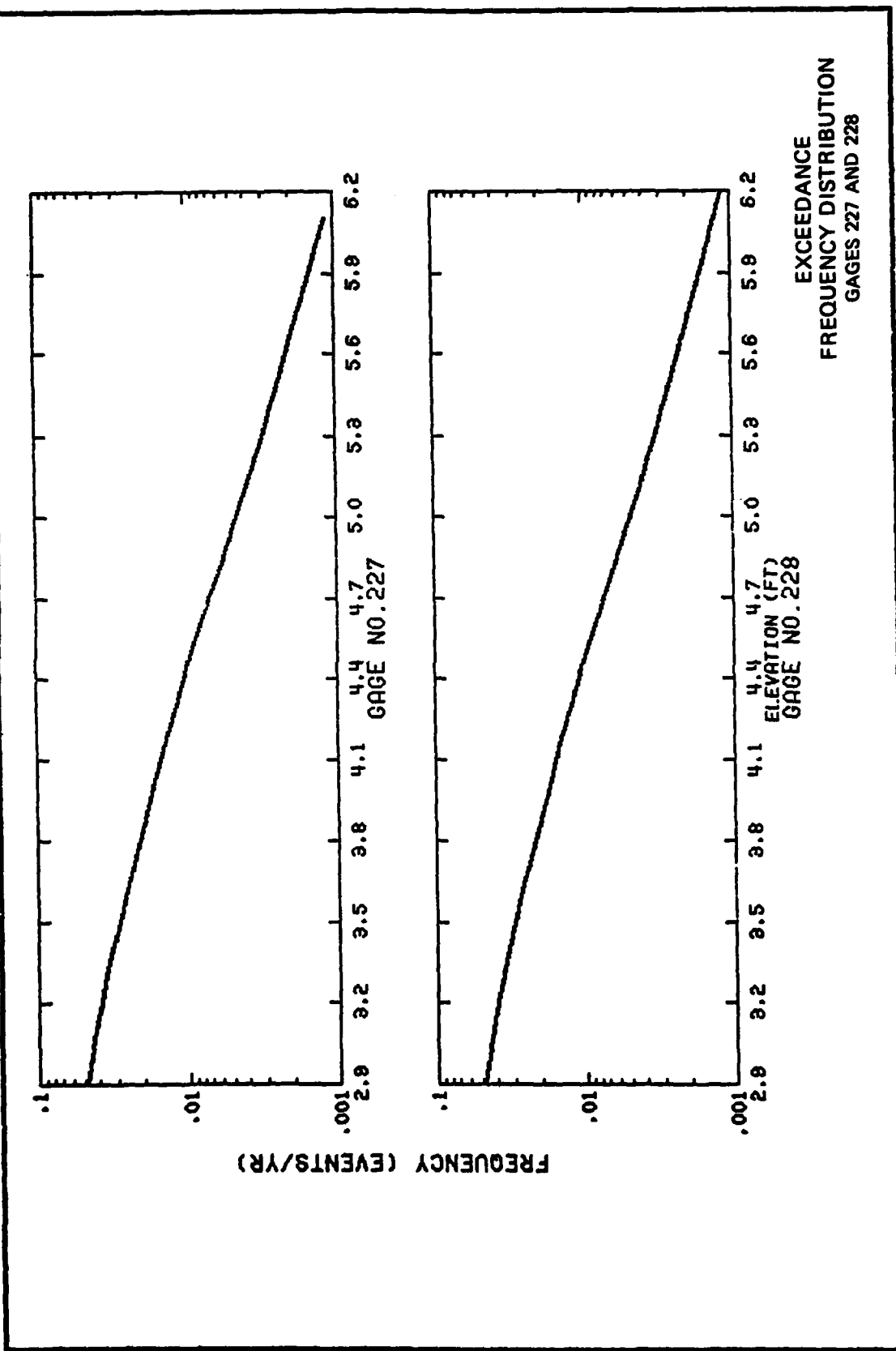
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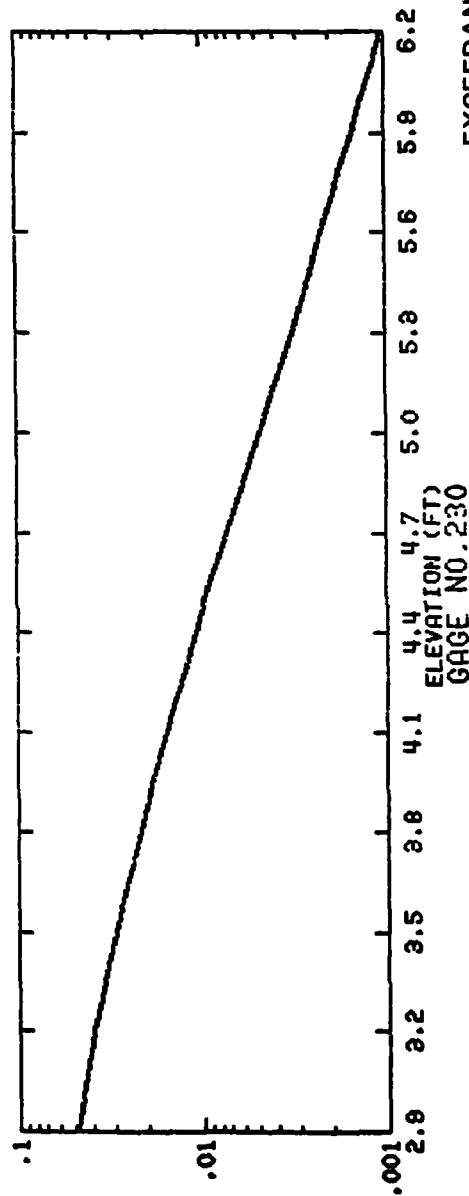
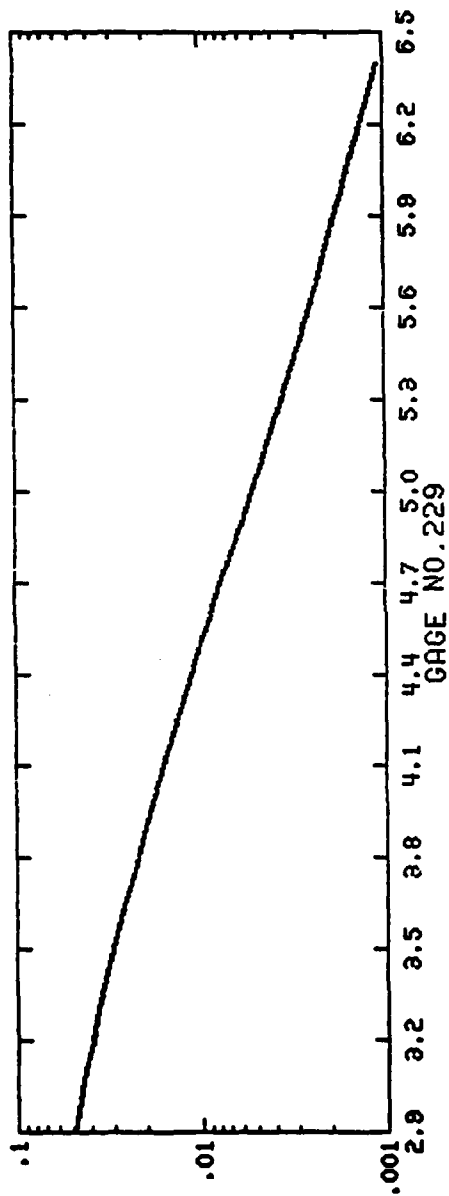


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GAGES 223 AND 224

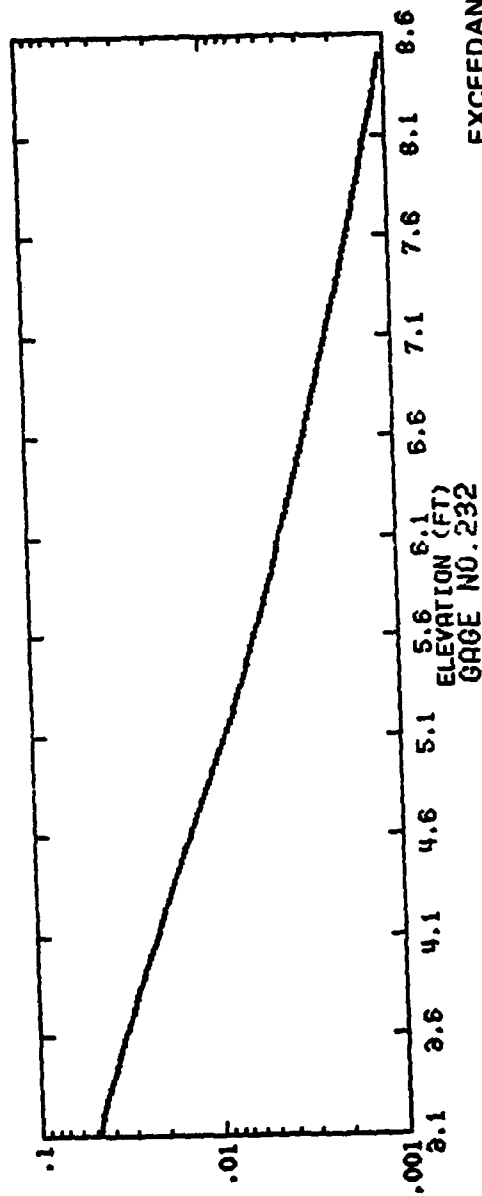
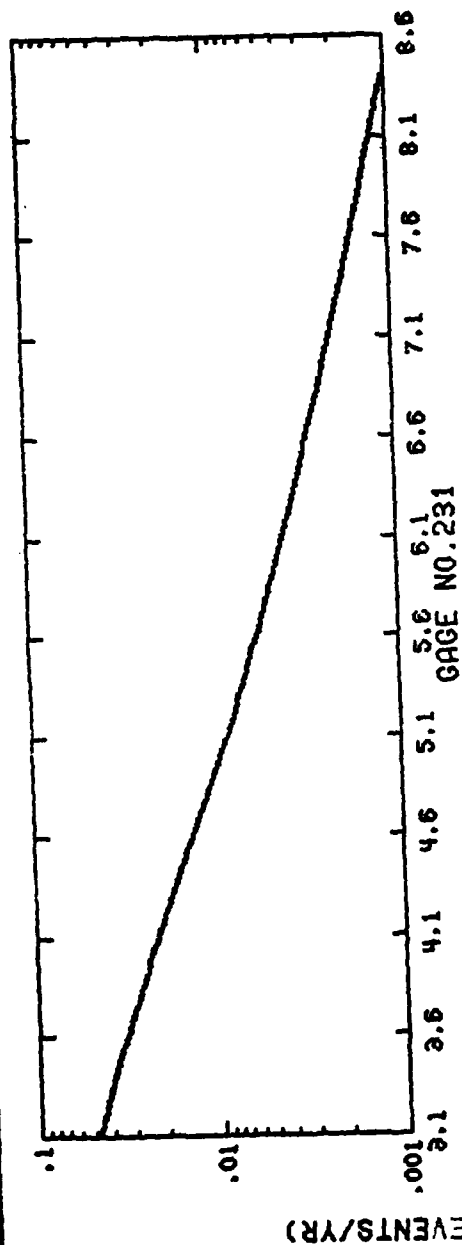


EXCEEDANCE
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GAGES 225 AND 226

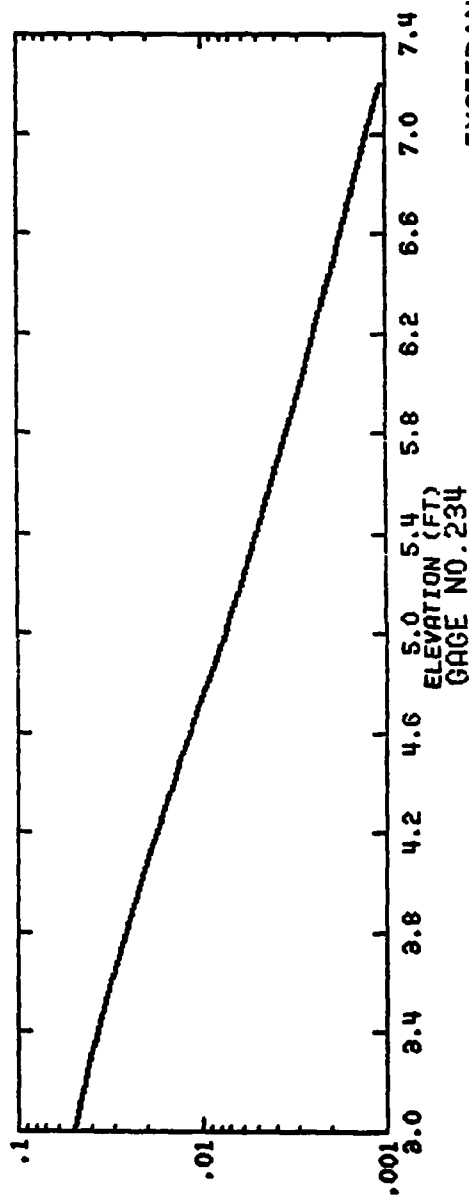
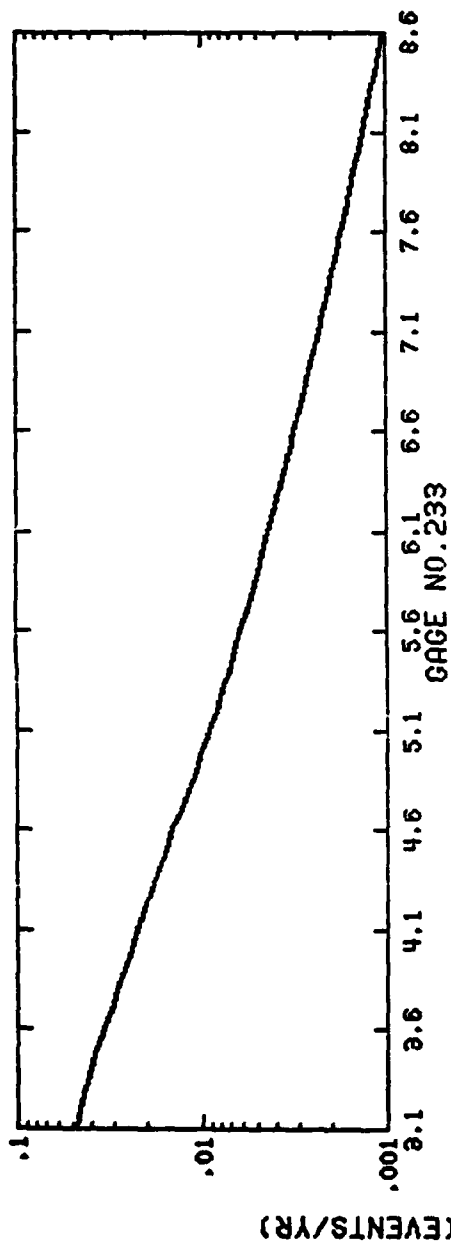




EXCEEDANCE
FREQUENCY DISTRIBUTION
GAGES 229 AND 230



EXCEEDANCE
FREQUENCY DISTRIBUTION
GAGES 231 AND 232



EXCEEDANCE
FREQUENCY DISTRIBUTION
GAGES 233 AND 234

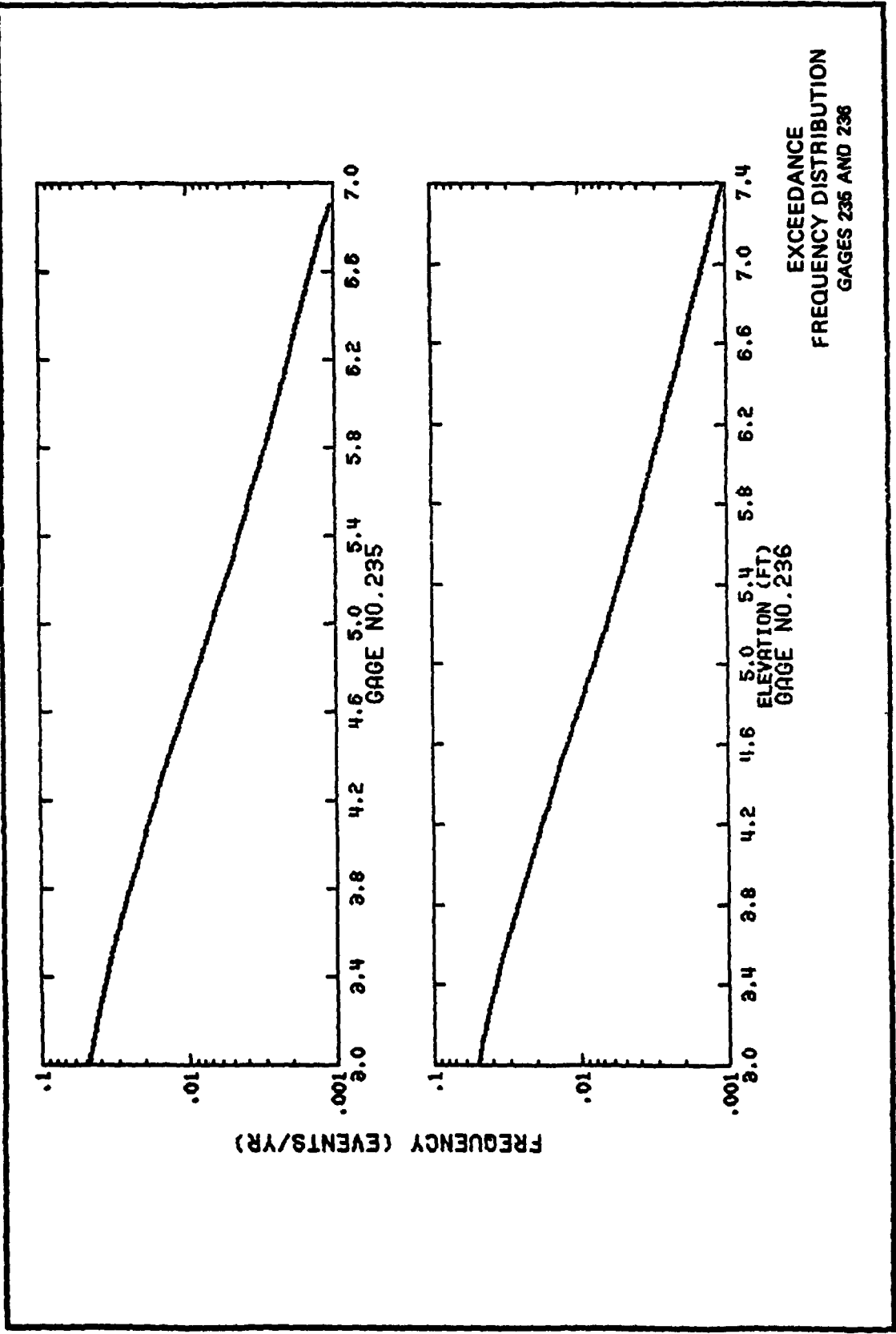
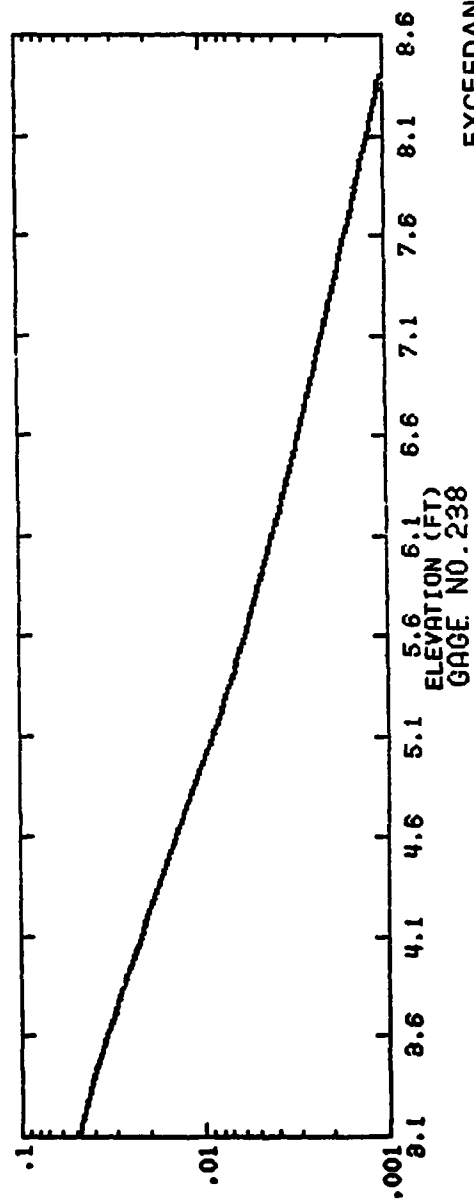
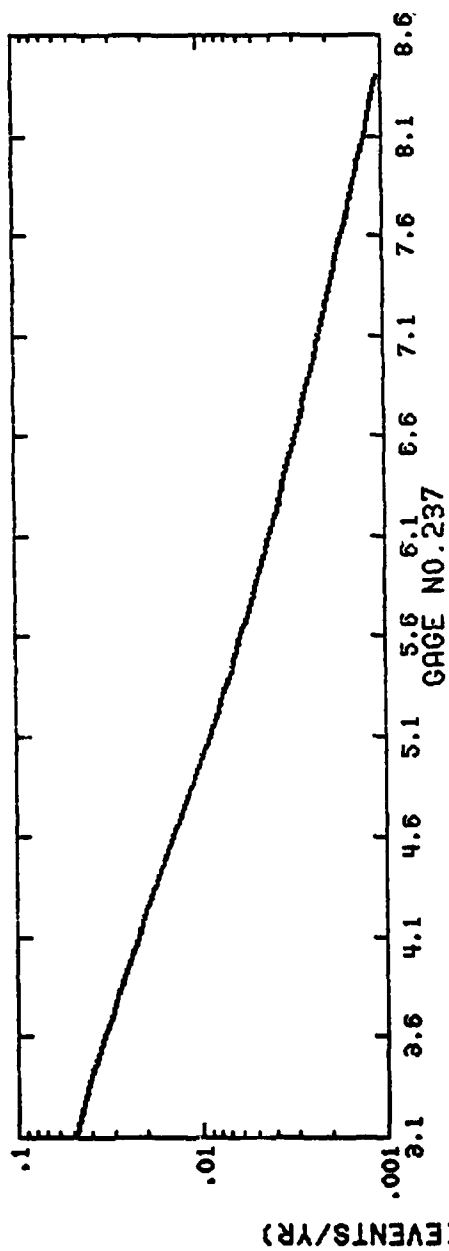


PLATE 118



EXCEEDANCE
FREQUENCY DISTRIBUTION
GAGES 237 AND 238

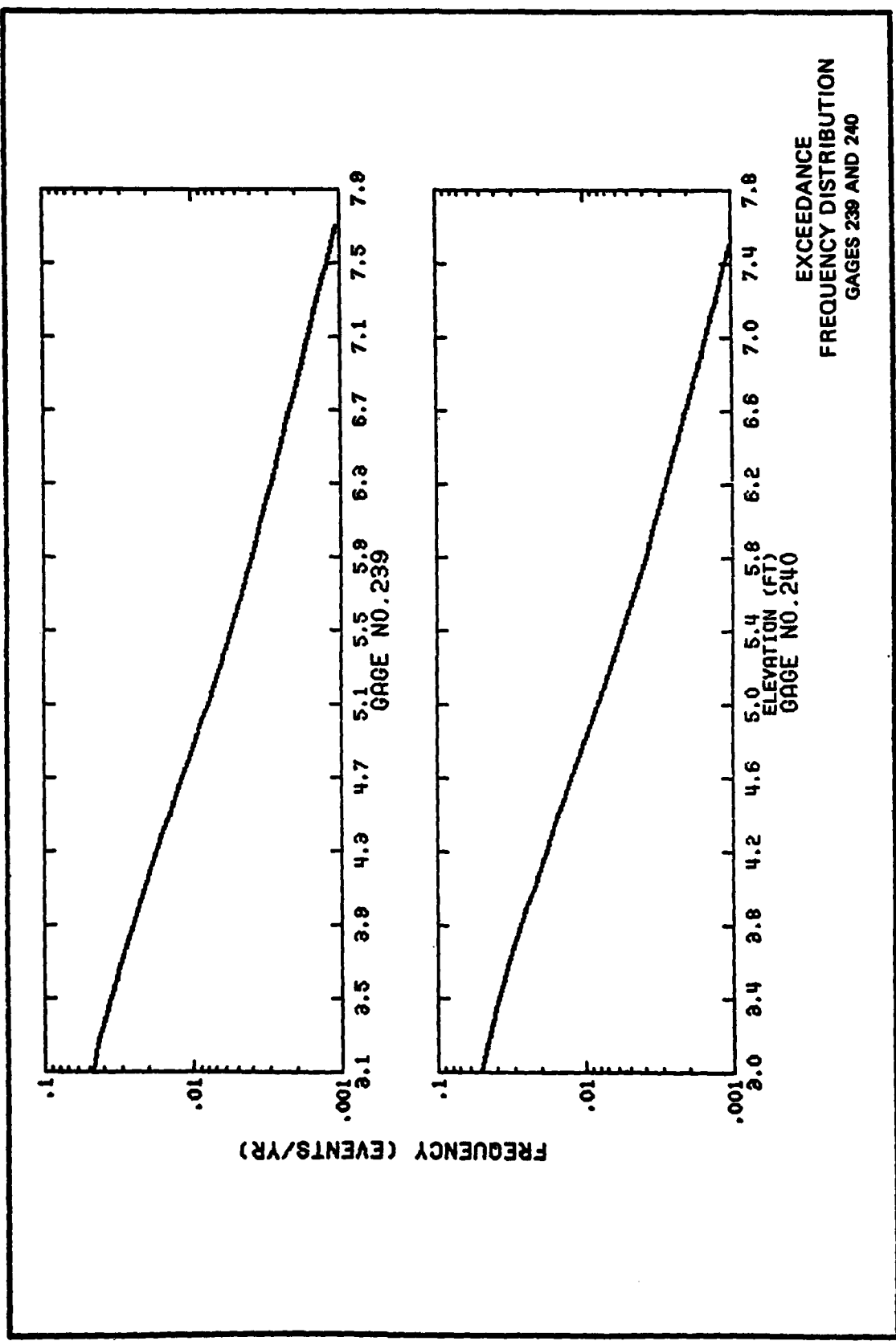


PLATE 120

APPENDIX A: EFFECT OF NODE FACTOR TEMPORAL VARIATION
ON JOINT PROBABILITIES

1. In constructing exceedance frequency distributions for extremal heights resulting from joint occurrences of tsunamis and the astronomical tide, a period of time for the analysis must be selected. However, the inclination of the moon's orbit to the plane of the earth's equator (called an obliquity factor) varies throughout an 18.6-yr cycle because of the revolution of the moon's node. The ratio obtained by dividing the true obliquity factor by its mean value is called a node factor since it is a function of the longitude of the moon's node. The node factor thus has an 18.6-yr cycle. If a period of time less than 18.6 yr is selected for an analysis of joint occurrences of tsunamis and the astronomical tide, the influence of the temporal variation of the node factor is neglected. In this appendix it will be shown that if a particular year (instead of 18.6 yr) is selected for the analysis, the effect of the temporal variation in the node factor on the exceedance frequency distribution is negligible. Thus only a single year instead of 18.6 yr needs to be considered in the analysis and this results in a significant reduction of required computational expense.

2. The effect of a temporal variation of the node factor on external heights resulting from joint occurrences of tsunamis and the astronomical tide can be estimated using an analytical solution described by Houston and Garcia (1974). Since tsunamis have periods much less than 18.6 yr, the variation in the node factor is assumed to be negligible during a tsunami (in fact, the node factor in standard tidal harmonic analysis is assumed to be constant over an entire year).

Let

z = the water elevation at any time above local mean sea level.

$P_T(z)$ = the exceedance frequency distribution for the water level at a site being equal to or exceeding z due only to the maximum wave of the tsunami.

$P_N(z)$ = the exceedance frequency distribution of the water level at a site being equal to or exceeding z due only to the temporal variation of the node factor of the astronomical tide.

$P(z)$ = the exceedance frequency distribution of the water level at a given site being equal to or exceeding z due to both the maximum wave of the tsunami and the node factor of the astronomical tide.

3. According to Chandrasekhar (1943), $P(z)$ can be calculated from

$$P(z) = \int_{-\infty}^{\infty} f_N(\lambda) P_T(z - \lambda) d\lambda \quad (A1)$$

where

$$f_N(z) = - \frac{dP_N(z)}{dz} \quad (A2)$$

and $f_N(z)$ is the frequency density for the astronomical tide. If $P_N(z)$ is approximated by a Gaussian distribution, then

$$f_N(z) = \frac{1}{\sqrt{2\pi}\sigma} e^{-(z^2/2\sigma^2)} \quad (A3)$$

where the variance, σ^2 , is given by

$$\sigma^2 = \sum_{m=1}^{\infty} C_m^2 \quad (A4)$$

and C_m equals the height variation of the node factor associated with the m th tidal constituent.

4. It is well-known that the logarithm of $P_T(z)$ is linearly related to tsunami elevations (see PART III). Therefore, let

$$P_T(z) = Ae^{-\alpha z} \quad (A5)$$

Substituting Equations A3 and A5 into Equation A1 yields

$$P(z) = Ae^{-\alpha[z - (\alpha\sigma^2/2)]} \quad (A6)$$

or

$$P(z) = Ae^{-\alpha z^1} \quad (A7)$$

where

$$z^1 = z - \frac{\alpha\sigma^2}{2} \quad (A8)$$

5. Thus, the net effect of the temporal variation in the node factor is to produce a $P(z)$ identical with $P_T(z)$ except for a shift of z by an amount $\alpha\sigma^2/2$. The variance σ^2 can be determined by multiplying the nodal factor variation for each tidal constituent (Schureman 1948) times the amplitude of the tidal constituents (tidal constituents available from the National Ocean Survey). This product equals C_m in Equation A4; α can be determined at a location using Plates 1-120 by approximating the curves with straight lines and determining the slope of the lines.

6. For example, gage 104 is the site of the Los Angeles tide gage. From Plate 52 α is found to be equal to approximately 0.54. σ^2 equals 0.17.

7. Thus $\alpha\sigma^2/2 \approx 0.05$ ft. Hence, the exceedance frequency distribution based upon a year for which the major tidal constituents have an average value (approximately 1.0) should be shifted relative to an 18.6-yr period by approximately 0.06 ft for all frequencies.

8. The analytic solution presented was shown to be correct by a direct numerical approach. The year 1964 was selected as the year for which the major tidal constituents have an average value. The 18.6-yr period was centered on 1964. Tsunami and tidal elevations were expressed to the nearest 0.1 ft. It was found that the exceedance frequency distributions for the 1-yr and 18.6-yr period had the same 50-yr, 200-yr, 500-yr, and 1000-yr elevations. The 100-yr elevation was different by

APPENDIX B: NOTATION

a	Length of major axis of elliptical source, miles
A	Amplitude constant
b	Length of minor axis of elliptical source, miles
c_m	m^{th} nodal constituent
$f(\)$	Probability density function
F	Tsunami frequency
H_a	Wave height in direction of major axis of ellipse, ft
H_b	Wave height in direction of minor axis of ellipse, ft
H_{avg}	Average runup over a coast, m
i	Tsunami intensity
$n(\)$	Tsunami probability function
p	Constant
$P(\)$	Exceedance frequency distribution for combined node factor variation and tsunamis
$P_N(\)$	Exceedance frequency distribution for node factor variation
$P_T(\)$	Exceedance frequency distribution for tsuanmis
q	Constant
r	Constant
x	Spatial coordinate, ft
y	Spatial coordinate, ft
z	Water-surface elevation above mean sea level (msl), ft
α	Exponential constant
λ	Variable of integration
σ^2	Variance

In accordance with letter from DAEN-RDC, DAEN-ASI dated 22 July 1977, Subject: Facsimile Catalog Cards for Laboratory Technical Publications, a facsimile catalog card in Library of Congress MARC format is reproduced below.

Houston, James R

Type 19 flood insurance study: Tsunami predictions for southern California / by James R. Houston. Vicksburg, Miss. : U. S. Waterways Experiment Station; Springfield, Va. : available from National Technical Information Service, 1980.

48, [6] p., [60] leaves of plates: ill. ; 27 cm. (Technical report - U. S. Army Engineer Waterways Experiment Station ; HL-80-18)

Prepared for Federal Insurance Administration, Federal Emergency Management Agency, Washington, D. C.

References: p. 46-48.

1. Floodplain insurance. 2. Mathematical models. 3. Numerical analysis. 4. Shorelines. 5. Southern California. 6. Tsunamis. I. United States. Federal Insurance Administration. II. Series: United States. Waterways Experiment Station, Vicksburg, Miss. Technical report ; HL-80-18.
TA7.W34 no.HL-80-18