UNIVERSITY OF MINNESOTA
ST. ANTHONY FALLS HYDRAULIC LABORATORY

Project Report No. 120

An Evaluation of Acoustic Techniques for Measuring Gas Bubble Size Distributions in Cavitation Research

by
FRANK R. SCHIEBE
and
JOHN M. KILLEN

This research was sponsored by the Naval Ship Systems Command General Hydromechanics Research Program administered by the Naval Ship Research and Development Center. Prepared under Contract N00014-67-A-0113-0014.

MAY 1971
MINNEAPOLIS, MINNESOTA

CONTENTS

Page

List of Illustrations v

Abstract vii

I. INTRODUCTION 1

II. CRITERIA FOR A BUBBLE SIZE DISTRIBUTION MEASUREMENT SYSTEM 2

III. THE ACOUSTIC PULSE ATTENUATION TECHNIQUE 4

IV. CONCLUSIONS 8

List of References 9

Figures 1 thru 8 11

LIST OF ILLUSTRATIONS

Figure

1 Typical Blunt Body, $C_{p,min} = -0.6$

2 Continuous Assumed Bubble Size Distribution

3 Bubble Size Distribution, 2×10^{-5} ft Subrange Width

4 Bubble Size Distribution, 1.5×10^{-5} ft Subrange Width

5 Bubble Size Distribution, 10^{-5} ft Subrange Width

6 Effect of Subrange Width and Volume Concentration on the Computed Cavitation Occurrence Rate Characteristics for Source Disk Body, $C_{p,min} = -0.6$

7 Volume Concentration Distribution, $\alpha = 0.0335$ vppm

8 Calculated Acoustic Amplitude Attenuation Distribution for various Volume Concentration Levels

ABSTRACT

The acoustic tone burst attenuation technique for measuring the gas bubble size distribution in water was critically reviewed. The findings reveal that the usefulness of the technique is limited to the bubble volume concentration range between 0.03 and 1.0 parts per million. Furthermore, resolution between size ranges is probably not possible with sufficient accuracy for many purposes.

AN EVALUATION OF ACOUSTIC TECHNIQUES FOR MEASURING GAS BUBBLE SIZE DISTRIBUTIONS IN CAVITATION RESEARCH

I. INTRODUCTION

The need to measure gas bubble size distribution in water tunnel research has been dealt with in the literature for a number of years. Many techniques and methods based on the principles of light, acoustics, gravitational separation, electronics, and photography have been investigated [1,2,3,4]*. In recent years technological progress in optics and acoustics has provided an impetus to pursue measurement techniques based on the attenuation and scattering of sound and light for application to the problem of cavitation.

A good deal of effort has been expended at the St. Anthony Falls Hydraulic Laboratory in studying the basic phenomena of what has been variously called limited, bubbly, and transient cavitation [5]. Briefly, in this process the trajectory of an entrained nucleus carries it into a region of fluid which is superheated by virtue of the low dynamic pressures.

The basic assumption has been made in these and other tunnel investigations that these nuclei are primarily gas filled microbubbles stabilized by the turbulent processes in the tunnel. Under certain conditions, when the bubble is very small the surface tension forces prevent vaporous expansion. At some critical size these forces are overcome and the liquid rapidly changes phase at the nucleus wall, which rapidly expands the bubble.

In conjunction with this fundamental work with the physics of cavitation, methods of measuring the bubble size distribution--deemed critical to an understanding of the process by many researchers--have been sought. The effect of the entrained microbubbles upon the acoustic properties of the water seemed to offer distinct possibilities for measuring this distribution.

Bubbles have primarily two effects on the acoustic properties of the entrained liquid: they generally tend to decrease the sonic velocity and they produce an attenuation due to the absorption and scattering. Initial efforts at this laboratory utilized the change in the sonic velocity as an indication of the total free gas concentration [6]. The two main difficulties with this measurement were that the change in sound speed was very

---

*Numbers in brackets refer to references listed on page 9.

small at the free gas concentrations of interest (a few parts per million or less) and that the measurement gave only a total concentration with no indication of how the sizes were distributed. As knowledge of cavitation grew it became apparent that this total concentration of free gas bubbles was insufficient for cavitation research and that gas bubble distributions were required. The St. Anthony Falls Hydraulic Laboratory then began developing an instrumentation technique based on the attenuation of an acoustic pulse as it is transmitted through a liquid with entrained microbubbles [2] and on the fact that only bubbles whose resonant sizes are at or near the carrier frequency of the acoustic pulse contribute to the attenuation of that pulse. This is the technique to be evaluated in this report. It will be analyzed in relation to the requirements of the cavitation problem and the measurement capabilities of the existing acoustic instrumentation system.

II. CRITERIA FOR A BUBBLE SIZE DISTRIBUTION MEASUREMENT SYSTEM

The output of any system designed to measure the size distribution would most likely take the form of a histogram with either constant or variable size ranges. In reality, of course, the size distribution is continuous, and questions arise regarding the accuracy of the bubble concentrations found in each size range and the width of size range required to adequately describe the real process.

It is first desirable to establish a set of requirements, based on a cavitation problem of interest, which a measuring instrument would have to satisfy. To accomplish this a typical cavitation example will be postulated and used to determine the accuracy of the measurement system.

The physical model to be used in the example is an axially symmetrical blunt body 5/8 of an inch in diameter in a six-inch water tunnel. The tunnel velocity will be 30 fps and the water temperature 70°F. The shape of the test body has been derived mathematically by placing a source disk in a uniform flow field and determining the streamline through the stagnation point. This body is shown in Fig. 1 along with its streamline and isobar patterns in the fluid. The advantage of using a body of this type is that the problem is amenable to analytical investigation.

The size distribution of the entrained microbubbles is, for the purposes of this example, described by the continuous function

$$p(r) = (r/\delta^2)\ \exp(-r^2/2\delta^2)$$

where r = bubble radius, δ = most probable size, and $p(r)$ = probability density; this distribution is shown in Fig. 2. The distribution is also assumed to be spatially homogeneous, which means that the statistical characteristics of the microbubbles entrained in any stream tube in the flow are identical. The total number of nuclei in the distribution or the total volume concentration will be varied in order to illustrate certain features and limitations of the acoustic measurement technique, but the distribution of the sizes will be considered typical and constant in the entire sample.

An analytical model which has been developed to relate the distribution of the entrained bubbles to the expected cavitation result [5] will be used. This model predicts the severity of cavitation in terms of cavitation occurrence rates based on the hydrodynamic characteristics of the test body, the pressure and velocity of the test water, and the numbers and sizes of entrained microbubbles. In this connection the cavitation occurrence rate is defined as the number of times per second that a nucleus enters the superheated region around the test body and cavitates. The number of cavitation events contributed by each stream tube is equal to the number of microbubbles flowing in the stream tube which exceed the critical size determined by the static stability theory. A good deal of experimental evidence has been accumulated concerning the cavitation occurrence rates associated with similar bodies. This experience will be used in selecting the number of bubbles in the distribution so that typical cavitation rates will occur.

It has been shown that the pressure gradient in front of the body deflects the bubbles out of the stream tube in which they were originally entrained [7]. This effect can modify the results somewhat, especially with small blunt bodies. However, the differences are expected to be small and to decrease as the body becomes more streamlined and as the relative size of the test body increases with respect to the bubble sizes. For the purposes of this example this effect will be neglected.

The distribution of sizes in this example was selected on the basis of previous experience with acoustic measurements. The number of bubbles in the entire range has been adjusted so that typical cavitation occurrence results are obtained. The analytical model will thus produce results which conform closely to observed experimental data.

The critical bubble size above which all bubbles can be assumed to cavitate in each stream tube was determined for several cavitation numbers. The distribution was integrated from the critical size to infinity to obtain the expected number of cavitation events per second in each stream tube. Summation of the contributions of all involved stream tubes at a particular cavitation number gave the total number of expected cavitation events.

As was mentioned previously, the distribution shown in Fig. 2 would normally be represented by measurements in definite size ranges, and thus the widths for these ranges must be determined. The total distribution was divided into eight, eleven, and sixteen subranges, respectively, and the results were compared. These distributions are shown in Figs. 3, 4, and 5 with subrange widths of 2×10^{-5}, 1.5×10^{-5}, and 10^{-5} ft. The cavitation occurrence characteristics as computed by the analytical model are compared with the result for the continuous distribution in Fig. 6. It is apparent that the width of the size ranges for the example presented should not exceed 10^{-5} ft for an accurate prediction of the severity of cavitation.

The precision with which the probability of bubbles in any given size range can be determined is also an essential parameter used directly in the computation for the cavitation occurrence rate. The individual errors incurred in determining the probability for each size range accumulate and contribute to a total error in the occurrence rate.

III. THE ACOUSTIC PULSE ATTENUATION TECHNIQUE

As stated previously, the measurement is based on the amplitude attenuation of an acoustic tone burst as it is propagated through the test water. The attenuation is measured as a function of the carrier frequency of the tone burst over the range of interest. The relationship between the bubble size and its resonant frequency and the fact that only bubbles at or near resonance contribute significantly to the sound attenuation are well known [8]. This effect can be measured using the tone burst technique, and the measured attenuation due to the bubbles is related to the concentration of bubbles. The ratio between the tone burst amplitudes under test conditions with bubbles present and under high-pressure conditions with bubbles absent is a measure of the attenuation due to the resonant and near resonant bubbles.

Since the acoustic attenuation is related to the volume concentration of resonance-size bubbles, and the analytical cavitation model requires the number of bubbles contained in any size range, the data reduction process must include the conversion from volume concentration to discrete numbers of bubbles.

The process of computing the bubble volume concentration in each size range from the distribution involves a somewhat complicated infinite series. However, as a first approximation the range volume concentration can be obtained by multiplying the number of bubbles flowing in the size range by the volume of the bubble size in the center of the range divided by the volume of water flowing through the test section. The accumulation of the concentrations determined in this manner differed by a factor of only approximately 6 per cent from the total concentration determined by integrating the assumed distribution function over the entire range using the relationship

$$c = \frac{4\pi N \times 10^6}{3Q\delta^2} \int_0^\infty r^4 e^{-r^2/2\delta^2} dr = \frac{2\sqrt{2}\ \pi^{3/2} N \delta^3}{Q} \times 10^6$$

where c = total volume concentration in ppm,

N = total number of bubbles flowing through the test section per second,

and Q = total volume of water through the test section per second.

In the present example the total number of bubbles flowing, N, is a parameter which can be used to illustrate several points. The data of Fig. 5 are presented in Fig. 7 on the basis of volume concentration in each range for an overall volume concentration of 0.335 ppm, which in this example amounts to $N = 10^5$ bubbles per second flowing through the test section. For other concentrations this plot is merely scaled by the value of N. It is significant that the maximum in the concentration distribution occurs at a much higher bubble size than the maximum of the nuclei number distribution.

The acoustic attenuation to be expected with the concentration and distribution of microbubbles present in a typical cavitation inception study was calculated. The results are shown in Fig. 8 based on an assumed acoustic path length of 16 cm. The computer program developed by Brockett [9] was used to make the computations shown. The program was modified to use concentration and size as input data and produce the value of acoustic attenuation.

Based on the results of Fig. 8 a theoretical estimate can be made of the sensitivity and precision required for an attenuation measuring technique to be useful in measuring microbubble size and concentration. The attenuation ratios given in Fig. 8 would correspond to voltage amplitude ratios as measured by the pulse height tone burst method of acoustic attenuation measurement [2].

The acoustic pulse propagation method places upper and lower practical limits on the microbubble concentration which can be measured. The upper limit is imposed by an attenuation which suppresses all signals from the transmitter received at the receiving transducer. High levels of transmitted power will alter the microbubble properties. The lower limit is imposed by the change in receiving transducer output which can be identified as due to microbubbles rather than to random effects of temperature, random microbubble structure, and diffraction effects [10].

The attenuations calculated in Fig. 8 are based on a plane wave solution. Acoustic measurements using the pulse method in a water tunnel have previously required the use of spherical waves (the sonic pulse frequency and wavelength to be used are determined by bubble size, and the size of the water tunnel test section limits the size of the transducer; these two tank limitations make the generation of plane waves in the test section very difficult). Spherical waves generated by a small transducer are only approximately spherical near the transducer; consequently diffraction effects arise which may give a changing virtual path length at different frequencies and concentrations. No study has been found which gives the precise correction necessary at the low attenuations (or concentrations).

Experience in reading the pulse height gives rise to the following optimistic estimates: The test section pressure, of the order of 1/4 atmosphere, is typical. Under these conditions the resonant frequencies of interest range from approximately 25 kHz to 300 kHz, and appropriate acoustic transducers should be utilized. Ceramic disks 0.25 inches in diameter by 0.1 inches thick would be satisfactory.

For the particular size distribution in this example, the total volume concentration range within which the technique could be useful is that between 0.033 ppm and 1.0 ppm, which correspond, respectively, to 10^5 and 3×10^6 nuclei per second through the test section. Similar reasonable size distributions should give results which differ very little from those reported here. Attempts to measure concentrations outside the concentration range specified above would result in attenuations either too small to be observed or so large that the signal was completely obliterated.

It is standard practice in many water tunnels to operate with a dissolved gas concentration whose relative saturation at test section pressure is unity. In most other sections of the tunnel the relative saturation based on the local pressure is therefore less than unity and the water is undersaturated. Based on atmospheric pressure rather than test section pressure, this amounts to a relative saturation of about 0.25 in the test section for the example discussed in this work.

A comparison between the results of the analytical model shown in Fig. 6 and extrapolations from experimental data taken by the authors [5] in the St. Anthony Falls six-inch water tunnel under very similar circumstances (identical flow conditions, minimum pressure coefficients, and body diameters) reveals that the free gas content of the experimental water is described by a cavitation characteristic similar to one of the lower curves of Fig. 6. In other words, the free gas content of the tunnel water in the test section is at least an order of magnitude lower than the 0.03 vppm which represents the lower limit of the acoustic attenuation method. In many practical situations, therefore, the acoustic method lacks sufficient sensitivity to be useful.

The minimum volume concentration for which the acoustic pulse attenuation technique is valid is indicated for the present example in Fig. 6 by the characteristic line representing a total concentration of 0.0335 vppm or, in terms of this example, by 10^5 nuclei per second passing through the test section. Under these circumstances very high cavitation occurrence rates are observed at cavitation numbers just under the absolute magnitude of the minimum pressure coefficient of the test body.

Comparison of this characteristic line with the experimental data shows that under these circumstances in the St. Anthony Falls tunnel the water must exhibit a relative saturation of 2 based upon the test section pressure. This value substantially exceeds the standard operating conditions of many tunnels.

Certain errors are also expected within the volume concentration range in which the acoustic pulse attenuation technique is valid. In the experiments, voltages are measured which represent the acoustic pulse heights. It is estimated that this measurement can be accurate only to plus or minus 3 per cent of full scale with present techniques. When this error is applied to the expected attenuations of Fig. 8, it becomes apparent that over large portions of the total range no differences can be detected experimentally in the volume concentration measurements. This would tend to flatten the distribution shown in Fig. 7.

No difference in volume concentration could be determined in the present example over 62 per cent of the total range of the distribution at the 0.033 ppm level under the worst conditions. At the 0.165 ppm volume concentration level this proportion dropped to 31 per cent. At the 0.33 ppm level about 19 per cent of the range could not be separated under the worst conditions. As the volume concentration rose from this value to the 1.0 ppm level, the proportion rose to 31 per cent again. As previously stated, beyond this concentration the errors are so large that the technique is probably not valid.

Presented from an alternate point of view, the calculation also revealed that in the usable range the technique is sensitive to approximately one resonant bubble per cubic wavelength at the usable minimum attenuation and to approximately 35 resonant bubbles per cubic wavelength at maximum usable attenuation. This calculation is nearly independent of resonant frequency.

IV. CONCLUSIONS

It is concluded that in general the acoustic tone burst attenuation technique is usable in a concentration range of approximately 0.03 to 1.0 parts per million, which is about an order of magnitude higher than the expected concentration level in water tunnel test sections under most usual cavitation inception test conditions. Furthermore, within the usable range the concentration contained in a small subrange cannot be resolved or determined using present methods and techniques with enough precision to be usable in the analytical cavitation model to produce valid cavitation occurrence rate results.

REFERENCES

[1] Keller, A., "Ein Streulicht-Zählverfahren, Angewandt zur Bestimmung des Kavitationskeimspektrums," Optic, 32, Band 1970, Seiten 165-176.

[2] Killen, J. M. and Ripken, J. F., A Water Tunnel Air Content Meter, Project Report No. 70, St. Anthony Falls Hydraulic Laboratory, University of Minnesota, February 1964.

[3] Ilichev, V. I. and Neuimin, G. G., "Size Distribution Law of Gas Bubbles in a Turbulent Liquid Flow," Soviet Physics-Acoustics, Vol. 11, No. 4, April - June, 1966.

[4] Ahmed, O. and Hammitt, F. G., "Determination of Particle Population Spectra from Water Tunnel Using Coulter Counter," 1969 Cavitation Forum, ASME, June 1969.

[5] Schiebe, F. R., The Influence of Gas Nuclei Size Distribution on Transient Cavitation near Inception, Project Report No. 107, St. Anthony Falls Hydraulic Laboratory, University of Minnesota, 1969.

[6] Ripken, J. F. and Killen, J. M., A Study of the Influence of Gas Nuclei on Scale Effects and Acoustic Noise for Incipient Cavitation in a Water Tunnel, Technical Paper No. 27-B, St. Anthony Falls Hydraulic Laboratory, University of Minnesota, 1959.

[7] Johnson, V. E., Jr., and Hsieh, T., "The Influence of the Trajectories of Gas Nuclei on Cavitation Inception," Sixth Symposium on Naval Hydrodynamics, Washington, D. C., September 28-October 4, 1966.

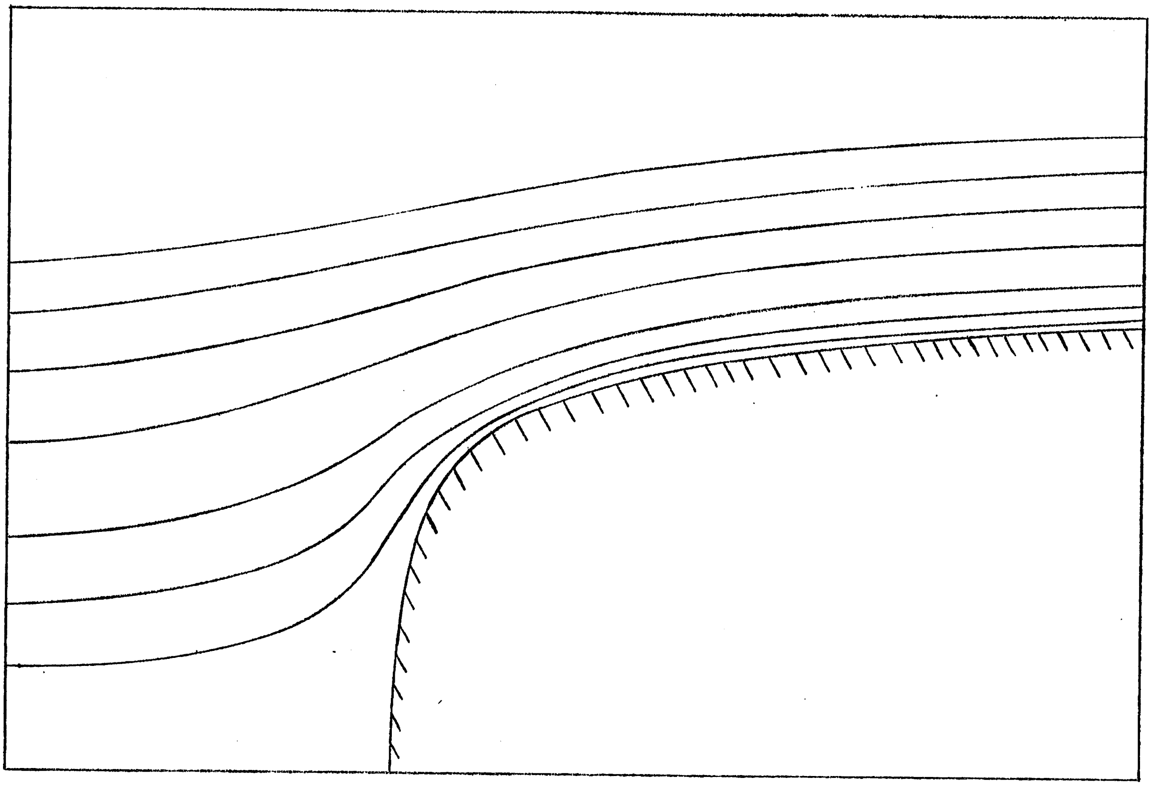
[8] Albers, V. M., Underwater Acoustics Handbook, The Pennsylvania State University Press, 1960, p. 81.

[9] Brockett, Terry, Computational Method for Determination of Bubble Distributions in Liquids, Report 2798, Naval Ship Research and Development Center, Washington, D. C., April 1969.

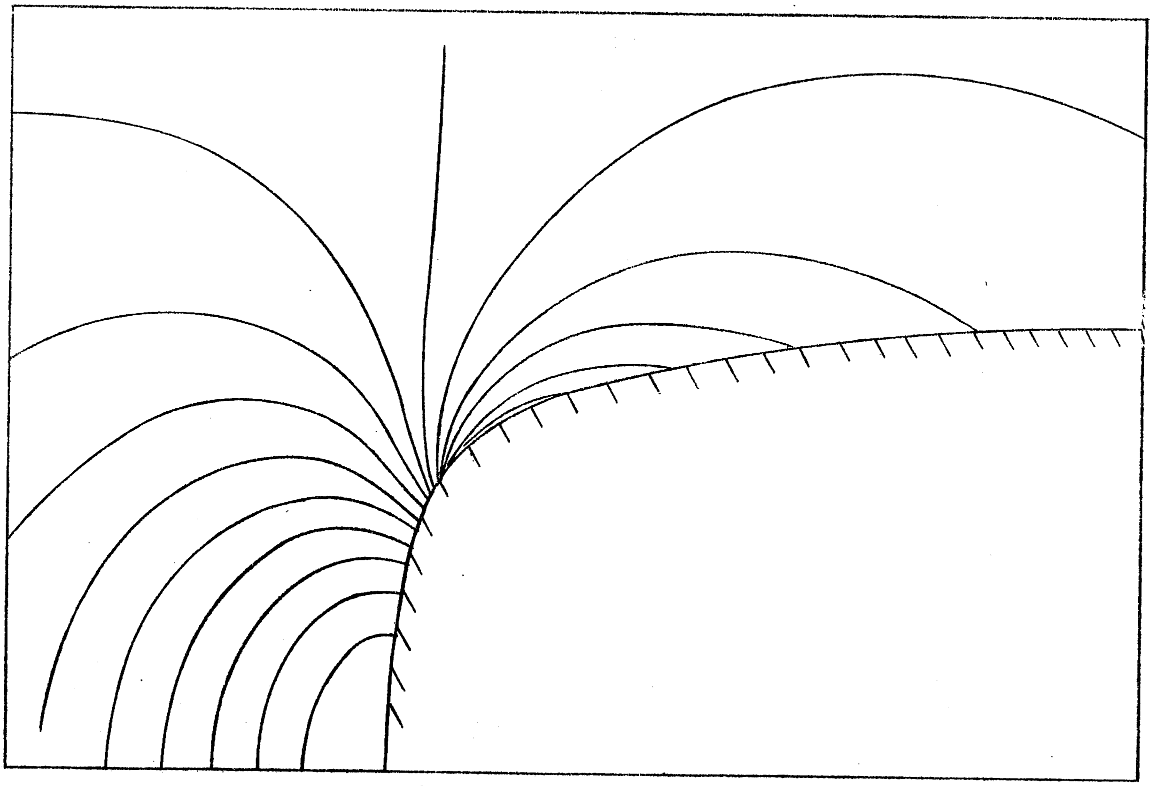
[10] Seki, H.; Granato, A.; and Truell, R., "Diffraction Effects in the Ultrasonic Field of a Piston Source and Their Importance in the Accurate Measurement of Attenuation," Journal of the Acoustical Society of America, Vol. 28, No. 2, March 1956.

ILLUSTRATIONS

(Figs. 1 thru 8)



a. Body with Streamlines



b. Body with Isobars

Fig. 1 - Typical Blunt Body, $C_{p,min} = -0.6$

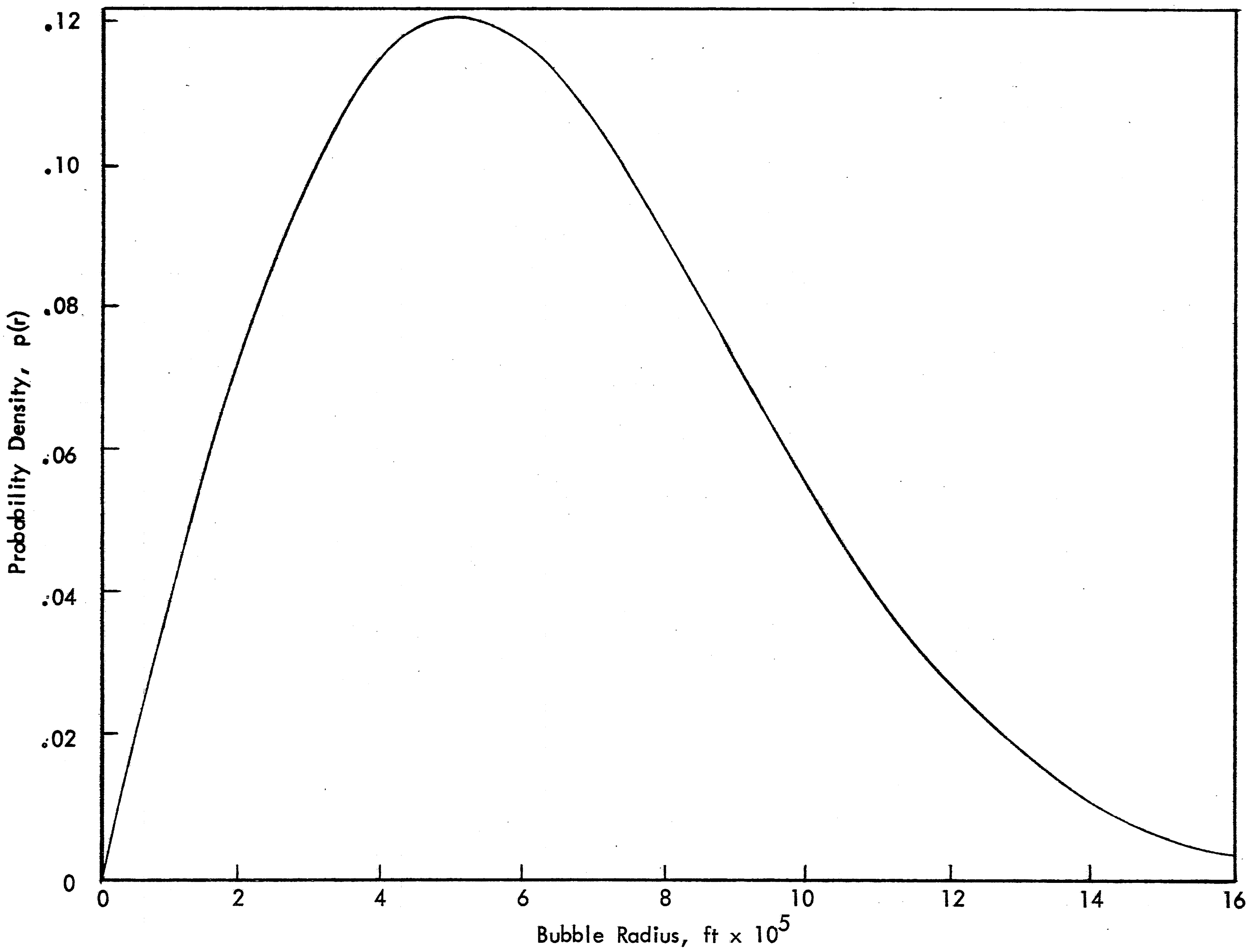
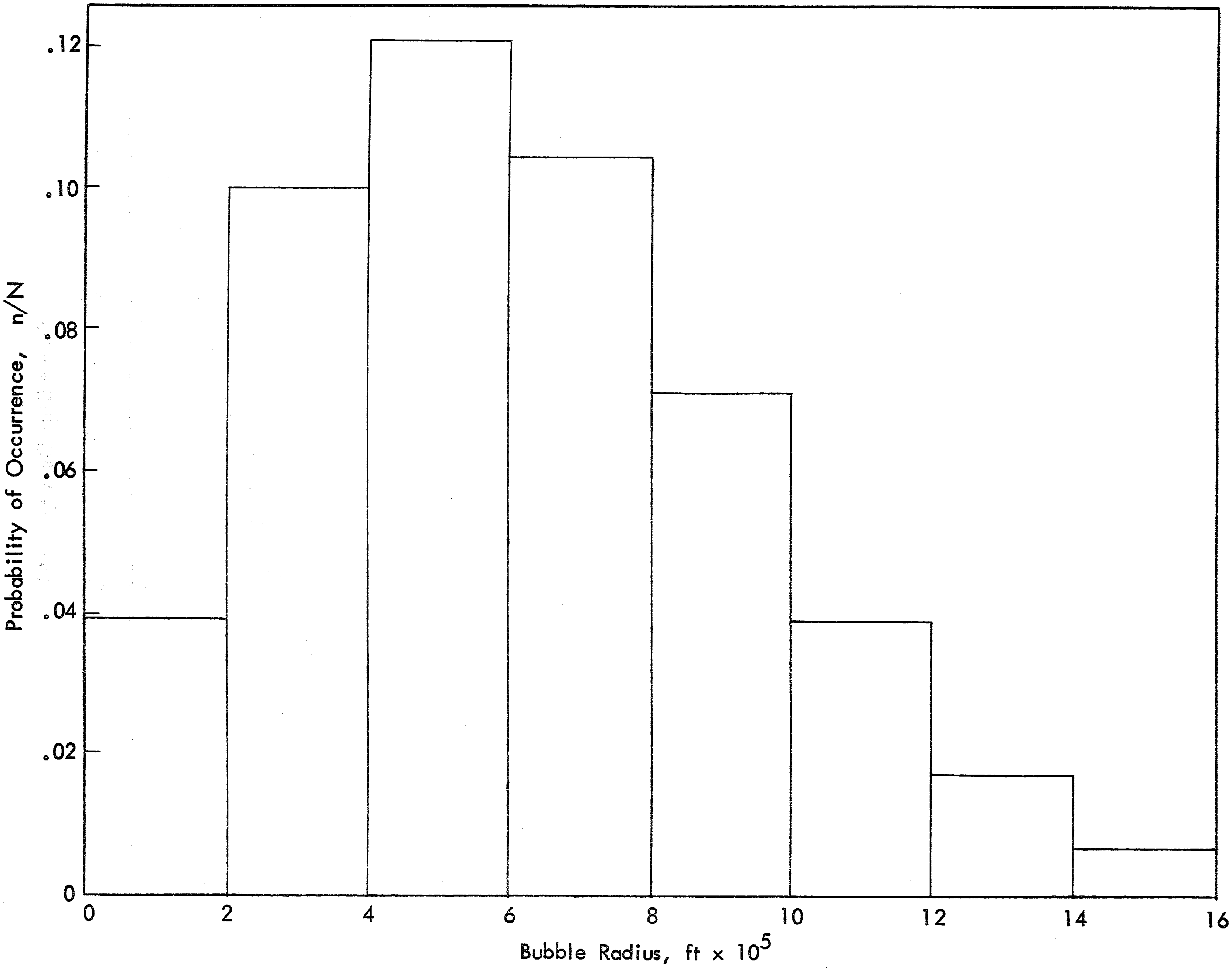


Fig. 2 - Continuous Assumed Bubble Size Distribution



Fif. 3 - Bubble Size Distribution, 2×10^{-5} ft Subrange Width

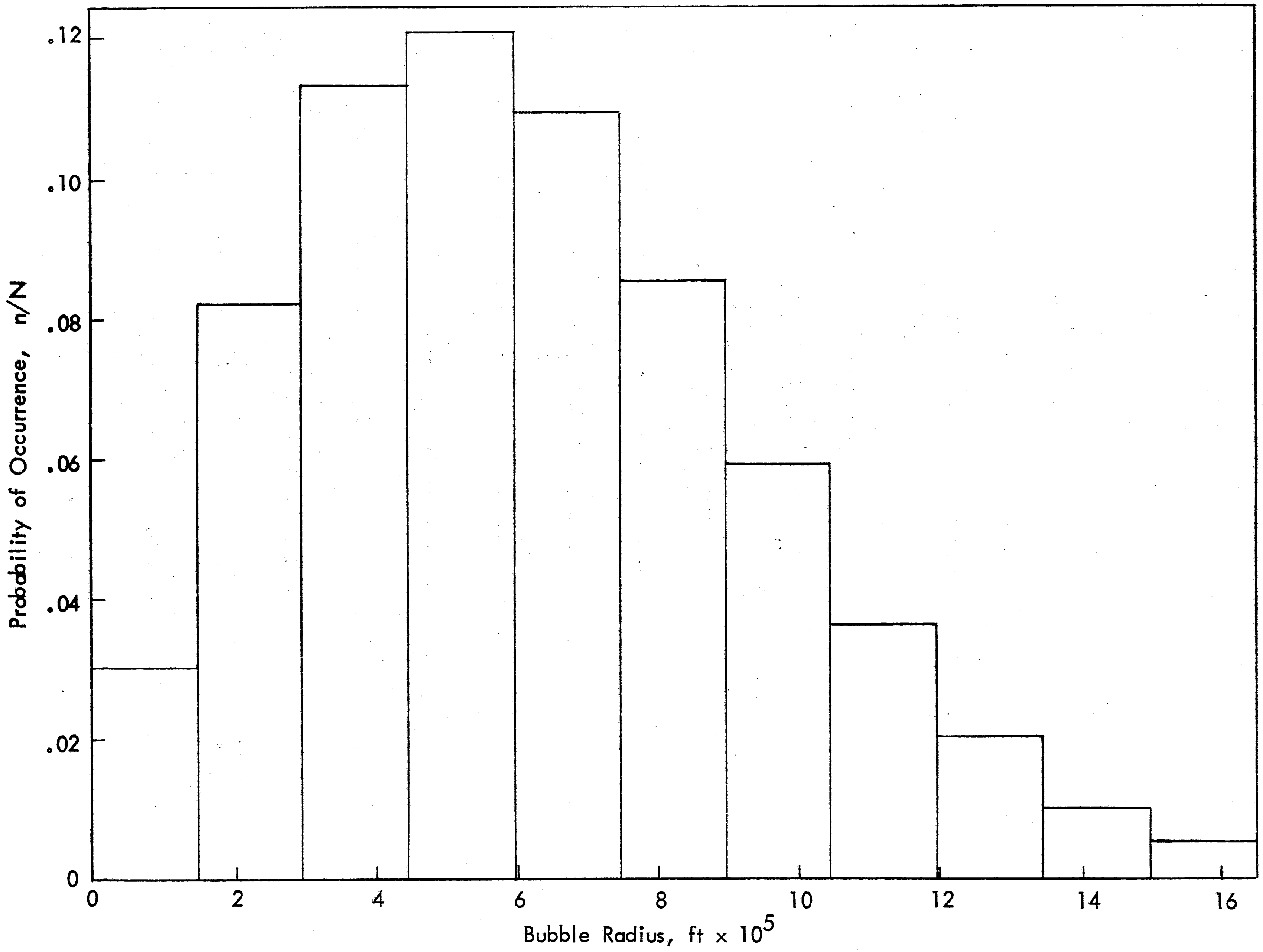


Fig. 4 - Bubble Size Distribution, 1.5 × 10^{-5} ft Subrange Width

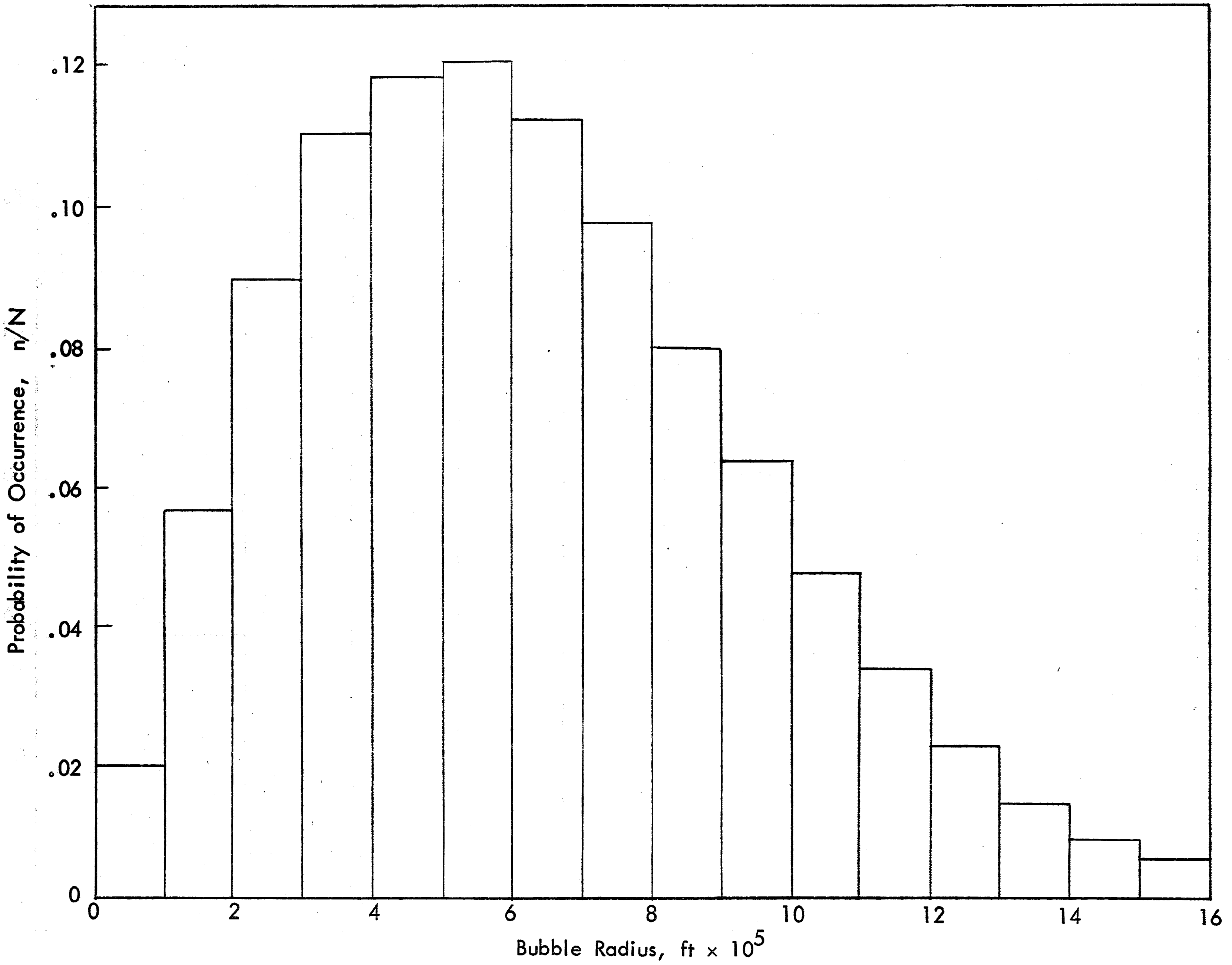


Fig. 5 - Bubble Size Distribution, 10^{-5} ft Subrange Width

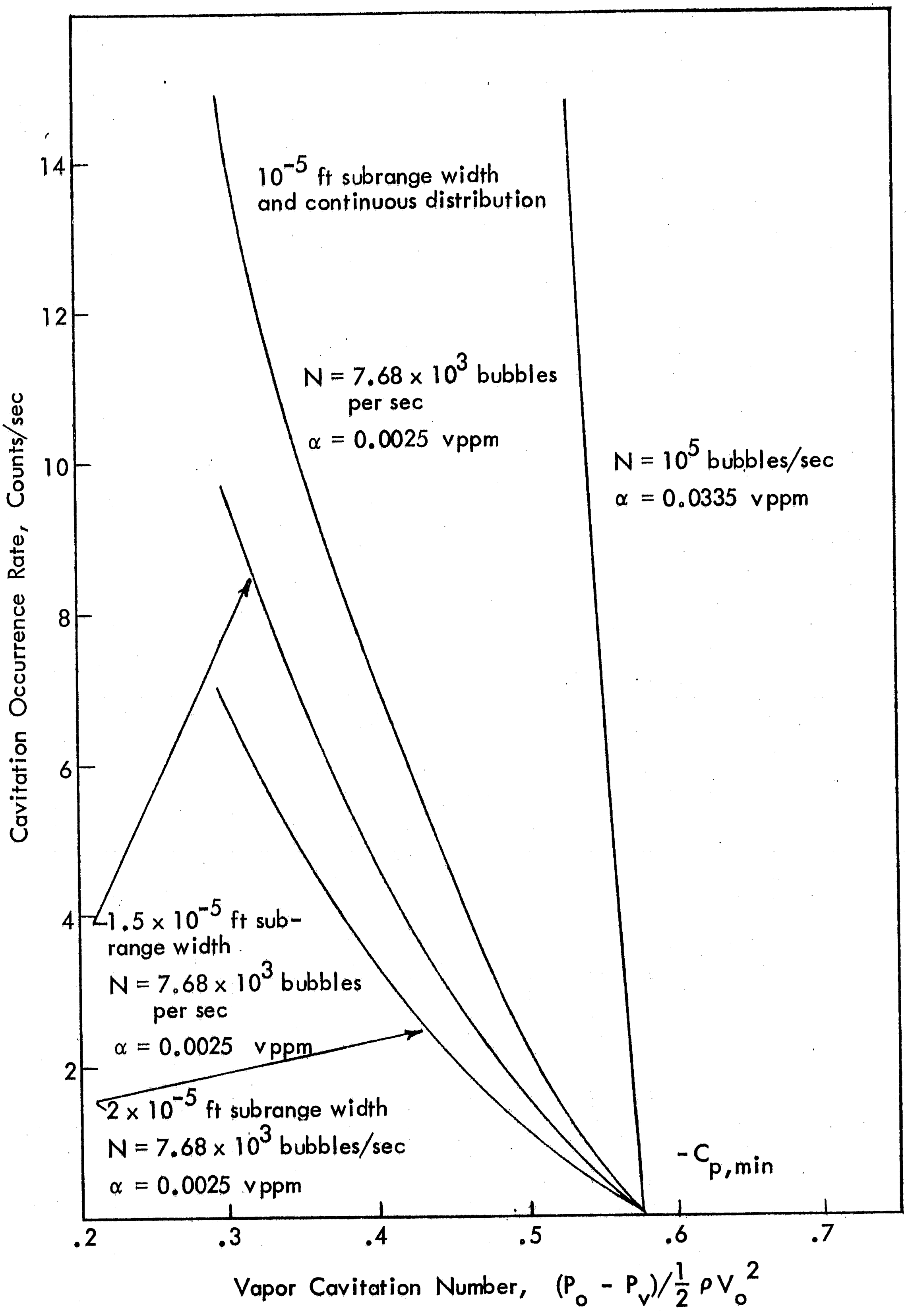


Fig. 6 - Effect of Subrange Width and Volume Concentration on the Computed Cavitation Occurrence Rate Characteristics for Source Disk Body, $C_{p,min} = -0.6$

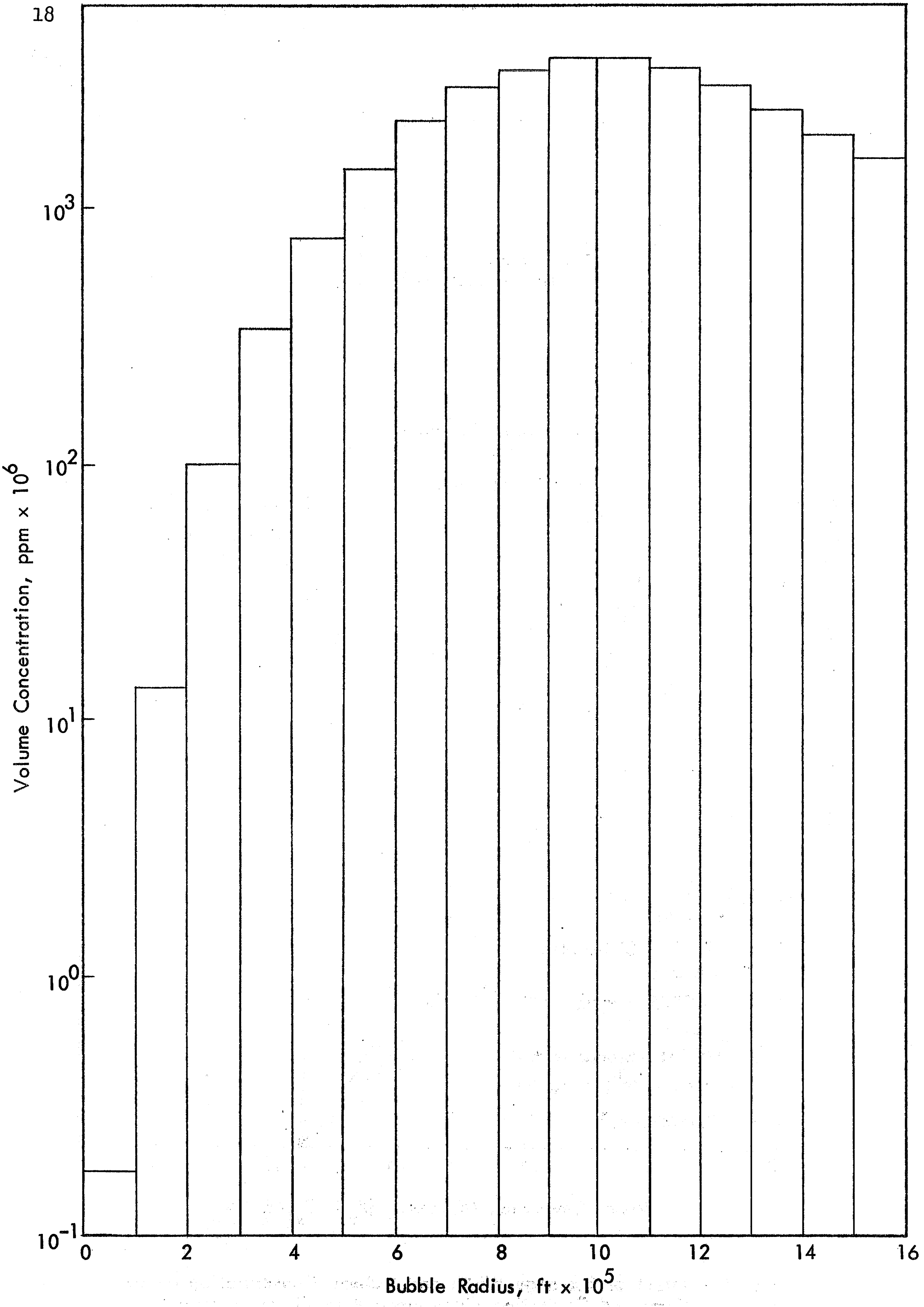


Fig. 7 - Volume Concentration Distribution, $\alpha = 0.0335$ vppm

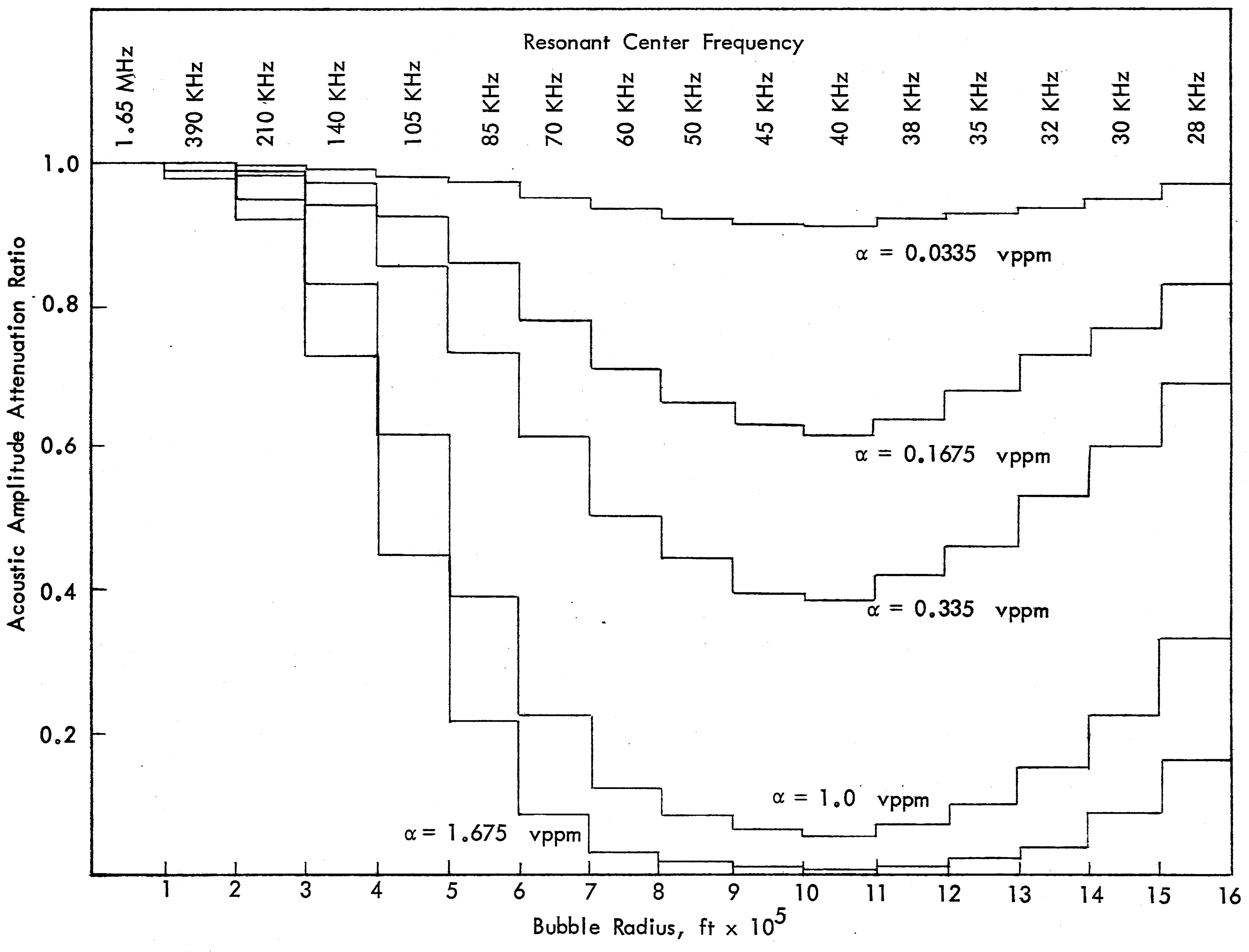


Fig. 8 - Calculated Acoustic Amplitude Attenuation Distribution for various Volume Concentration Levels

DISTRIBUTION LIST FOR PROJECT REPORT NO. 120
of the St. Anthony Falls Hydraulic Laboratory

Copies	Organization
40	Commander, Naval Ship Research and Development Center, Washington,D.C. 20034, Attn: 39 - Code L41 1 - Code 513
2	Commanding Officer, Naval Ship Research and Development Laboratory, Annapolis, Maryland 21402, Attn: Library
2	Commanding Officer, Naval Ship Research and Development Laboratory, Panama City, Florida 32402, Attn: Library
8	Commander, Naval Ship Systems Command, Department of the Navy, Washington, D.C. 20360, Attn: 1 - Code 0342 DEF 1 - Code 037 ADF 1 - Code 00V F 3 - Code 2052 1 - Code PMS381 ABCDF 1 - Code 03412
12	Director, Defense Documentation Center, 5010 Duke Street, Alexandria, Virginia 22314
1	Chief of Naval Research, Department of the Navy, Arlington, Virginia 22217, Attn: Mr. Ralph D. Cooper, Code 438
1	Director, Office of Naval Research Branch Office, 495 Summer Street, Boston, Massachusetts 02210
1	Director, Office of Naval Research Branch Office, 219 S. Dearborn Street, Chicago, Illinois 60604
1	Office of Naval Research Resident Representative, 207 West 24th Street, New York, New York 10011
1	Chief Scientist, Office of Naval Research Branch Office, 1030 East Green Street, Pasadena, California 91101
1	Director, Office of Naval Research Branch Office, 50 Fell Street, San Francisco, California 94102
3	Director, Naval Research Laboratory, Washington, D.C. 20390, Attn: Library, Code 2029 ONRL

Copies	Organization
1	Commander, Naval Facilities Engineering Command, Department of the Navy, Washington, D.C. 20390, Attn: Code 0321 BCDE
5	Commander, Naval Ship Engineering Center, Department of the Navy, Center Building, Prince Georges Center, Hyattsville, Maryland 20782, Attn: Code 6110 Code 6114D Code 6136 Code 6140 ADEF Code 6144G (ADEF) Code 6034B
1	Commanding Officer, Naval Air Development Center, Johnsville Warminster, Pa. 18974, Attn: Technical Library
1	Commanding Officer and Director, Naval Applied Science Laboratory, Flushing & Washington Avenues, Brooklyn, New York 11251
2	Officer-in-Charge, Naval Undersea Research & Development Center, 3202 E. Foothill Boulevard, Pasadena, California 91107, Attn: Dr. J. Hoyt AD Dr. A. Fabula AD
1	Commander, Naval Electronics Laboratory Center, San Diego, California 92152, Attn: Library DEF
1	Director, (Code 2027), Naval Research Laboratory, Washington, D.C. 20390
1	Commanding Officer, Navy Underwater Weapons Research and Engineering Station, Newport, Rhode Island 02840
1	Commander, Hunters Point Naval Shipyard, San Francisco, California 94135, Attn: Library
1	Commander, Naval Oceanographic Office, (Library), Department of the Navy Washington, D.C. 20390, BEF
1	Commander, Naval Proving Ground, Dahlgren, Virginia 22448, Attn: Technical Library BDE
1	Commanding Officer and Director, Naval Civil Engineering Laboratory, Port Hueneme, California 93401, Attn: Code L31 DE
1	Director, Naval Research Laboratory F , Underwater Sound Refer- Division, P.O. Box 8337, Orlando, Florida 32806, Attn: Code 8207
1	Commander D , Naval Weapons Center (Code 753), China Lake, California 93555

Copies	Organization
1	Commander, Boston Naval Shipyard, Boston, Massachusetts 02129, Attn: Technical Library
1	Commander, Charleston Naval Shipyard, Naval Base, Charleston, South Carolina 29408, Attn: Technical Library
1	Commander ABCF , Long Beach Naval Shipyard, Long Beach, California 90802, Attn: Technical Library
1	Commander, Norfolk Naval Shipyard, Portsmouth, Virginia 23709, Attn: Technical Library
1	Eastern Research Group, P.O. Box 222, Church Street Station, New York, New York 10008
1	Commander, Pearl Harbor Naval Shipyard, Box 400, Fleet Post Office, San Francisco, California 96610, Attn: Code 246-P
1	Commander, Philadelphia Naval Shipyard, Philadelphia, Penna. 19112, Attn: Code 240 ABCF
1	Commander, Portsmouth Naval Shipyard, Portsmouth, N.H. 03801, Attn: Technical Library
1	Commander, Puget Sound Naval Shipyard, Bremerton, Washington 98314, Attn: Engineering Library
3	Commander, San Francisco Bay Naval Shipyard, Vallejo, California 94952, Attn: 1 - Technical Library 1 - Code 250 1 - Code 130L1 BDE
1	AFFDL (FDDS - Mr. J. Olsen), Wright-Patterson AFB, Dayton, Ohio 45433 BDE
1	NASA Scientific and Technical Information Facility, P.O. Box 33, College Park, Maryland 20740
1	AFORSR (SREM), 1400 Wilson Blvd BD , Arlington, Virginia 22209
1	Library of Congress, Science and Technology Division, Washington, D.C. 20540
1	U.S. Coast Guard, 1300 E Street N.W., Washington, D.C. 20591, Attn: Division of Merchant Marine Safety
1	Director, National Bureau of Standards D , Washington, D.C. 20234, Attn: Dr. G.B. Schaubauer, Chief, Fluid Mechanics Branch

Copies	Organization
1	Director of Research, National Aeronautics and Space Administration, 600 Independence Avenue, S.W., Washington, D.C. 20546 D
1	Director, Waterways Experiment Station, Box 631, Vicksburg, Mississippi 39180, Attn: Research Center Library BDE
1	Commander, Naval Ordnance Systems Command, Department of the Navy, Washington, D.C. 20360, Attn: Code ORD-035 D
1	Commandant (E) , U.S. Coast Guard (Sta 5-2), 1300 E Street N.W., Washington, D.C. 20591
1	University of Bridgeport, Bridgeport, Connecticut 06602, Attn: Prof. Earl Uram, Mech, Engr. Dept. ABDE
1	Brown University, Providence, Rhode Island 02912, Attn: Div of Applied Math D
4	Naval Architecture Department, College of Engineering, University of California, Berkeley, California 94720, Attn: 1 - Librarian 1 - Prof. J.R. Paulling 1 - Prof. J.V. Wehausen 1 - Dr. H.A. Schade
3	California Institute of Technology, Pasadena, California 91109, Attn: 1 - Dr. A.J. Acosta ABDE 1 - Dr. T.Y. Wu 1 - Dr. M.S. Plesset BDE
1	University of Connecticut, Box U-37, Storrs, Connecticut 06268, Attn: Prof. V. Scottorn DE , Hydraulic Research Lab
1	Cornell University, Graduate School of Aerospace Engr, Ithaca, New York 14850, Attn: Prof. W.R. Sears
1	Harvard University DE , 2 Divinity Avenue, Cambridge, Massachusetts 02138, Attn: Prof. G. Birkhoff, Dept. of Mathematics
1	Pierce Hall D , Harvard University, Cambridge, Massachusetts 02138, Attn: Prof. G.F. Carrier
1	University of Illinois DE , College of Engineering, Urbana, Illinois 61801, Attn: Dr. J.M. Robertson, Theoretical & Applied Mechanics Department
1	The University of Iowa, Iowa City, Iowa 52240, Attn: Dr. Hunter Rouse

Copies	Organization
2	The University of Iowa, Iowa Institute of Hydraulic Research, Iowa City, Iowa 52240, Attn: 1 - Dr. L. Landweber 1 - Dr. J. Kennedy
2	The John Hopkins University, Mechanics Department, Baltimore, Maryland 21218, Attn: 1 - Prof. O.M. Phillips DF 1 - Prof. W.H. Schwarz F
1	Kansas State University DE , Engineering Experiment Station, Seaton Hall, Manhattan, Kansas 66502, Attn: Prof. D.A. Nesmith
1	University of Kansas D , Lawrence, Kansas 60644, Attn: Chm Civil Engr Dept
1	Lehigh University DE , Bethlehem, Penna. 18015, Attn: Fritz Laboratory Library
1	Long Island University, Graduate Department of Marine Science, 40 Merrick Avenue, East Meadow, N.Y. 11554, Attn: Prof. David Price
1	Massachusetts Institute of Technology, Hydrodynamics Laboratory, Cambridge, Massachusetts 02139, Attn: Prof. A.T. Ippen DEF
7	Massachusetts Institute of Technology, Department of Naval Architecture and Marine Engineering, Cambridge, Massachusetts 02139, Attn: 1 - Dr. A.H. Keil 1 - Prof. P. Mandel ADE 1 - Prof. J.R. Kerwin 1 - Prof. P. Leehey DEF 1 - Prof. M. Abkowitz ABCDE 1 - Prof. F.M. Lewis D 1 - Dr. J.N. Newman ACD
1	U.S. Merchant Marine Academy, Kings Point, L.I., N.Y. 11204, Attn: Capt L.S. McCready, Head, Dept of Engineering AB
3	University of Michigan, Department of Naval Architecture and Marine Engineering, Ann Arbor, Michigan 48104, Attn: 1 - Dr. T.F. Ogilvie 1 - Prof. H. Benford 1 - Dr. F.C. Michelsen
5	St. Anthony Falls Hydraulic Lab, University of Minnesota, Mississippi River at 3rd Ave. S.E., Minneapolis Minnesota 55414, Attn: 1 - Director 1 - Dr. C.S. Song 1 - Mr. J.M. Killen BDEF 1 - Mr. F. Schiebe DEF 1 - Mr. J.M. Wetzel DE

Copies Organization

2 U.S. Naval Academy, Annapolis, Maryland 21402, Attn:
    1 - Library
    1 - Dr. Bruce Johnson ADF

3 U.S. Naval Postgraduate School, Monterey, California 93940, Attn:
    1 - Library
    1 - Prof. J. Miller D
    1 - Dr. T. Sarpkaya D

New York University, University Heights, Bronx, New York 10453,
Attn: Prof. W. Pierson, Jr.

New York University DE , Courant Institute of Mathematical
Sciences, 251 Mercier Street, New York, New York 10012, Attn:
    1 - Prof. A.S. Peters
    1 - Prof. J.J. Stoker

University of Notre Dame, Notre Dame, Indiana 46556, Attn:
    1 - Dr. A. Strandhagen BDE
    1 - Dr. J. Nicolaides BD

ennsylvania State University, Ordnance Research Laboratory,
rsity Park, Penna 16801, Attn:
    1 - Director ABDE

ado State University, Department of Civil Engineering, Fort
ns, Colorado 80521, Attn: Prof. M. Albertson BDEF

ynamics Laboratory, Department of Aerospace and Mechanical
ces, The James Forrestal Research Center, Princeton Univer-
Attn: Prof. G. Mellor DF

ps Institution of Oceanography, University of California,
lla, California 92038, Attn:
    1 - J. Pollock
    1 - M. Silverman ABCF

ord University, Stanford, California 94305, Attn:
    1 - Prof. H. Ashley, dept. of Aeronautics and Astronautics DE
    1 - Prof. R. Street
    1 - Prof. B. Perry, Dept Civil Engr

Stevens Institute of Technology, Davidson Laboratory, 711 Hudson
Street, Hoboken, New Jersey 07030, Attn:
    1 - Dr. J.P. Breslin
    1 - Dr. S. Tsakonas
    1 - Library

Copies	Organization
1	University of Texas, Defense Research Laboratory, P.O. Box 8029, Austin, Texas 78712, Attn: Director DF
1	University of Washington, Applied Physics Laboratory, 1013 N.E. 40th Street ABDF , Seattle, Washington 98105, Attn: Director
2	Webb Institute of Naval Architecture, Cresent Beach Road, Glen Gove, L.I., N.Y. 11542, Attn: 1 - Prof. E.V. Lewis 1 - Prof. L.W. Ward
1	Worcester Polytechnic Institute, Alden Research Laboratories, Worcester, Massachusetts 01609, Attn: Director ADE
1	Aerojet-General Corporation, 1100 W. Hollyvale Street, Azusa, California 91702, Attn: Mr. J. Levy, Bldg 160, Dept 4223
1	Bethlehem Steel Corporation, Central Technical Division, Sparrows Point Yard, Sparrows Point, Maryland 21219, Attn: Mr. A. Haff, Technical Mgr
1	Bolt Beranek & Newman, Inc., 1501 Wilson Blvd, Arlington, Virginia 22209, Attn: Dr. F. Jackson DF
	Bolt Beranek & Newman, Inc., 50 Moulton Street, Cambridge, Massachusetts 02138, Attn: 1 - Library F
1	Cornell Aeronautical Laboratory, Applied Mechanics Department, P.O. Box 235, Buffalo, New York 14221, Attn: Dr. I. Statler BDE
1	Electric Boat Division, General Dynamics Corporation, Groton, Connecticut 06340, Attn: Mr. V. Boatwright, Jr.
1	Esso International, 15 West 51st Street ABCD , New York, New York 10019, Attn: Mr. R.J. Taylor, Manager, R & D Tanker Department
1	General Applied Sciences Laboratories Inc. DEF , Merrick & Stewart Avenues, Westbury, L.I., New York 11590, Attn: Dr. F. Lane
1	Gibbs & Cox, Inc., 21 West Street, New York, New York 10006, Attn: Technical Library
1	Grumman Aircraft Engineering Corp Bethpage, L.I., N.Y. 11714, Attn: Mr. W. Carl
2	Hydronautics, Inc., Pindell School Road, Howard County, Laurel, Maryland 20810, Attn: 1 - Mr. P. Eisenberg 1 - Mr. M. Tulin

Copies	Organization
1	Lockheed Missiles & Space Co., P.O. Box 504 AE , Sunnyvale, California 94088, Attn: Mr. R. Waid, Facility # 1, Dept 57-01, Bldg 150
2	McDonnell Douglas Aircraft Co, Douglas Aircraft Division, 3855 Lakewood Boulevard DE , Long Beach, California 90801, Attn: 1 - Mr. John Hess 1 - Mr. A.M.A. Smith
1	Measurement Analysis Corporation, 10960 Santa Monica Boulevard, Los Angeles, California 90025 DF
1	National Science Foundation, Engineering Division, 1800 G. Street N.W., Washington, D.C. 20550 DE , Attn: Director
1	Newport News Shipbuilding and Dry Dock Company, 4101 Washington Avenue, Newport News, Virginia 23607, Attn: Technical Library Dept.
1	Oceanics, Incorporated, Technical Industrial Park, Plainview, L.I., N.Y. 11803, Attn: Dr. Paul Kaplan
1	U.S. Merchant Marine Academy, Kings Point, L.I., N.Y. 11204, Attn: Technical Library
1	Robert Taggart, Inc., 3930 Walnut Street, Fairfax, Virginia 22030, Attn: Mr. R. Taggart
1	Prof. Paul Van Mater, U. S. Naval Academy, Annapolis, Maryland 21402
1	Sperry Systems Managememt Div., Sperry-Gyroscope Company B , Great Neck, L.I., N.Y. 11020, Attn: Mr. D. Shapiro (Mail Sta G2)
1	Society of Naval Architects and Marine Engineers, 74 Trinity Place, New York, New York 10006
2	Southwest Research Institute 8500 Culebra Road BCDEF , San Antonio, Texas 78206, Attn: 1 - Dr. H. Abramson 1 - Applied Mechanics Review
1	Tracor, Incorporated, 6500 Tracor Lane, Austin, Texas 78721 BDF
1	Naval Ship Engineering Center, Norfolk Division, Boat Engineering Department, Norfolk, Virginia 23511, Attn: Mr. D.L. Bount, Code 6660
1	Woods Hole Oceanographic Institute, Woods Hole, Massachusetts 02543, Attn: Reference Room ABCDF

Copies	Organization
1	Prof. Jerome Lurye, Department of Mathematics, St. John's University ABCDE , Jamaica, New York 11432
1	Mr. B.H. Ujihara BD , North American Aviation Inc., Space and Information Systems Div, 12214 Lakewood Boulevard, Downey, California 90241
1	Stanford Research Institute, Menlo Park, California 94025, Attn: Library
1	Cambridge Acoustical Associates, Inc., 129 Mount Auburn Street, Cambridge, Massachusetts 02138, Attn: Mr. M.C. Junger ABDF
1	Dr. Roland W. Jeppson, College of Engineering BDE , Utah State University, Logan, Utah 84321
1	Dr. Albert T. Ellis D , Department of Applied Mechanics University of California at San Diego, P.O. Box 109, La Jolla, California 92038

Unclassified
Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)* St. Anthony Falls Hydraulic Laboratory University of Minnesota	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE
AN EVALUATION OF ACOUSTIC TECHNIQUES FOR MEASURING GAS BUBBLE SIZE DISTRIBUTIONS IN CAVITATION RESEARCH

4. DESCRIPTIVE NOTES *(Type of report and, inclusive dates)*
Project Report - October 1 1969 - December 30 1970

5. AUTHOR(S) *(First name, middle initial, last name)*
Frank R. Schiebe
John M. Killen

6. REPORT DATE May 1971	7a. TOTAL NO. OF PAGES 19	7b. NO. OF REFS 8

8a. CONTRACT OR GRANT NO. N00014-67-A-0113-0014 b. PROJECT NO. c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) Project Report No. 120 9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*

10. DISTRIBUTION STATEMENT
Approved for public release; distribution unlimited.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY Naval Ship Research and Development Center, Washington, D. C. 20034

13. ABSTRACT

The acoustic tone burst attenuation technique for measuring the gas bubble size distribution in water was critically reviewed. The findings reveal that the usefulness of the technique is limited to the bubble volume concentration range between 0.03 and 1.0 parts per million. Furthermore, resolution between size ranges is probably not possible with sufficient accuracy for many purposes.

Unclassified
Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Instrumentation						
Acoustics						
Bubbles						
Size distribution						
Cavitation						

DD FORM 1 NOV 65 1473 (BACK)
S/N 0101-807-6821

Unclassified
Security Classification

A-31409