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Laboratory Measurement of Water Surface Bubble Life Time

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The bubble life times of various water samples were measured in the laboratory. The statistical features of bubble life time on water surfaces are discussed. The measurement results showed that the distribution of bubble life times of various water samples follow a Rayleigh distribution and that the mean life times are a function of the bubble sizes. The total average of life times of various sizes for tap water is 2.24 s, it is 2.98 s for Delaware Bay water, and 3.89 s for Atlantic Ocean water, respectively. Comparing the statistical features of the bubble life time generated under different conditions, we found that the bubble life times are independent of the methods used to generate them.

INTRODUCTION

Air bubbles on the sea surface are the fundamental elements forming oceanic whitecaps, which are very important for studies of air-sea interactions and remote sensing oceanography [*Wu*, 1979; *Ross et al.*, 1974]. Oceanographers have studied them and have published many papers [*Miyake et al.*, 1948; *Monahan et al.*, 1969, 1971, 1980, 1981; *Cipriano and Blanchard,* 1981]. Calculations and measurements showed that the microwave reflectivity of the sea surface covered by whitecaps was almost equal to zero at high frequencies [*Zheng et al.*, 1982], and the emissivity was equal to unity [*Droppleman*, 1970; *Rosenkranz et al.*, 1972; *Webster et al.*, 1976]. Therefore, their effects on the measurement results by microwave remote sensing, whether passive or active, were not negligible.

This study aims to measure the life time of bubbles on the open surface for various water samples, including tap water, Delaware Bay water, and Atlantic Ocean water in the laboratory; to analyze their statistical features; and to determine relationships between the mean life time and the bubble sizes to compare the laboratory results with those in situ. The study is considered to be an important step toward learning the whitecap life time at high sea state conditions. However, the bubble life time is not equivalent to whitecap life time. This is because (1) the breaking waves entraining the air into sea water form a bubble source that provides the sea surface the bubbles during some continuous period; (2) in whitecaps the upper bubbles act as a shield to the lower ones and make their life time longer than those of bubbles exposed to the air; (3) at high sea states, the breaking waves generate a large number of bubbles simultaneously and there is a sufficient quantity of bubbles with larger size to keep whitecaps alive a little longer than the ones consisting of bubbles with smaller sizes.

Therefore, the whitecap or foam layer life time would be longer than the mean life time of single bubbles. However, studies of bubble life time still form the base for learning the whitecap life time and their dispersion mechanism.

METHODOLOGY

The experimental apparatus for measuring the bubble life time and their diameters is illustrated in Figure 1. The tank was made of lucite for convenience to measure the bubble diameter with a laser beam.

During measuring, the tank was kept open to make the bubble environment similar to that of the sea surface, and during pausing the tank was covered. Bubbles were generated by forcing air through capillary tubes, whose tips were put at 10 cm below the water surface. The bubble diameters were controlled by choosing the inner diameter of the tubes, since one tube could only produce one size of bubbles [*Blanchard and Syzdek*, 1977]. Those used in this experiment were from 0.3 through 1.4 mm. The bubble diameters produced were from 0.14 through 0.74 cm, which are common sizes in the field. The bubble generation rate was controlled by the air pressure down to one by one. Usually there were several bubbles simultaneously on the water surface. The bubble life times were measured by an electronic stop watch. A laser, optical system, photo-detector, and oscilloscope were used to measure the bubble diameters. When a bubble passed through the laser beam, it scattered the light. Consequently, the energy received by the detector was decreased and the output level of the detector had to be proportionally decreased [*Wu*, 1977]. The bubble diameters could be calculated from the level changes recorded by the oscilloscope. The nonsphericity of larger bubbles was noticed. The measurement results can be considered to be the equivalent spherical diameters of these bubbles. For every bubble size, the level having the highest probability was used to calculate the diameter of this group of bubbles, although sometimes the bubbles only partially intercepted the laser beam. The laser beam was located below the water surface as near as possible to the surface to minimize the bias between the diameter measurements of bubbles in water and on the water surface.

The water samples used in the experiments were taken from 20 m off the beach in Delaware Bay and 10 m off the beach in the Atlantic Ocean near Cape Henlopen, as well as tap water stored in the laboratory for a week. The sea water samples were contained in clean plastic buckets on the beach, then transported to the laboratory over a 5 min driving distance. The sea water samples were stored in the laboratory for 12 hours to settle out suspended particles in the water, then placed in the tank. For every sample, five or six bubble sizes were produced. The measured sequence for every bubble size was random. For every size, the measurements of single bubble life time were performed 150 or 200 times to obtain the statistical features of bubble life time. The measurement for every sample was usually performed for less than 8 hours. The surface tension of water samples

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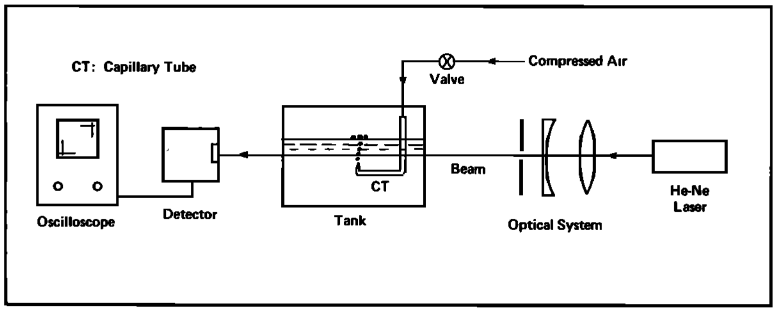

Fig. 1. Sketch of experimental apparatus.

was measured by a Roller-Smith Precision Balance Rosano Surface Tensiometer (model L6). The temperature of samples and salinity of sea water were also measured.

RESULTS

The means and standard deviations (rms) of bubble life time. The statistical data of bubble life time and the relative data were listed in Table 1. It can be seen that the bubble life times of fresh water are less than those of sea waters. The total average of the former is 2.24 s and the latter is 2.98 s for Delaware Bay water and 3.89 s for Atlantic Ocean water, respectively.

The relationships between the mean life time and diameters of various samples are shown in Figures 2–4. It is interesting to note that all three groups of data can be closely fitted by the same function

$$\bar{T}_l = k \frac{d}{\sigma^2} \exp(-d/2\sigma^2) \tag{1}$$

where $\bar{T}_l$ is the mean of bubble life time in seconds, d is the bubble diameter in centimeters, and k and σ^2 are empirical constants whose values for different samples are listed in Table 2. Studying this relationship will help learn the mechanism for bubble bursting.

Statistical features of bubble life time of various water samples. The life times of each bubble size were averaged at an interval of 0.5 s, and their probability densities were calculated. For every sample, a set of probability density data was obtained, and plotted in Figures 5–7, respectively. Notice that on the X axis is the relative life time, t, which was the life time of clusters, T_l, normalized by the mean life time of the same diameter, $\bar{T}_l$. That is,

$$t = T_l/\bar{T}_l \tag{2}$$

The Y axis is the probability density. The solid curves in Figures 5–7 represent Rayleigh distribution, that is,

$$S(t) = \begin{cases} 0 & t < 0 \\ \frac{t}{a^2} \exp(-t^2/2a^2) \cdot & t \geq 0 \end{cases} \tag{3}$$

where t equals $T_l/\bar{T}_l$, and a equals $\sqrt{\pi/2}$. It can be seen that the Rayleigh distribution fits the measurement data fairly well. The fitted rms are 0.18, 0.17, and 0.20, respectively. For different bubble size, the data of smaller bubbles fit the curves better than those of the larger.

TABLE 1. Mean and rms Values of Bubble Life Time

Temperature (°C)					Life Time (s)	
Air	Water	Salinity (‰)	Surface Tension (Dyn/cm)	Diameter, cm	Mean	rms
			Atlantic			
24.5	22.8	31	75.1 ± 1.2	0.17	1.84	1.02
24.5	22.7	31	75.1 ± 1.2	0.27	3.71	1.98
24.5	22.7	31	75.1 ± 1.2	0.28	3.25	1.87
23.7	22.2	31	75.1 ± 1.2	0.52	4.85	2.77
23.7	22.2	31	75.1 ± 1.2	0.67	5.48	2.97
24.4	22.7	31	75.1 ± 1.2	0.74	4.21	2.52
			Delaware Bay			
23.6	20.9	32	72.5 ± 1.7	0.12	1.27	1.01
22.6	20.1	32	72.5 ± 1.7	0.21	4.51	3.76
22.0	20.0	32	72.5 ± 1.7	0.22	4.08	3.45
23.7	21.1	32	72.5 ± 1.7	0.67	2.89	2.52
23.7	21.1	32	72.5 ± 1.7	0.74	2.13	1.46
			Tap Water			
22.8	20.9	0	75.2 ± 0.8	0.14	1.26	0.57
23.4	20.9	0	75.2 ± 0.8	0.15	1.43	1.03
24.5	21.6	0	75.2 ± 0.8	0.19	1.67	0.93
23.3	20.9	0	75.2 ± 0.8	0.23	1.87	1.36
24.1	21.2	0	75.2 ± 0.8	0.67	3.87	3.26
24.0	21.4	0	75.2 ± 0.8	0.74	3.36	3.30

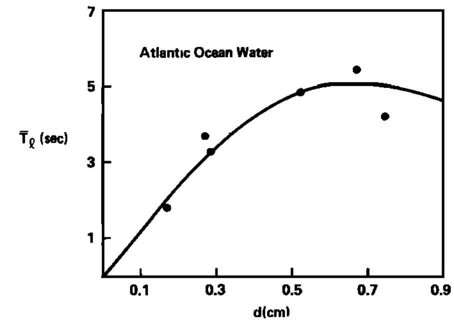

Fig. 2. The means of bubble life time of different diameters and their fit curve. The water sample was taken on Atlantic Ocean beach near Cape Henlopen, Delaware.

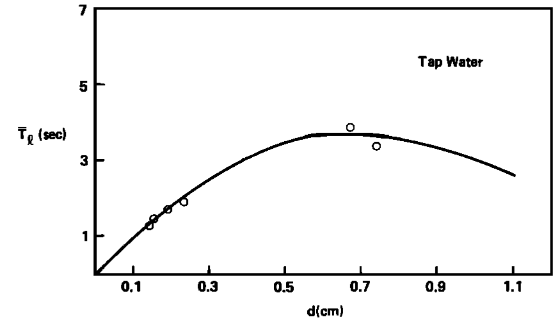

Fig. 4. The means of bubble life time of different diameters and their fit curve. The water sample consisted of tap water stored in the laboratory for a week.

Comparisons of statistical features of bubble life time generated by different methods. To determine whether the bubble life times are dependent on the bubble generation methods, the statistical features of the life times of bubbles generated by different techniques, but in the same water sample, were compared. Figure 8 contains the histograms of the life time of Delaware Bay water bubbles. The solid line shows the data taken on the beach when the bubbles were generated by breaking waves and had a mean life time of 2.35 s. The dotted line shows the data taken in the tank where the bubbles were produced by capillary tubes and compressed air and exhibited a mean life time of 2.51 s. It is necessary to point out that laboratory data for bubbles with diameters of 0.67 and 0.74 cm were only used, because in the field it was difficult to measure the life time of bubbles of smaller sizes than those. Thus, we compared the larger bubbles in the laboratory with those in the field. It can be seen that both histograms were very similar and the mean life times were almost equal. The peak of the laboratory data is located a little more to the left than that of the field. This is because it was easier to measure the short life times in the laboratory than in the field, and more short time data were taken. The bubble sizes in the field were not precisely measured, and most of bubble diameters were estimated in a region of 0.5–0.8 cm.

Figure 9 shows the histograms of life times of tap water bubbles. The solid line shows the data taken from the wind-wave-current research facility at Henlopen Lab., College of Marine Studies, University of Delaware. The bubbles were generated by artificial waves breaking on a simulated beach. Because the period of the waves was approximately 3 s, no data longer than 3 s were taken. The mean life time of these data was 1.61 s, and the rms was 0.59 s. The dotted line shows the data of 0.67 and 0.74 cm diameter bubbles generated by capillary tubes and compressed air. The data with life time longer than 3 s were cut down. The mean life time was 1.45 s, and the rms was 0.66 s. The histograms are very similar, and the mean and rms values are also close.

The above-mentioned two examples tell us that the bubble life time seems to be independent of the methods used to generate them.

Measurement results of foam layer life time in the field. On August 19 and 20, 1981, tropical storm Dennis was moving up the Atlantic coast. Although Dennis did not reach the Delaware Bay area, the hurricane generated winds of 30 knots and averaged wave heights of 6 feet around Cape Henlopen. The waves coming from the Atlantic Ocean broke in the surf zone. During wave breaking, a foam layer was formed on the sea surface, providing us a good opportunity to measure the foam layer life time in the field. The total of 69 data points were obtained by an electronic stop watch. In this study, foam layer life times were defined as the period from a wave's breaking through foam layer's separating as streaks on the sea surface. This period is of great significance for active microwave remote sensing of sea state conditions. The measurement results showed that the foam layer life time did not have a unique value but follows a distribution. Figure 10 shows the distribution frequencies of foam layer life time, of which the mean is 15.4 s and the rms is 5.1 s. In Figure 11 the solid curve has a Rayleigh distribution, and the open circles are the measured probability densities of foam layer life times. The fitted rms value is 0.32 s. The temperatures of water and air were 20.70°C and 22.00 ± 0.50°C, respectively, during the measurement.

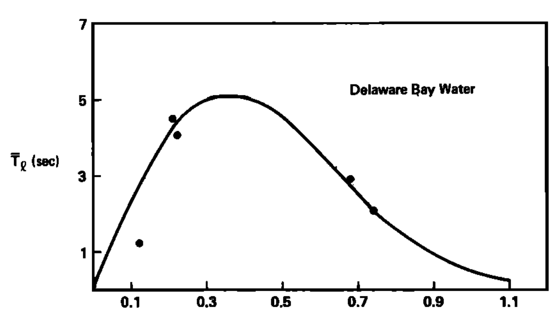

Fig. 3. The means of bubble life time of different diameters and their fit curve. The water sample was taken on Delaware Bay beach near Cape Henlopen.

DISCUSSIONS

It is well known that the monomolecular layers at the water surface and contamination in the water would have marked influence on bubble life time on the water surface

TABLE 2. The Values of k, σ^2, and Fitted rms

Sample	k (s)	σ^2 (cm)	Fitted rms (s)
Atlantic	5.64	0.450	0.38
Delaware Bay	3.06	0.130	0.69
Tap Water	4.09	0.447	0.14

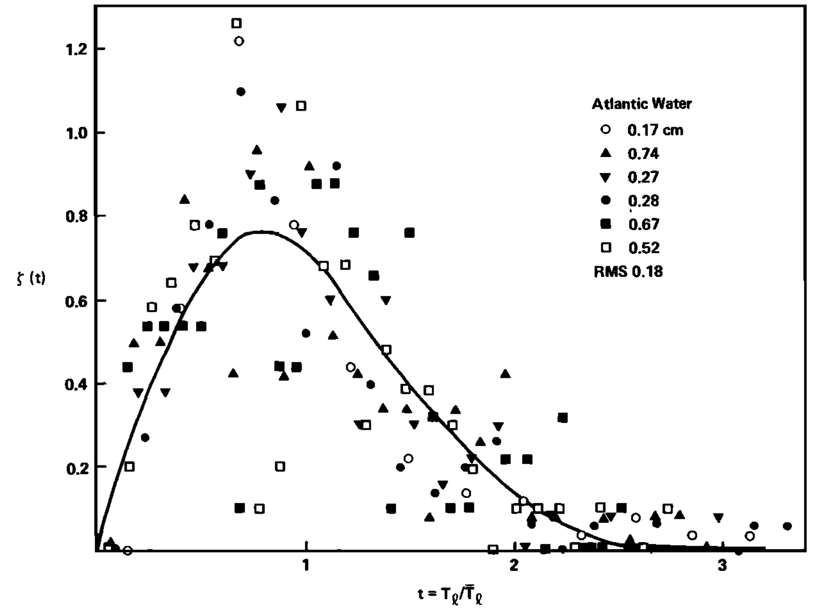

Fig. 5. The statistical distribution of bubble life time of Atlantic Ocean water. *X* axis is relative life time normalized by their mean; *Y* axis is probability density and the solid curve is Rayleigh distribution.

[*Blanchard and Syzdek*, 1978]. However, in our experiment we did not try to clean the water surface. The purpose was to simulate the natural water surfaces of the sea and lakes where the bubbles were formed. Therefore, the pure water and artificial seawater were not used as experimental samples, but natural seawater and tap water. Consequently, the experimental results can be considered to be bubble life times under conditions in which a monomolecular layer could exist on the water surface.

A number of processes may cause random breakup of bubbles and droplets. Most of present papers focus on studies of water droplets in air or air bubbles in water [*Clift et al.*, 1978]. Unfortunately, the quantitative or qualitative discussions about mechanism of air bubble breakup on the water surface have not been abundant. In this experiment the relationships between the mean life times on the water surface and bubble diameter were obtained. All three groups of data of various samples can be closely fitted by the same function (1) (see Figures 2–4). This fact indicates that bubble size is an important factor in the mechanism of bubble breakup on water surfaces for the same sample. A detailed explanation will be provided in future studies.

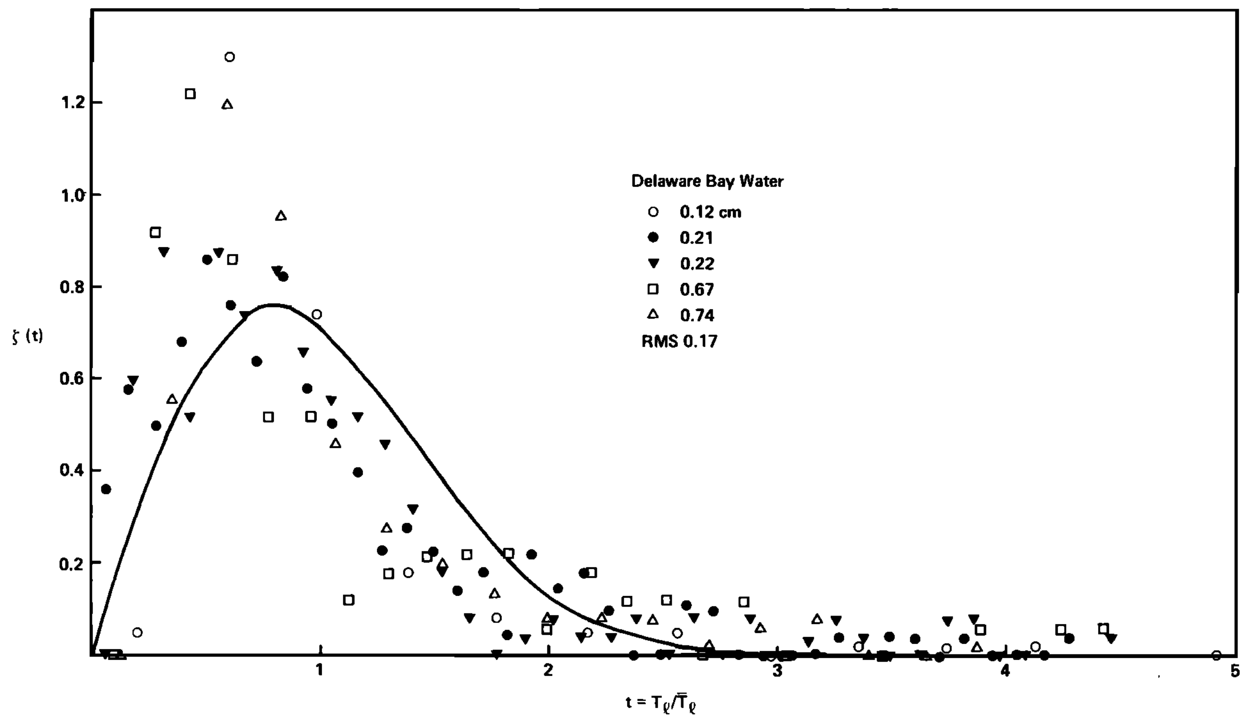

Fig. 6. The statistical distribution of bubble life time of Delaware Bay water.

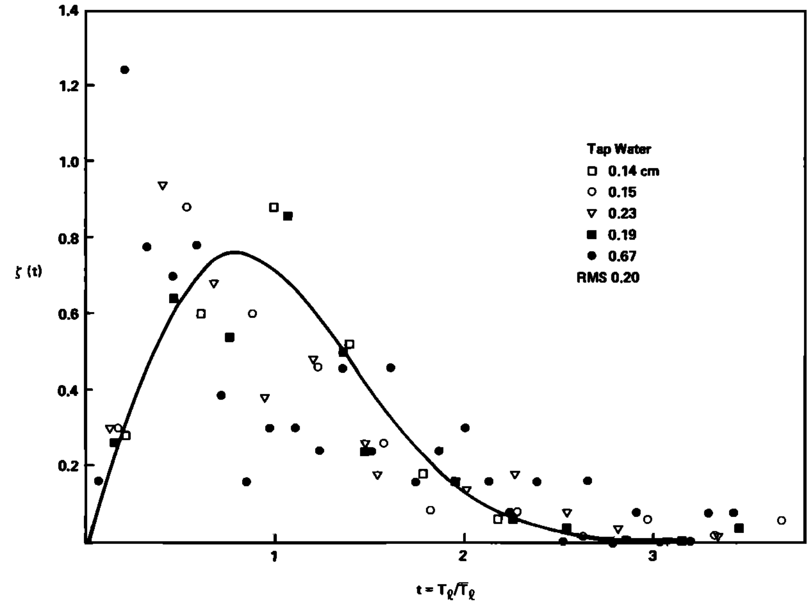

Fig. 7. The statistical distribution of bubble life time of tap water.

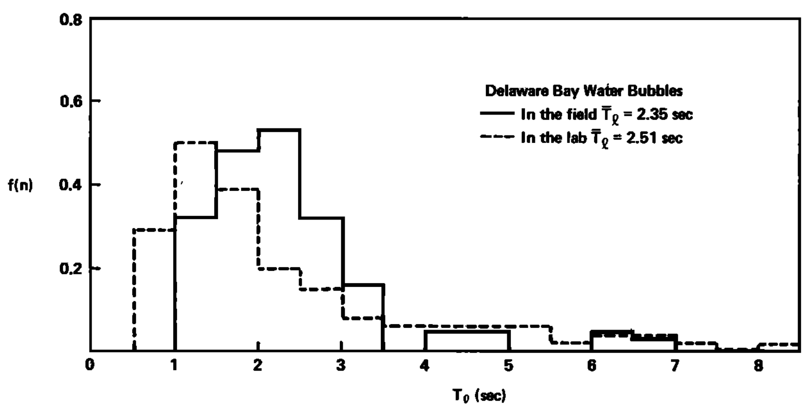

Fig. 8. Histogram of bubble life time of Delaware Bay water. The solid line is of data taken in the field with a 2.35 s mean, the dotted line is of data taken in the laboratory with a 2.51 s mean lifetime.

It is well known that

$$P = 4T/R \tag{4}$$

where P is the pressure difference between the inner and outer sides of the bubble, R is the bubble radius, and T is the surface tension of the water sample [*Millikan,* 1965]. Equation (4) seems to indicate that larger bubbles will have a longer life time due to smaller pressure inside. However, the bursting of a bubble is complicated by the fact that part of the bubble is protruding from the water surface. The position is determined by the balance between floatation and surface tension. The detailed dynamics of water draining from a bubble surface, which plays a critical role in determining breakage conditions, remains to be worked out.

The normal, Rayleigh, and F distribution were used to fit statistical features of bubble life times. Finally, the Rayleigh distribution was found to give the best fit. However, the data still have bias, particularly in Figures 6 and 7. It should be possible to find another distribution to represent the statistical features of the data better than Rayleigh distribution.

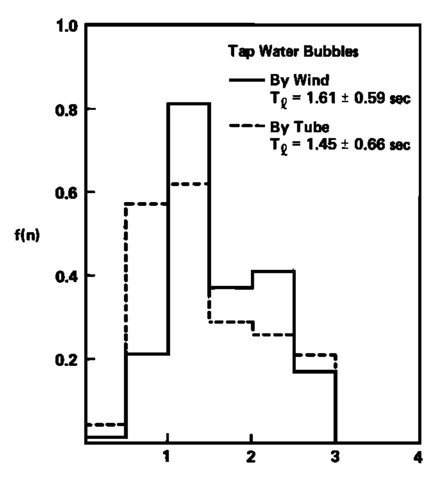

Fig. 9. Histogram of bubble life times of tap water. The solid line is of data taken from the wind-wave-current tank with a 1.61 s mean; the dotted line is of data taken in the laboratory with a 1.45 s mean lifetime.

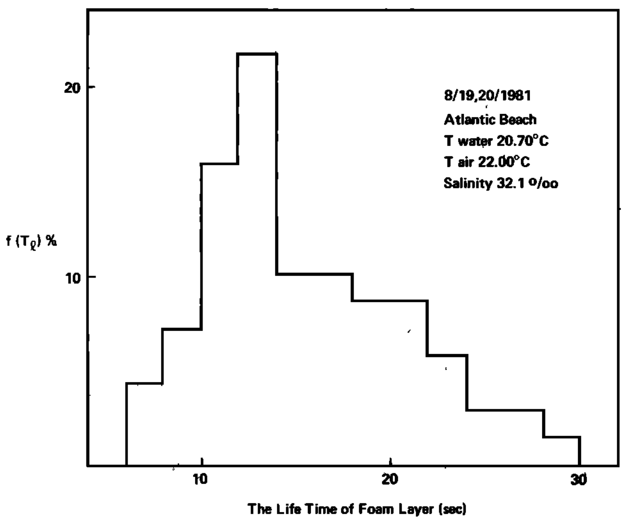

Fig. 10. Histogram of life times of a foam layer taken at an Atlantic Ocean beach near Cape Henlopen, August 20, 1981.

CONCLUSIONS

The measurement results of three water samples in the laboratory indicate that the bubble life times on the water surface follow Rayleigh distribution. The bubble life times of fresh water are less than those of sea water, the total average of tap water being 2.24 s, that of Delaware Bay water 2.98 s, and that of Atlantic Ocean water 3.89 s.

The relationship between the bubble life times and their diameters can be expressed by the following empirical formula

$$\bar{T}_l = k \frac{d}{\sigma^2} \exp(-d/2\sigma^2)$$

where $\bar{T}_l$ is the mean of bubble life time in seconds, d is the bubble diameter in centimeters, and k and σ^2 are empirical constants.

Comparison of statistical features of bubble life time generated by different methods showed that the bubble life time seemed to be independent of the methods used to generate them.

The foam layer life times were measured in the field. The results showed that their mean is 15.4 s and the rms is 5.1 s. The foam layer life times could also be fitted by a Rayleigh distribution.

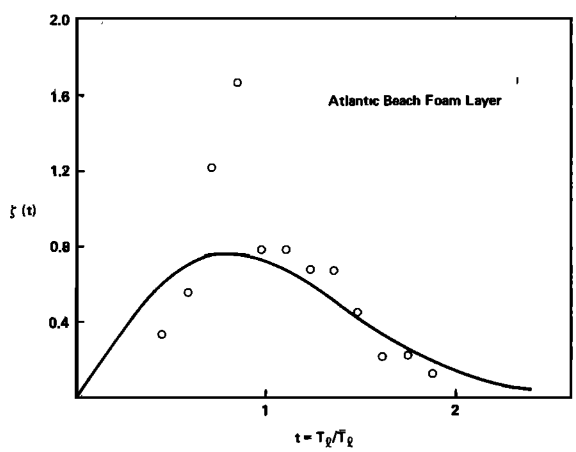

Fig. 11. The statistical distribution of life times of foam layers. The solid curve is Rayleigh distribution.

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