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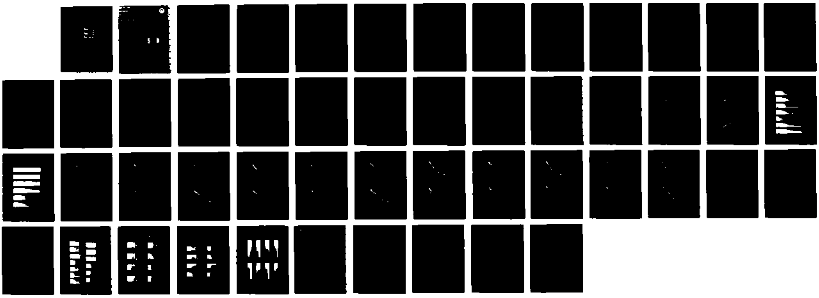

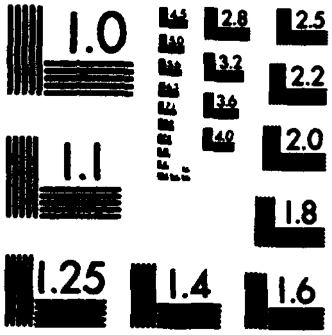

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Stability and Decay Properties of Foam in Seawater

R. D. PELTZER AND O. M. GRIFFIN

Laboratory for Computational Physics and Fluid Dynamics

April 24, 1987

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Surface foam is formed by the entrainment of air in the form of small bubbles at and just beneath the water surface during white-capping, when steep waves break and when a displacement ship moves through the water. The residence time of a single- or multi-layer foam at the surface depends on the stability of the bubbles in that layer. This report presents the results of a study which examined the influence of salt content on the foaming ability of water and on the stability of a three-dimensional foam produced by blowing air through controlled laboratory samples of simulated sea water together with a sample of sea water obtained from an Atlantic coastal site.

The results clearly show that varying the salt content of a clean water sample between 0 and 16 ppt. significantly influences its foaming ability and the corresponding stability of a layer of surface foam. For salinities between 16 and 36 ppt. there is no appreciable change in the foaming characteristics of a water sample. The behavior of the real seawater sample closely followed that of the simulated seawater samples. The stability characteristics of a multilayer surface foam are summarized in the report.

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CONTENTS

STABILITY AND DECAY PROPERTIES OF FOAM IN SEAWATER

INTRODUCTION

Foam is formed by the entrainment of air in the form of small bubbles at and just beneath the surface of a body of water There are many dynamic events which are responsible for the production of surface foam in sea water. These include white-capping, the breaking of steep waves, the motion of a displacement ship through the water, and the formation of tidal bores and hydraulic jumps.

The remote sensing signatures of a water surface covered with foam are appreciably different than those of a surface which is free of foam. The reflective characteristics of the surface in the solar spectral region are increased by the presence of foam [13]. Surface foam can contribute measurable additional backscattered power to microwave radar from both specular and volume scattering [3,11]. Foam also increases the microwave emissivity of the water surface, resulting in a large increase in the microwave brightness temperature of the surface [8,18,21,24].

The residence time of a single- or multi-layer foam at the surface depends on the stability of the bubbles in that layer. Major factors that increase the stability of a bubble at the surface are increasing salinity [14,16,20]; decreasing water temperature [14,19]; decreasing humidity [6]; increasing the speed of the air over the surface of the water [6]; increased surface viscosity [12]; a stable air-sea temperature difference [5,23]; and the presence of organic surface-active materials which reduce the surface tension and modify the surface rheology [1,2,5].

Huang et al. [10] have developed an analytical expression that relates the extent of oceanic whitecap coverage to environmental parameters, namely the sea state and surface wind stress. Previous models have been based on wind speed only. None of these models gives any information about the stability characteristics of the three-dimensional surface foam layer produced by the white-capping

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event. There are also no models that describe the three-dimensional foam layer bubble distribution and decay characteristics at the surface in the wake of a ship. Studies have been conducted to measure the lifetimes of single bubbles of various sizes at real and simulated seawater surfaces [4,6,22,25]. These bubble lifetimes are not equivalent to whitecap or ship wake foam lifetimes because they account neither for the three-dimensionality of the foam layer nor the bubbles rising from underneath to feed the foam layer.

A recent study by Podzimek [18] has examined how the size distributions of foam patches formed by wave action on a sandy beach vary with time. It was found that the mean diameter of the bubbles in the foam patch varied between 1200μm (early) and 4050 μm (late) depending on the age of the foam. They found that the lifetime of a typical foam patch was 25 seconds. Zheng et al [25] also measured the average lifetime of a foam layer formed at the surface by wave breaking on a beach. They found that the mean lifetime value was 15.4 sec and the rms deviation about the mean was 5.1 sec. No information concerning changes in the thickness of the foam patch with time was given in either paper.

The purpose of this report is to present the results of a study which was conducted to examine the influence of salinity on the foaming ability of water and on the stability of a three-dimensional foam layer produced by the passage of air through a volume of water. Controlled laboratory samples of simulated seawater were used in the experiment, together with a sample of seawater obtained from an Atlantic coastal site. The results of the experiments show that the behavior of the simulated seawater closely follow that of the ocean water.

DESIGN OF THE EXPERIMENT

Figure 1 shows a diagram of the experimental setup. Breathing-quality air from a high-pressure cylinder was blown through a porous glass disc into a 1.5 cm or 5.0 cm high volume of water. This produced a dense stream of small gas bubbles covered by a three-dimensional layer of foam in a 17.5 cm long, 16.0 cm diameter Pyrex Buchner funnel. The average pore sizes ranged between 4.0 and 5.5 μm in the fine disc and between 10.0 to 15.0 μm in the medium disc. The volume flow rate of air ranged between 2000 and 22000 ml/min. The volume flow rates were measured by one of two

Fischer and Porter glass tube variable-area flowmeters which had maximum measurable flow rates of 18400 ml/min and 51540 ml/min, respectively.

The height of the three-dimensional foam in the funnel was measured by a linear array of 1024 photo diodes in a Reticon camera. The camera was interfaced to a Hewlett Packard 1000 Series A600 computer through an A/D card. Calibrated data were obtained at a rate of 300 points per second. Photographs of the bubbles and foam in the funnel were made with a Nikon FG 35 mm camera.

The salinity of the water was varied by adding Instant Ocean to type 1 reagent-grade water from a Barnstead NANOpure II four-cartridge water purification system. The Pyrex Buchner funnels were cleaned and continually rinsed with the pure water after each test to remove salt residues and other contaminants. The salinity of the water samples was measured with a YSI portable conductivity/salinity meter.

A seawater sample that was collected on the latter half of the incoming tide in deep water at the Indian River Inlet in Delaware was included for a comparison with the simulated seawater. The salinity of the ocean water was 26 ppt. The seawater was passed through a laboratory sand filter prior to the time that it was supplied to NRL by the University of Delaware Marine Sciences Laboratory in Lewes, DL.

FOAMING ABILITY

The foaming ability of a water sample is characterized by how voluminous a foam layer is produced when air is blown into the sample through a porous disc. The level of the air-water interface before foaming was taken as the lower boundary of the foam in the present experiments because in most cases there was no sharp, identifiable boundary between the air emulsion and the foam above the emulsion.

When air flow through the porous disc starts and then continues at a constant rate, the foam height initially increases at a nearly constant rate. The rate then decreases until a constant equilibrium height, H_o, is reached. Figures 2 through 5 show the values of the equilibrium height H_o, as a function of the volume flow rate of air (V) through both the medium and fine discs with initial water levels of 1.5 and 5.0 cm. Each of the thirteen different colored curves in the four figures represent one of the thirteen water samples tested, as outlined in Table 1. The individual curves in all the figures show an increase in the equilibrium height H_o when the volume flow rate of air through the disc is increased.

Table 1 — Water Sample Color Code
for Figures 2 Through 5

Color	Salinity Value
Brown	36 ppt.
Aqua	32 ppt.
Dark Green	30 ppt.
Violet	28 ppt.
Burnt Orange	26 ppt.
Lime Green	26 ppt. (sea water sample)
Medium Blue	24 ppt.
Light Red	20 ppt.
Yellow	16 ppt.
Orange	12 ppt.
Dark Blue	8 ppt.
Red-Violet	4 ppt.
Dark Red	0 ppt. (fresh water)

The ratio $H_o \pi R^2/V$, where $R = 8.25$ cm in the present experiments, is sometimes used as an approximate measure of the foam-forming characteristics of a liquid [5]. It is approximately equal to the time an average bubble exists in the foam before bursting. Using this ratio as a guide, the results in the four figures can be analyzed to determine how the foaming ability of the samples was influenced by salt concentration (salinity), pore size (bubble size), and initial water depth (wetness of the foam). Several significant results were found and are discussed in the following sections of the report.

SALT CONCENTRATION

When the salt concentration of the water was increased from 0 ppt to 16 ppt there was a significant increase in the foaming ability of the water sample. The differential height values ΔH_0 between curves of increasing salinity were relatively large over this range at all of the flow rates considered. Further increases in the salt content between 16 ppt and 36 ppt only slightly increased the foaming ability of the water samples as evidenced by the small or negligible changes in ΔH_0 between curves of increasing salinity over this range. Monahan [15] previously had found that increasing salt content increased the amount of surface foam generated by a simulated whitecap. In their early study Miyake and Abe [14] showed that the foaming ability of a salt water solution increased exponentially with increasing salt concentration and reached a finite maximum at a salinity near 35 ppt. Their results show that the height of a foam layer decreased by only 30% with decreasing salinity between 35 ppt. and 16 ppt. In the present experiments the height decreased by an average of 14, 22, 11, and 24 percent respectively between 36 and 16 ppt in Figures 2 through 5.

The seawater obtained from the Delaware field site behaved nearly identically to the laboratory water samples with salinity values near 26 ppt. This suggests that the foaming ability of seawater does not vary significantly in the open ocean because of salinity differences. However, there are many other factors that can influence the foaming ability of seawater besides its salt content. These include temperature, cleanliness (pollutants and particulate matter), and the presence of surfactant materials and biological organisms. The effects of these factors were not studied in the present initial experiments, but should be included in any follow-on work.

Figure 6 is an assembly of photographs of the bubble columns which demonstrates the influence of salt content on the foaming ability of a 5.0 cm column of water when 18550 ml/min of air is blown through the fine porous disc into the water sample. The entire range of salinities, 0 to 36 ppt, is shown. There is a readily noticeable increase in the foaming ability (height H_0 of the foam column) of the water samples as the salinity is increased from 0 to 16 ppt. Between 20 and 36 ppt, there is only a slight increase in the foaming ability. The salt content also has a significant influence on the size distribution and on the number of individual bubbles within the column. At 0 ppt, the bubbles are large because they coalesce almost immediately as they come together. At 4 ppt. the salt has already begun to influence the size of the bubbles within the column, as evidenced by the decrease in size and the corresponding increase in the number of bubbles in the column. At 8 ppt. the number of bubbles increases and their size decreases still further. From 12 to 20 ppt. the size distribution is not significantly influenced, but the number of bubbles and height H_o of the foam column continues to increase as the salt content increases. Above 20 ppt. there is no further change in the size distribution and only a slight variation in the height of the column. Bubbles in salt water are greater in number, more densely packed and smaller than those in fresh water. There are no observable differences between the real and simulated seawater samples at 26 ppt.

The mean diameter of the bubbles in the present water samples with salinities greater than 16 ppt. appears to fall directly into the range of mean bubble diameters, 1.2 to 4.05 mm that was measured by Podzimek [18] in a foam patch created by wave breaking on a beach.

Scott [20] has shown that there is a rapid decrease in the mean size of the bubbles rising in water as the salt content is increased from 0 to 8 ppt., and again as it is increased from 8 to 35 ppt. He concluded that the rapid decrease in mean bubble size was due to surface activity of the salt which appears to retard bubble coalescence. Pounder's experiments [19] have conclusively shown that two bubbles will always coalesce in clean, fresh water, but will push each other aside in salt water and then proceed to rise separately. He, as well as Gucinski [9] hypothesizes that in salt water some preferential ion attachment into the surface electrical double layer occurs which then causes a repulsion to take place at the surfaces, and thus prevents coalescence. Whatever the mechanism, the present results also demonstrate the rapid decrease in mean size of the bubbles in salt water and the retarding effect of the salt on bubble coalescence.

DISK POROSITY

The porosity of the disc in the foam generator influences the foaming ability of the water samples. For water samples with the same salinity, volume flow rate and initial water volume, a larger volume of foam is produced by blowing air through the fine, porous disc than is produced by blowing air through the medium, porous disc. A likely explanation for this behavior is that smaller, more densely packed bubbles are produced initially when air is blown through the fine, porous disc than those initially produced by air blown through the medium, porous disc. The smaller, more closely packed bubbles are more stable and do not coalesce or rupture as quickly as do the larger bubbles, and consequently the residence time of a bubble produced by the fine, porous disc is longer than that produced by the medium disc.

WATER DEPTH

A larger volume of foam is produced when the initial depth of the water sample above the disc is increased. Bikerman [5] notes that when more time is given for a gas-liquid interface to approach an equilibrium state, the persistence of the bubbles increases. If the residence time of the bubbles in the column increases, then height increases correspondingly. Another factor which may contribute to the larger amount of foam is a possible increase in the wetness of the foam in the column as a result of the larger initial water depth. The lamallae in a wetter foam are thicker and more resistant to bursting, and therefore more bubbles can reside longer in close proximity.

FOAM LAYER STABILITY AND DECAY

The lifetime of a layer of foam formed by bubbling air through a column of water is a measure of the stability of that foam. When the airflow through the porous disc is stopped after the foam has reached a steady-state height H_o, the height of the foam begins to decrease. The top layer of bubbles loses liquid by drainage. The thin lamallae then burst at a rate dependent upon their original thickness. When the bubbles burst, the liquid flows down further in the column. The downward flow of liquid in the entire column is balanced by the arrival of liquid from the bursting bubbles in the upper layer, thereby stabilizing the lower layers. The foam column then collapses from the top downward. The influences of disc porosity, initial water depth, and salt content on the stability (collapse) of a foam column were investigated and the results of that investigation are discussed next.

Figures 7 to 30 summarize the experimental results which show the decrease in the height of the foam column after the airflow through the disc was stopped. The lifetimes of the single bubbles that sometimes remained on the surface for up to ten seconds after the foam column collapsed completely were not considered in the analysis of the data. There are six groups of four figures each, in which the steady-state height, H_o, achieved before ceasing the airflow is common to each group. The six values of H_o are 1.0, 1.5, 2.0, 3.0, 4.5 and 6.0 cm. In each group of four figures the pore size (fine or medium) and the initial water depth (1.5 cm or 5.0 cm) were varied. Table 2 summarizes the relevant parameters pertaining to the figures. The color coded curves in all the figures show how the salt content of the water samples influenced the stability of the foam column. Table 3 summarizes the color code.

Table 2 — Summary of the Relevant Parameters
Pertaining to Figures 7 Through 30

Figure	Equilibrium Foam Height, H_o (cm)	Initial Water Depth, H_w (cm)	Porous Disc Size
7	1.0	1.5	Fine
8	1.0	5.0	Fine
9	1.0	1.5	Medium
10	1.0	5.0	Medium
11	1.5	1.5	Fine
12	1.5	5.0	Fine
13	1.5	1.5	Medium
14	1.5	5.0	Medium
15	2.0	1.5	Fine
16	2.0	5.0	Fine
17	2.0	1.5	Medium
18	2.0	5.0	Medium
19	3.0	1.5	Fine
20	3.0	5.0	Fine
21	3.0	1.5	Medium
22	3.0	5.0	Medium
23	4.5	1.5	Fine
24	4.5	5.0	Fine
25	4.5	1.5	Medium
26	4.5	5.0	Medium
27	6.0	1.5	Fine
28	6.0	5.0	Fine
29	6.0	1.5	Medium
30	6.0	5.0	Medium

Table 3 — Water Sample Color Code
for Figures 7 Through 30

Color	Salinity Value
Brown	36 ppt.
Aqua	32 ppt.
Dark Green	30 ppt.
Violet	28 ppt.
Burnt Orange	26 ppt.
Lime Green	26 ppt. (sea water sample)
Medium Blue	24 ppt.
Light Red	20 ppt.
Yellow	16 ppt.
Orange	12 ppt.
Dark Blue	8 ppt.
Red-Violet	4 ppt.
Dark Red	0 ppt. (fresh water)
Black	Mean curve*

*The mean curve is an averaged sum of the individual curves from 16 or 20 ppt to 36 ppt that showed similar decay properties.

When the figures are compared and analyzed there are several identifiable trends which emerge. In general, the decay rate of the foam column, dH/dt, was dependent upon the initial value of H_o, such that dH/dt increased when H_o increased. In those figures where H_o was greater than 1.0 cm, the rate of decay was constant with time until H had decreased to a value between 0.5 cm and 1.5 cm. The decay rate decreased significantly with time after this point to another approximately constant value. Some factors responsible for the variation of dH/dt within the foam column are the bubble size distribution within the column, the moisture content within the column, and drainage through the column. The average size of the bubbles in the column increases toward the top, so that the larger bubbles at the top are less stable and burst at a faster rate. It has been shown that the wetness (moisture content) of a three dimensional foam, formed by blowing air through a porous septum into a pool of liquid, also decreases toward the top of the column [5,7]. Assuming that the moisture content in the foam columns decreases toward the top, this will contribute further to the vertically upward decrease in stability. The lower layers are also stabilized by the water draining down through the column from the top layers as they collapse. In the figures where H_o was equal to 1.0 cm, the decay rate was essentially single-valued throughout the entire decay period.

The decay rate in all of the figures was not significantly influenced by the salt content of the water for salinities between 16 ppt. or 20 ppt. and 36 ppt. This result is plausible because the foaming ability of the various salt solutions also was not influenced by the salt content in this range of salinities. The foam decay rate increased markedly with decreasing salt content for water samples with salinities less than 16 ppt., just as the foaming ability also decreased over the same range of salinities.

In addition to the influence of H_o just discussed, the foam decay properties also were affected by the porosity of the disc and by the initial water volume above the disc. The influences of porosity and water depth on the decay properties become apparent when the average decay curves are compared. Table 4 summarizes the linear decay rates of the twenty-four average curves, the applicable portion of the decay curve, and the average foam lifetime. Also included in the Table are average decay rates and lifetimes for foam columns with initial height of 0.50 and 0.75 cm. Figure 31 is a summary plot of the linear decay rates, (dH/dt), of the average curves as a function of the equilibrium foam height, H_o. Figure 32 summarizes the corresponding average lifetimes, T_A, of the foam layers.

Again it must be emphasized that the average lifetime values do not include the single bubbles that remained on the surface for up to 10 sec after the foam column collapsed. Table 5 provides a summary of the results from four experimental studies that examined the surface lifetimes of single bubbles. Although there were a variety of conditions and methods under which the bubbles were produced and the surface lifetimes were measured, there is general agreement between the values of surface lifetimes in the data that overlap. The following is a brief summary of the equipment and sample preparations that were employed in the experiments summarized in Table 5.

Zheng et al [25] used two seawater samples in their experiments: one was taken at a location 20 m off the beach in the Delaware Bay and the second was taken from a location 10 m off a beach near Cape Henlopen, Delaware. Both samples were allowed to sit for twelve hours in order to let any suspended particles settle out before the samples were tested. No surface preparations were made to remove surfactants if they were present and there was no mention in the paper about any extraordinary procedures used to clean the equipment.

Burger and Blanchard [6] used a seawater sample of unknown origin and a 30 ppt. NaCl solution prepared in distilled water for their experiments. Their air supply was filtered and the water surface was free of surface-active materials. No mention was made of any methods used to clean the test equipment. It is interesting to note the order of magnitude increase in the bubble surface lifetime that they found when air was blown across the surface of their sample. These results were repeatable.

Table 4 — Summary of Foam Layer Lifetime and Decay Results
(a) Fine Porous Disk, Initial Water Depth, H_w = 1.5 cm

Equilibrium Foam Height, H_o (cm)	Rate of Decay dH/dt (cm/sec)	Applicable Portion of the Decay Curve	Average Foam Lifetime, T_A (sec)
0.5	0.23	$0.0 \le H \le 0.50$	2.10
0.75	0.22	$0.0 \le H \le 0.75$	3.41
1.0	0.31	$0.0 \le H \le 1.0$	3.13
1.5	0.57	$0.9 \le H \le 1.5$	3.66
	0.40	$0.3 \le H \le 0.9$	
	0.26	$0.0 \le H \le 0.3$	
2.0	0.72	$0.55 \le H \le 2.0$	4.13
	0.26	$0.0 \le H \le 0.55$	
3.0	1.06	$0.65 \le H \le 3.0$	4.60
	0.27	$0.0 \le H \le 0.65$	
4.5	1.67	$1.0 \le H \le 4.5$	5.13
	0.32	$0.0 \le H \le 1.0$	
6.0	2.43	$0.85 \le H \le 6.0$	5.22
	0.30	$0.0 \le H \le 0.85$	

Table 4 (Cont'd) — Summary of Foam Layer Lifetime and Decay Results
(b) Fine Porous Disk, Initial Water Depth, $H_w = 5.0$ cm

Equilibrium Foam Height, H_o (cm)	Rate of Decay dH/dt (cm/sec)	Applicable Portion of the Decay Curve	Average Foam Lifetime, T_A (sec)
0.50	---	-------------	---
0.75	0.23	$0.0 \leq H \leq 0.75$	3.20
1.0	0.29	$0.0 \leq H \leq 1.0$	3.50
1.5	0.55	$0.5 \leq H \leq 1.5$	3.20
	0.37	$0.0 \leq H \leq 0.5$	
2.0	0.75	$0.65 \leq H \leq 2.0$	3.88
	0.30	$0.0 \leq H \leq 0.65$	
3.0	1.01	$0.65 \leq H \leq 3.0$	4.23
	0.33	$0.0 \leq H \leq 0.65$	
4.5	1.28	$0.5 \leq H \leq 4.5$	5.05
	0.26	$0.0 \leq H \leq 0.5$	
6.0	1.55	$0.7 \leq H \leq 6.0$	5.25
	0.36	$0.0 \leq H \leq 0.7$	

Table 4 (Cont'd) — Summary of Foam Layer Lifetime and Decay Results

(c) Medium Porous Disc, Initial Water Depth, $H_w = 1.5$ cm

Equilibrium Foam Height, H_o (cm)	Rate of Decay dH/dt (cm/sec)	Applicable Portion of the Decay Curve	Average Foam Lifetime, T_A (sec)
0.50	0.32	$0.0 \le H \le 0.50$	1.60
0.75	0.32	$0.0 \le H \le 0.75$	2.40
1.0	0.40	$0.0 \le H \le 1.0$	2.50
1.5	0.86	$0.90 \le H \le 1.5$	2.80
	0.51	$0.0 \le H \le 0.90$	
2.0	0.88	$0.75 \le H \le 2.0$	3.31
	0.41	$0.0 \le H \le 0.75$	
3.0	1.16	$0.85 \le H \le 3.0$	3.64
	0.46	$0.0 \le H \le 0.85$	
4.5	1.80	$0.65 \le H \le 4.5$	4.67
	0.25	$0.0 \le H \le 0.65$	
6.0	2.45	$0.80 \le H \le 6.0$	5.25
	0.26	$0.0 \le H \le 0.80$	

Table 4 (Cont'd) — Summary of Foam Layer Lifetime and Decay Results

(d) Medium Porous Disc, Initial Water Depth, H_w = 5.0 cm

Equilibrium Foam Height, H_o (cm)	Rate of Decay dH/dt (cm/sec)	Applicable Portion of the Decay Curve	Average Foam Lifetime, T_A (sec)
0.50	----	------------	----
0.75	0.24	$0.0 \le H \le 0.75$	3.12
1.0	0.37	$0.0 \le H \le 1.0$	2.69
1.5	0.68	$1.1 \le H \le 1.5$	3.30
	0.49	$0.5 \le H \le 1.1$	
	0.35	$0.0 \le H \le 0.5$	
2.0	0.78	$0.5 \le H \le 2.0$	3.39
	0.33	$0.0 \le H \le 0.5$	
3.0	1.03	$0.65 \le H \le 3.0$	4.25
	0.44	$0.0 \le H \le 0.65$	
4.5	1.33	$0.8 \le H \le 4.5$	4.74
	0.42	$0.0 \le H \le 0.8$	
6.0	1.58	$0.75 \le H \le 6.0$	6.25
	0.26	$0.0 \le H \le 0.75$	

Table 5 — Summary of Measured Single Bubble Lifetimes on a Water Surface

Zheng et al [25]

Atlantic Ocean Water T_w = 22.8°C, S = 31 ppt.		Delaware Bay Water T_w = 21°, S = 32 ppt.	
Diameter (µm)	Lifetime ± rms (sec)	Diameter (µm)	Lifetime ± rms (sec)
1700	1.84 ± 1.02	1200	1.27 ± 1.01
2700	3.71 ± 1.98	2100	4.51 ± 3.76
2800	3.25 ± 1.87	2200	4.08 ± 3.45
5200	4.85 ± 2.77	6700	2.89 ± 2.52
6700	5.48 ± 2.97	7400	2.13 ± 1.46
7400	4.21 ± 2.52	Average lifetime = 2.98 sec.	
Average lifetime = 3.89 sec			

Burger and Blanchard [6]

Seawater Sample (origin unknown) and 30 ppt. NaCl solution.

All bubble sizes were ~ 1000 µ diameter.

Test Conditions	Lifetime (sec)
Stagnant air, RH = 98%	1-2
Slight air motion, 60 ≤ RH ≤ 98%	~ 3
Strong air currents (~ few cm/sec), 50-60% RH	5-10
Blowing air (0.5m/sec) over the surface, 50-60% RH	20-35

Struthwolf and Blanchard [22]

Diameter (µm)		Lifetime (sec)	
	Sargasso Seawater	30 ppt. NaCl Solution	Old Orchard Beach Seawater
< 80	$\leq 10^{-2}$	$\leq 10^{-2}$	$\leq 10^{-2}$
100	0.08	0.078	0.082
300	0.30	0.27	0.33

Table 5 (Cont'd) — Summary of Measured Single Bubble Lifetimes on a Water Surface

Bikerman [4]

NaCl Solutions, S = 30 and 35 ppt.

Diameter (μm)	Lifetime (sec)
16-60	0.19
60-130	0.14
130-190	0.09
190-300	0.10
300-600	0.22
900-1600	0.91

Struthwolf and Blanchard [22] used a 30 ppt. NaCl solution prepared in very clean, filtered and distilled water, together with two unprocessed seawater samples, one from the Sargasso Sea and a second from Old Orchard Beach, Maine. They took great care to clean their equipment. No mention was made about any surface preparations. The air supply was filtered.

Bikerman [4] used two NaCl solutions, 30 and 35 ppt., in his tests. The salt was heated to a dull red condition to remove any organic impurities, the water was doubly distilled, the air was filtered and great care was taken to clean the equipment.

When the initial water depth H_w above the porous disc was increased in the present experiments, the foam decay rates decreased. This increased stability was especially noticeable at the higher equilibrium foam heights, regardless of the average pore size of the disc. There is more time for the gas-liquid interface to approach an equilibrium state in the deeper water samples. The result is an increase in the persistence (lifetime) of the bubbles. In addition to the above effects, the foam created in the deeper water samples probably has a higher moisture content and thicker lamallae than the foam created in the lower volume samples. The liquid takes more time to drain from thicker lamallae, so that it takes more time for the bubbles to burst, thus resulting in a more stable, persistent foam. The bubble sizes in all of the columns increased toward the top of the column. There was a noticeable decrease in the average size distribution of the bubbles in the column when the water depth was increased. The smaller, more densely packed bubbles were more stable than the larger ones, and therefore the foam created in the deep water did not collapse as fast as the foam created in the shallower water columns.

For foam heights above 2.0 cm, there were no significant changes in the decay rates of the foam when the pore size was increased. The bubble distributions within the columns are visually identical, and the foam layer structure and decay are independent of pore size. Below 2.0 cm the decay rate increased when the pore size was increased. This increased decay rate may be due to the slight increase in the size of the bubbles generated by blowing air through the medium disc.

Figure 33 is an assembly of photographs of the 3.0 cm equilibrium height foam columns that were generated when air was blown through the fine, porous disc into 5.0 cm samples of water with varying salt content. The photographs show the rapid decrease in the mean size of the bubbles in the column as the salt content increases from 0 to 12 ppt. Again, bubbles in salt water are smaller, greater in number and more densely packed than those in fresh water. The mean size of the bubbles and visual properties of the foam column do not change appreciably as the salinity increases further to 36 ppt. The stability of the column did not change either as the salinity increased from 16 to 36 ppt. However, the foam stability decreased as the salinity decreased from 16 to 0 ppt. in that the larger bubbles were less stable. Scott [20] also found that the salt stabilized the surface bubbles and thereby increased the lifetime of the surface bubbles from much less than 0.5 sec at 0 ppt. to between 1.0 and 1.5 sec at 35 ppt.

Figures 34, 35 and 36 show the structure of the real and simulated seawater foam columns (S = 26 ppt.) at equilibrium heights of 1.5, 3.0 and 6.0 cm respectively for all the water samples considered. There are no noticeable qualitative differences in the visual properties of the simulated and real foam columns in any of the individual pairs, thus leading to the conclusion that the foaming properties of the real and simulated seawater samples used in the experiments are nearly identical. Generally, changing the porous disc size does not significantly influence the structure of the foam column. However, when the initial water height H_w above the porous disc is increased from 1.5 to 5.0 cm, the average size of the bubbles in the column decreases in the thicker foam columns. This decrease is especially evident in the 6.0 cm columns. Looking at Figure 31, the columns of foam that were generated using the H_w = 1.5 cm water samples collapse at a much faster rate than those generated in the H_w = 5.0 cm samples for equilibrium heights above 3.0 cm, primarily because of the larger average bubble size and decreased wetness.

SUMMARY AND CONCLUDING REMARKS

The results of these experiments clearly show that varying the salt content of a clean water sample between 0 and 16 ppt. significantly influences its foaming ability, and the corresponding stability of a layer of foam residing on the surface. However, for salinities between 16 and 36 ppt. there is no appreciable change in the foaming characteristics of a water sample. The foaming characteristics of clean laboratory-simulated seawater should not vary greatly relative to a comparable sample from the open ocean.

Figure 31 of this report summarizes the measured stability characteristics of a three-dimensional foam layer. As was noted earlier in this report, the size distribution of the bubbles in the three-dimensional foam columns was comparable to the bubble size distribution in foam patches created by a wave breaking on a beach. Assuming that the stability characteristics of an in-situ foam layer can best be represented by a curve fitted through the 5.0 cm initial water depth data for foam heights greater than or equal to 1.0 cm and by the lower dashed line (constant dH/dt) for heights below 1.0 cm, one can determine the lifetime of a three-dimensional foam layer of thickness H_o at the surface by employing the following procedure.

1) Using Figure 31, find the value of decay rate dH/dt corresponding to the equilibrium foam height H_o.

2) Calculate the corresponding lifetime, $L_{22^\circ C}$, at 22°C using one of the following equations.

$$L_{22^\circ C}(sec) = \left[(H_o - 1.0)/\, dH/dt + 4.35\right], \; H_o \geq 1.0 \text{ cm};$$

$$L_{22^\circ C}(sec) = \left[H_o/0.23\right], \; H_o < 1.0 \text{ cm}.$$

If one is interested in calculating the total lifetime of a surface foam layer including the few remaining surface bubbles, then a reasonable approach is to choose some representative single bubble lifetime value from Table 5 and add it to the estimated value obtained from the above equations.

3) One major variable that influences the residence time of a layer of foam on a clean ocean surface is the temperature of the water. If the temperature of the water is different than 22°C, then the following temperature correction factor can be applied [14],

$$L_{T^\circ C} = L_{22^\circ C}\, e^{-0.0401\,(T^\circ C\, -\, 22^\circ C)}.$$

The value of $L_{T^\circ C}$ derived here does not take into account variations in the cleanliness of the water surface, whether or not surface-active agents are present, and the rising of bubbles from beneath into the surface foam layer. It also does not account for any air-sea temperature difference, the relative humidity of the air, the velocity of the air over the water surface, the presence in the water of biological organisms, or any agitation of the layer by waves or currents. These factors generally will lead to an increase in the value of $L_{T^\circ C}$. However, the lifetime value estimated using the results of the present experiments should give a reasonable first approximation to the stability of a foam layer on a clean water surface.

Further experiments are required in order to investigate the influences of the various factors mentioned in the preceding paragraph.

ACKNOWLEDGMENT

This work was conducted as part of a research program in free surface hydrodynamics supported by the Naval Research Laboratory.

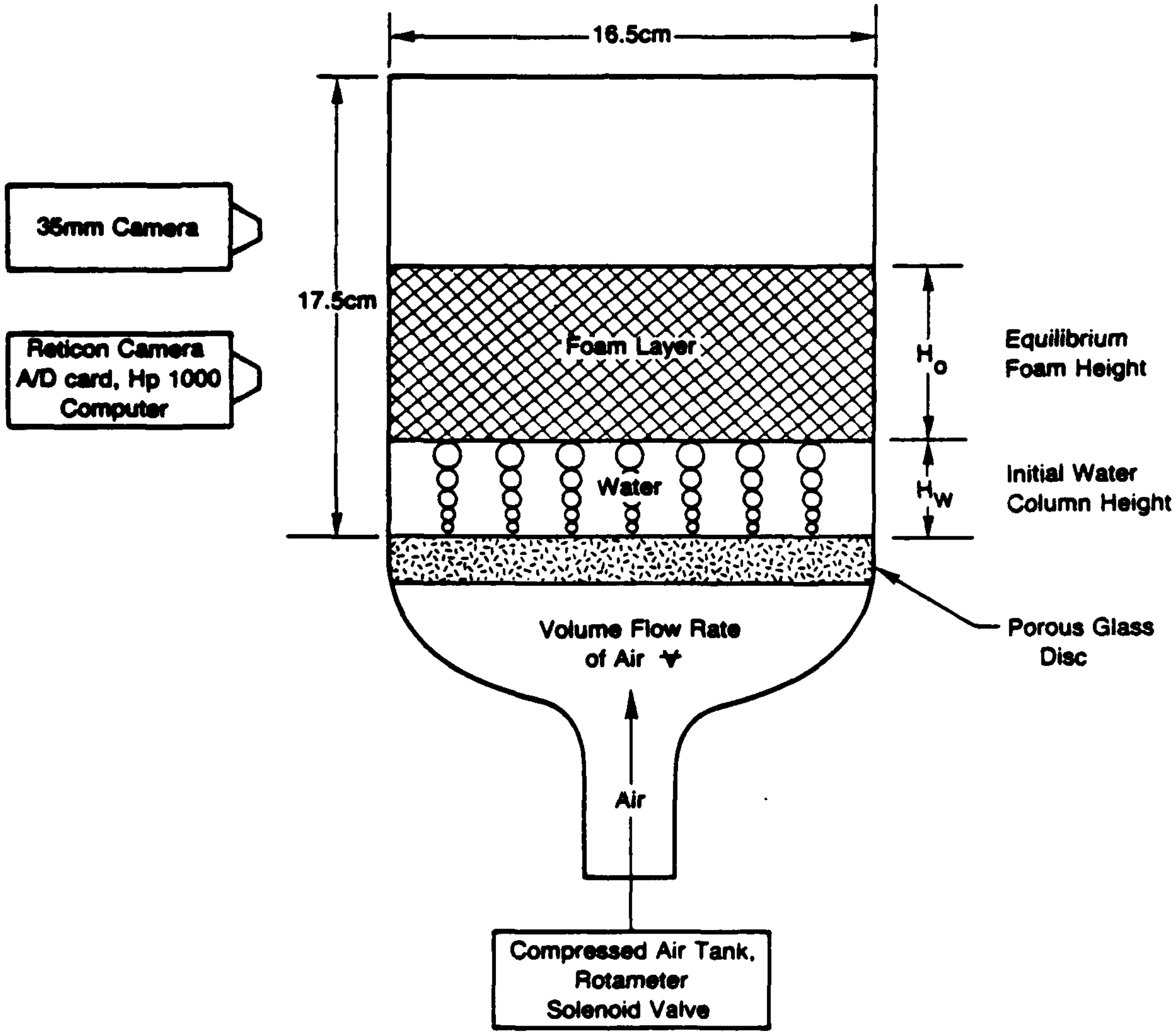


Fig. 1 — Diagram of the experimental apparatus

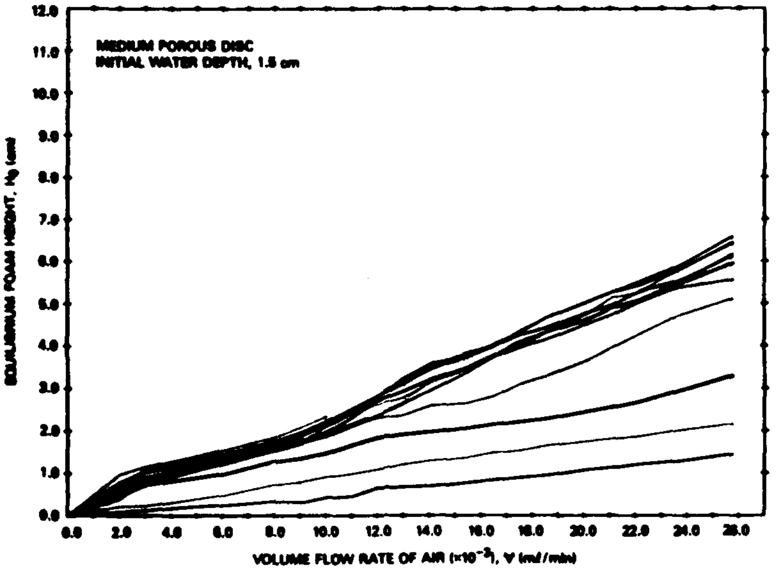


Fig. 2 — Equilibrium foam height as a function of volume flow rate for salinities between 0 and 36 ppt

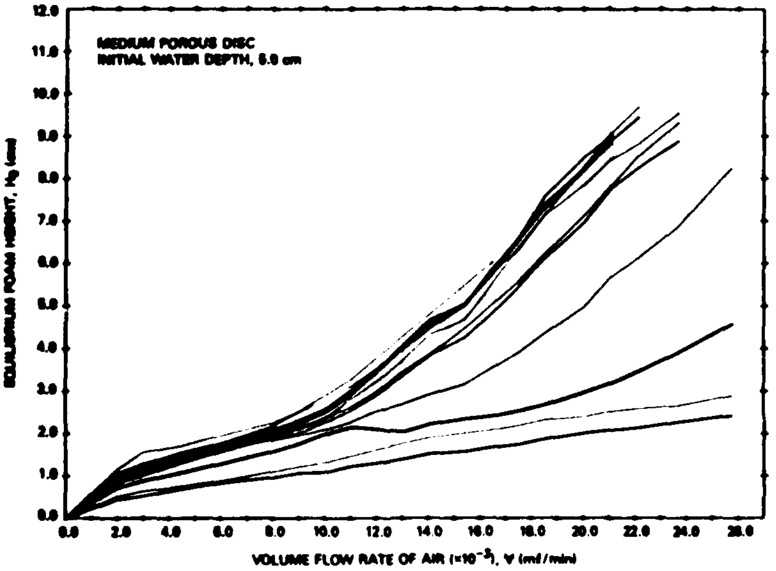


Fig. 3 — Equilibrium foam height as a function of volume flow rate for salinities between 0 and 36 ppt

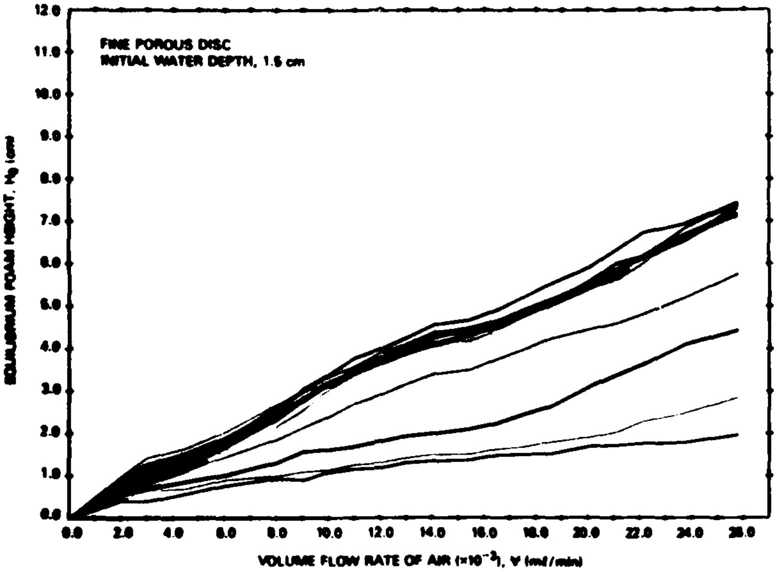


Fig. 4 — Equilibrium foam height as a function of volume flow rate for salinities between 0 and 36 ppt

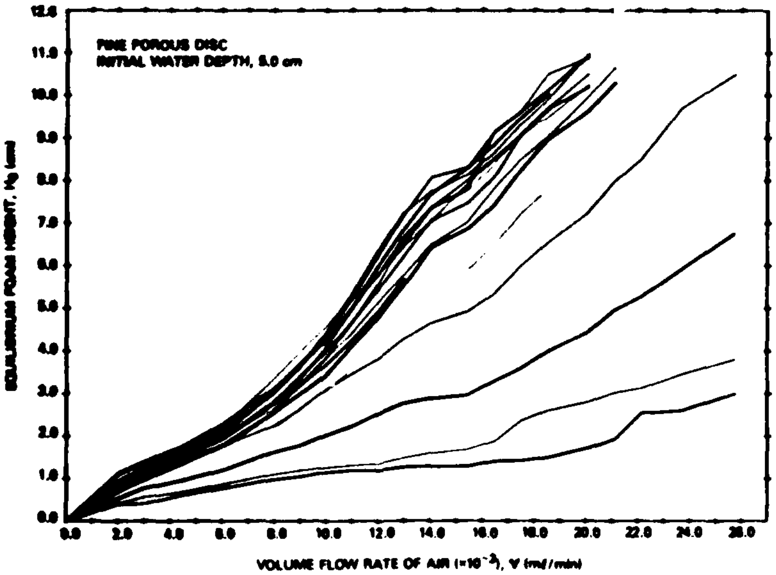


Fig. 5 — Equilibrium foam height as a function of volume flow rate for salinities between 0 and 36 ppt

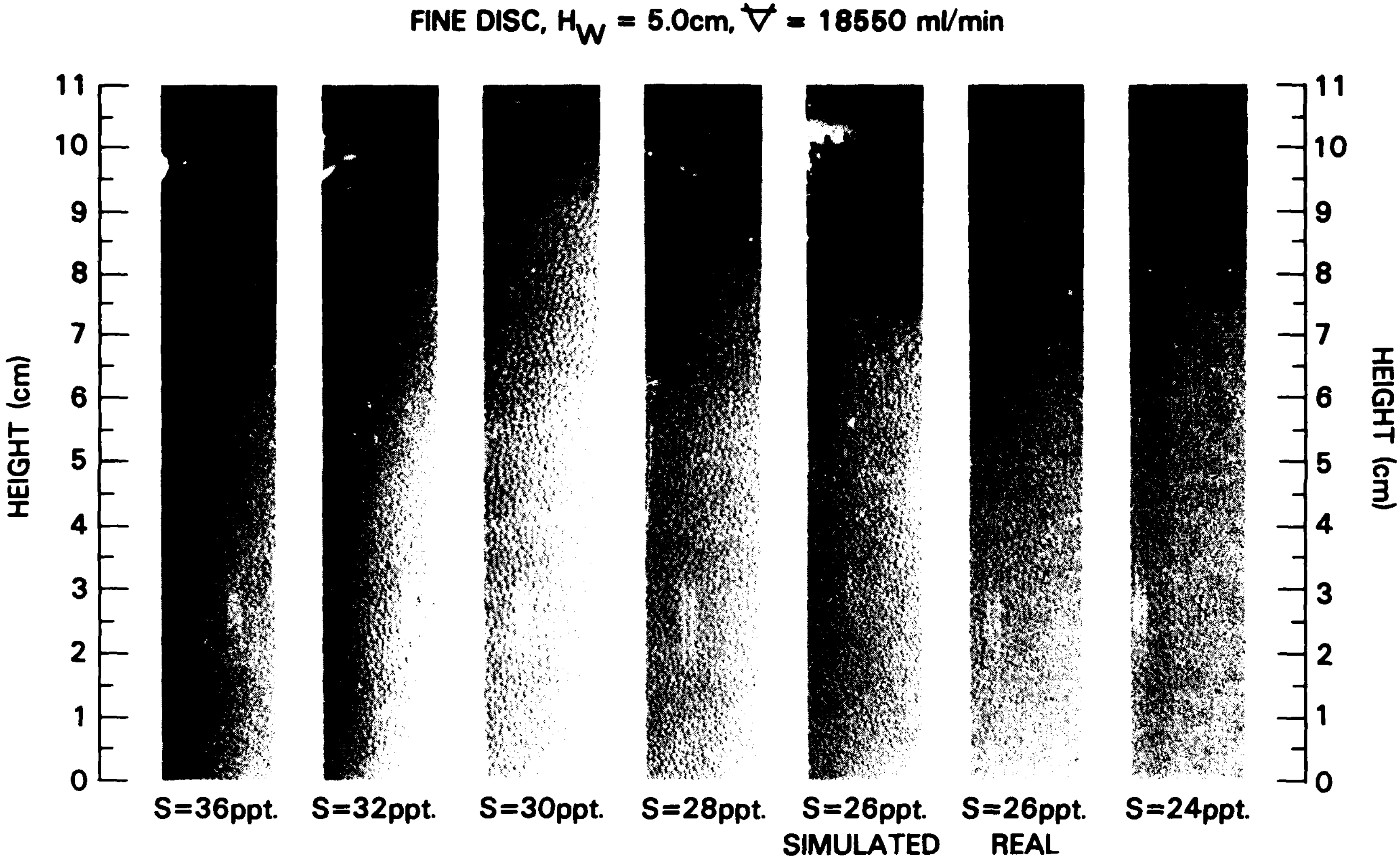


Fig. 6a — Photographs of the bubble size distribution and equilibrium foam height variation for salinities between 0 and 36 ppt

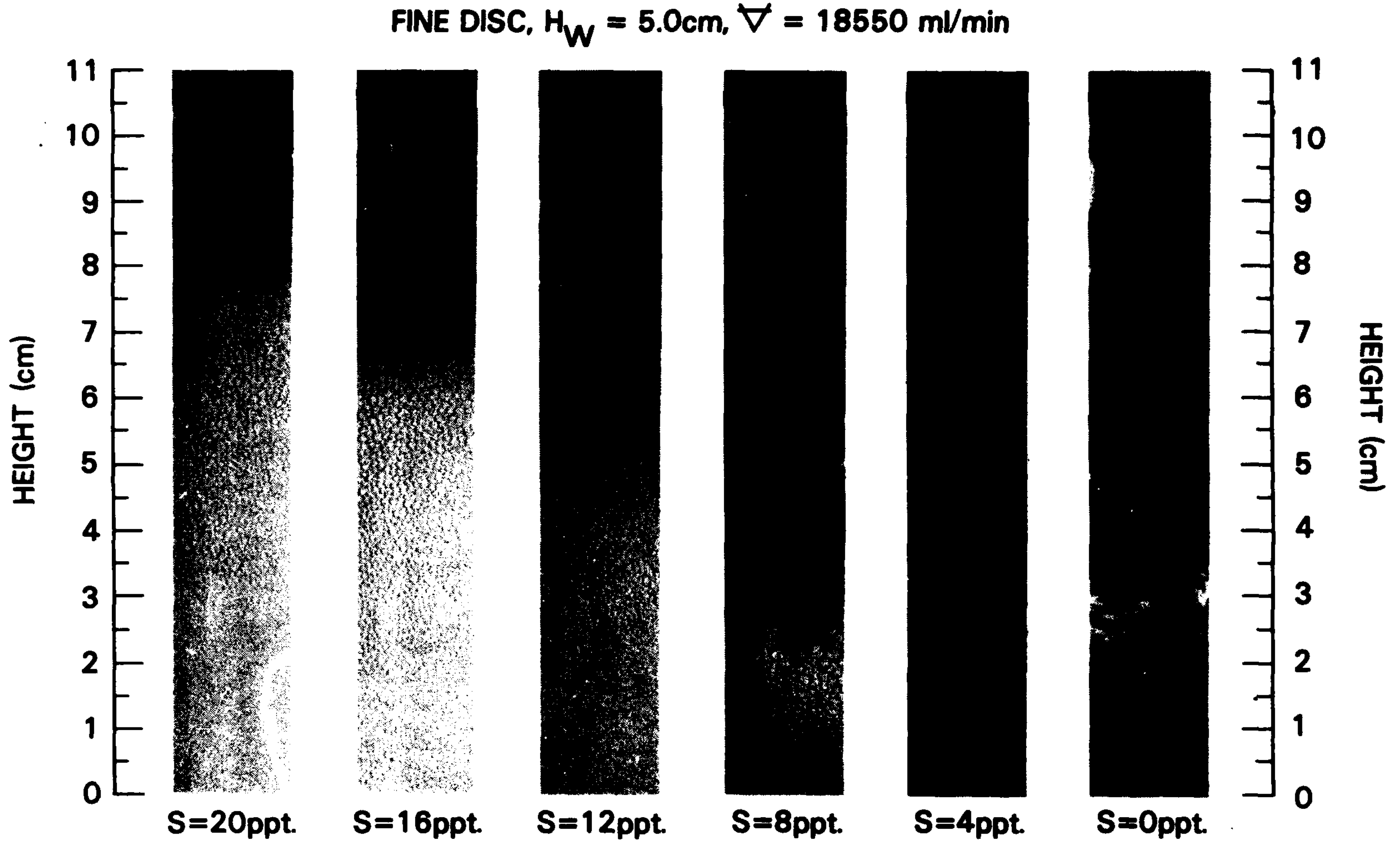


Fig. 6b — Photographs of the bubble size distribution and equilibrium foam height variation for salinities between 0 and 36 ppt

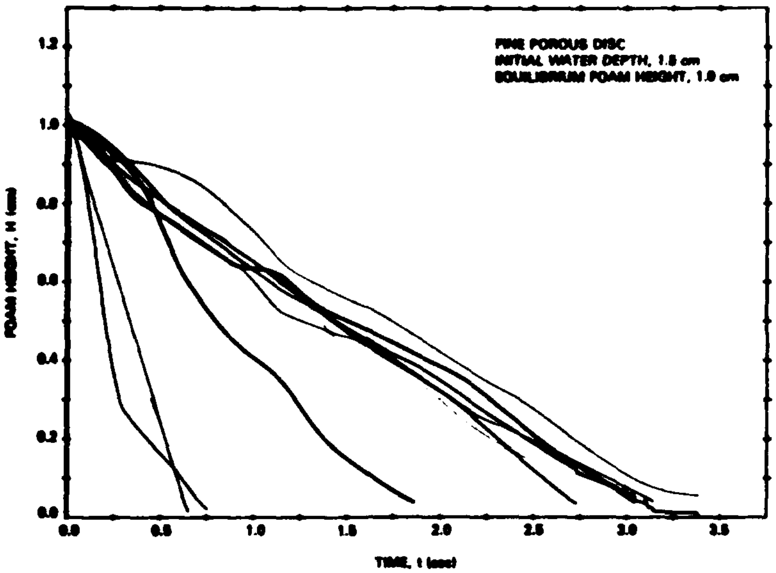


Fig. 7 — Influence of salt content on the decay properties of an equilibrium foam column

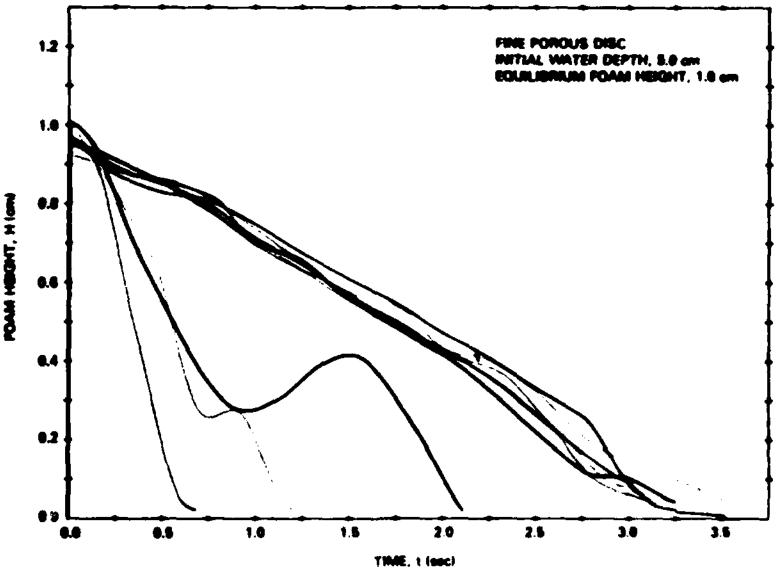


Fig. 8 — Influence of salt content on the decay properties of an equilibrium foam column

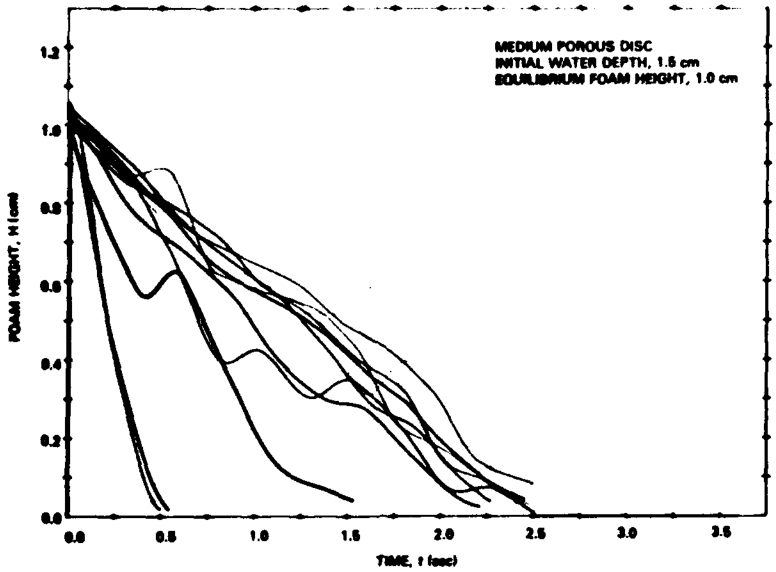


Fig. 9 — Influence of salt content on the decay properties of an equilibrium foam column

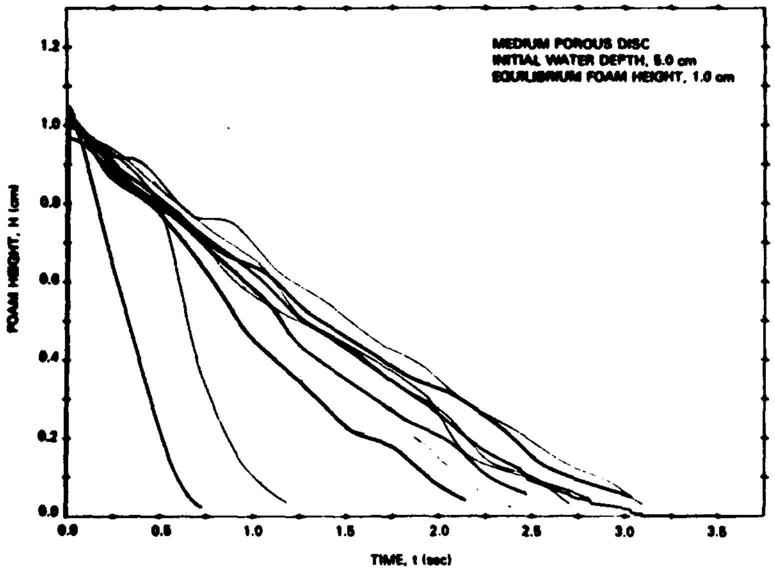


Fig. 10 — Influence of salt content on the decay properties of an equilibrium foam column

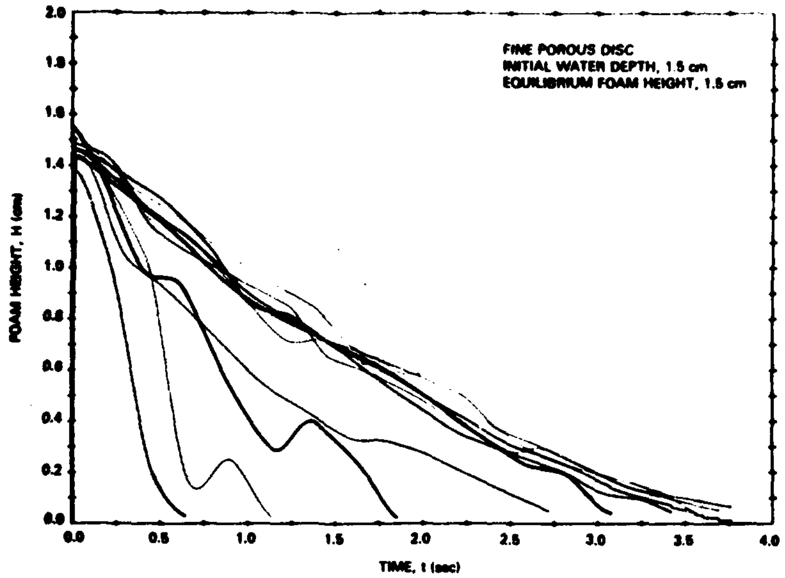


Fig. 11 — Influence of salt content on the decay properties of an equilibrium foam column

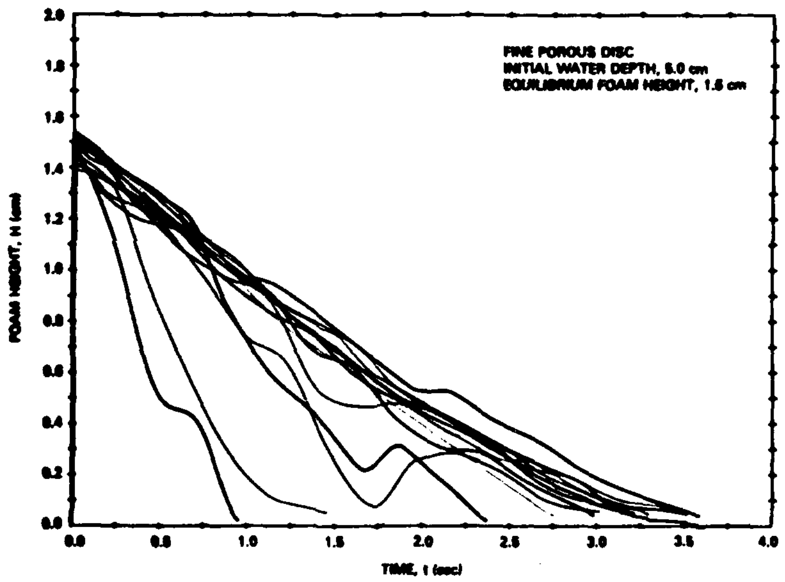


Fig. 12 — Influence of salt content on the decay properties of an equilibrium foam column

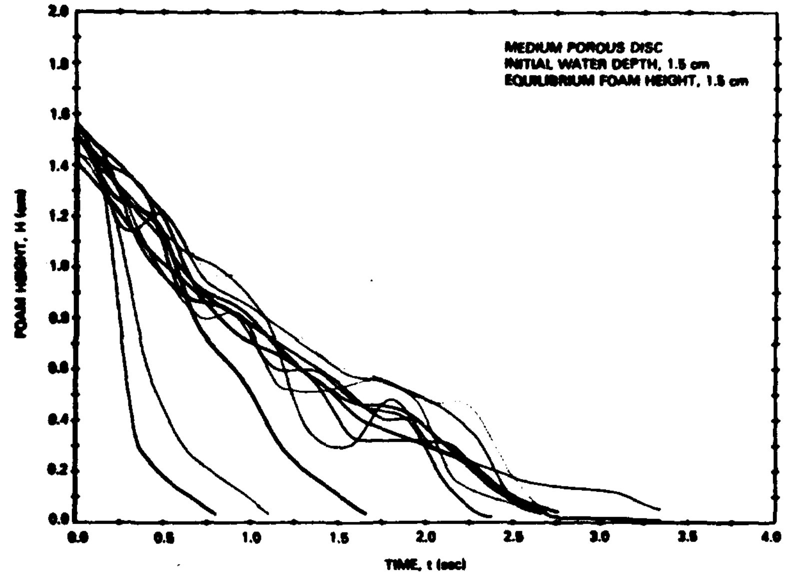


Fig. 13 — Influence of salt content on the decay properties of an equilibrium foam column

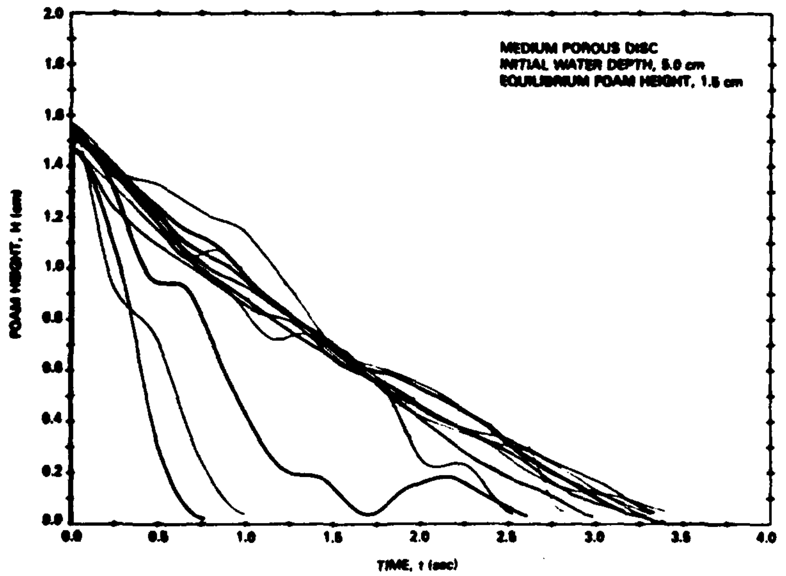


Fig. 14 — Influence of salt content on the decay properties of an equilibrium foam column

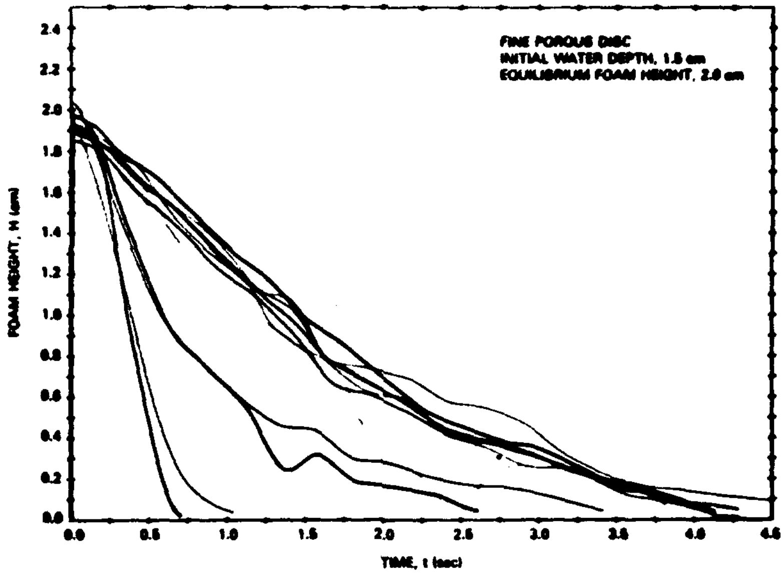


Fig. 15 — Influence of salt content on the decay properties of an equilibrium foam column

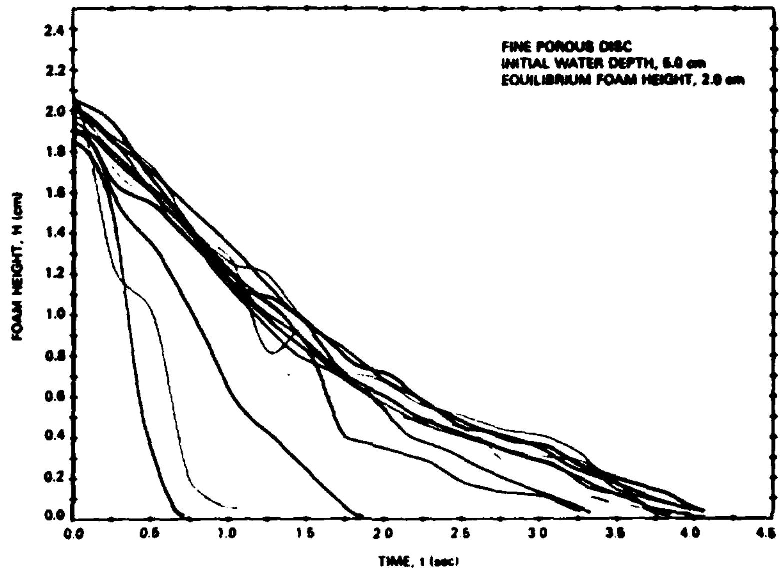


Fig. 16 — Influence of salt content on the decay properties of an equilibrium foam column

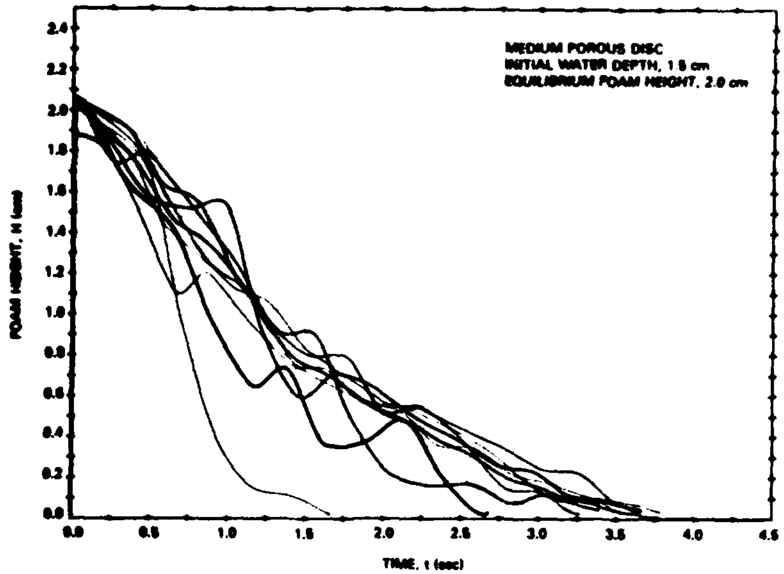


Fig. 17 — Influence of salt content on the decay properties of an equilibrium foam column

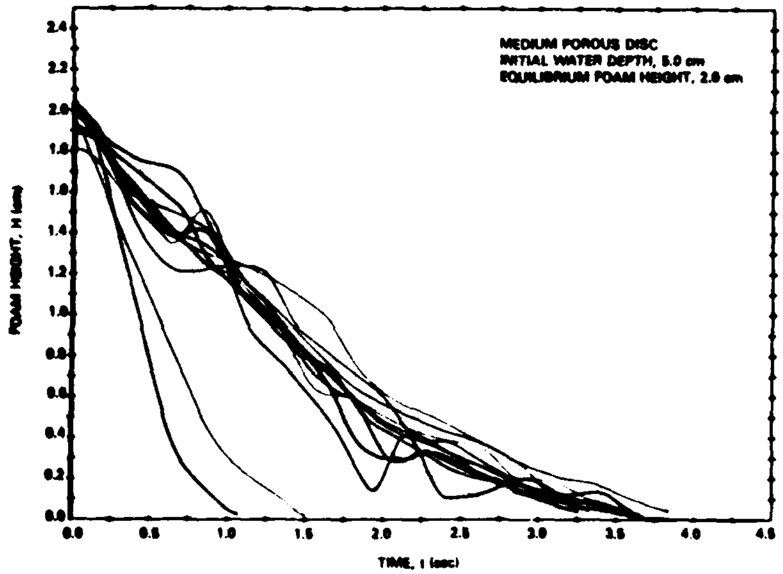


Fig. 18 — Influence of salt content on the decay properties of an equilibrium foam column

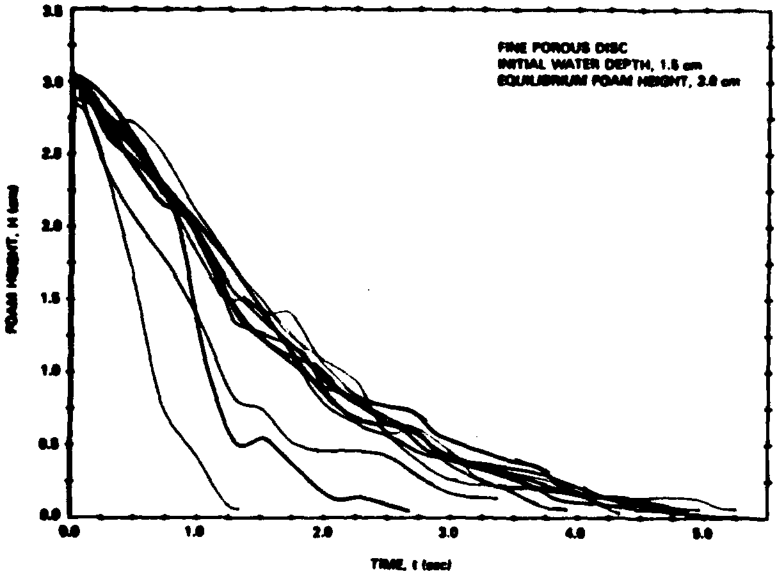


Fig. 19 — Influence of salt content on the decay properties of an equilibrium foam column

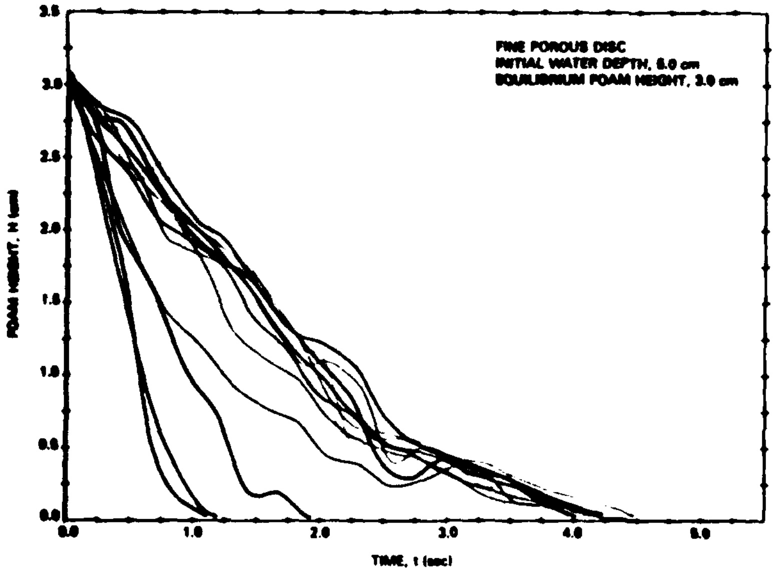


Fig. 20 — Influence of salt content on the decay properties of an equilibrium foam column

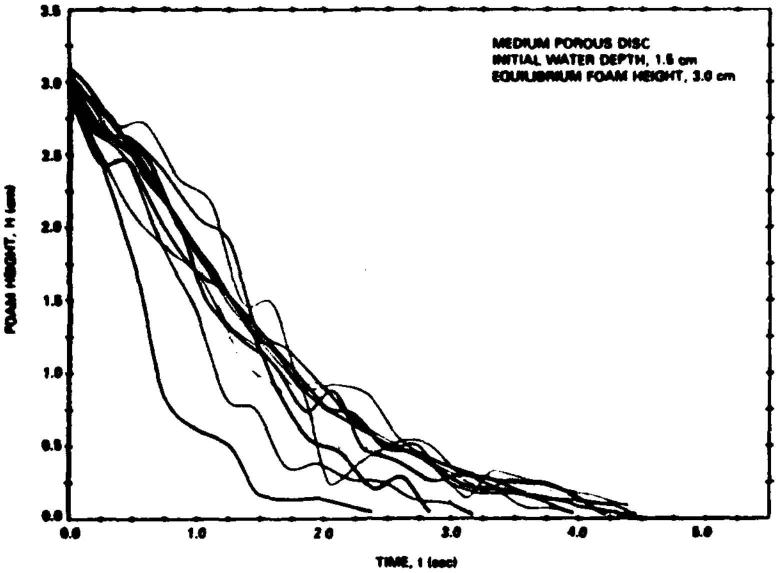


Fig. 21 — Influence of salt content on the decay properties of an equilibrium foam column

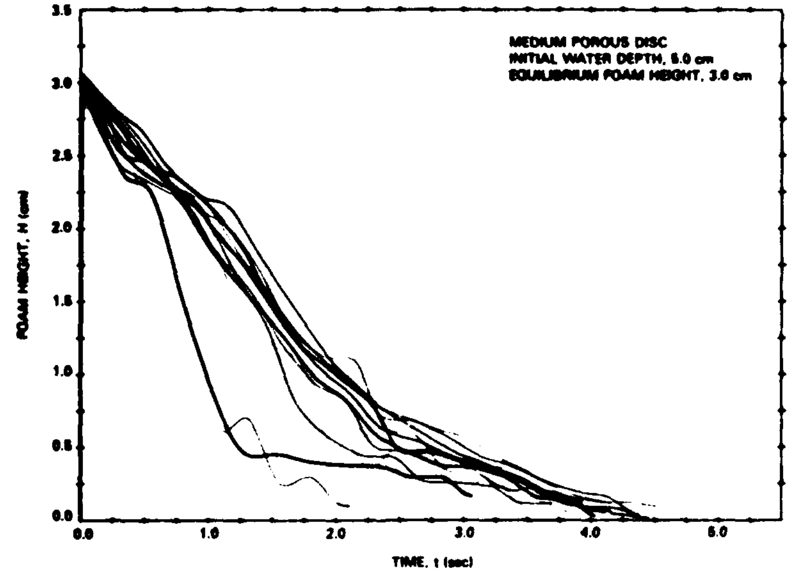


Fig. 22 — Influence of salt content on the decay properties of an equilibrium foam column

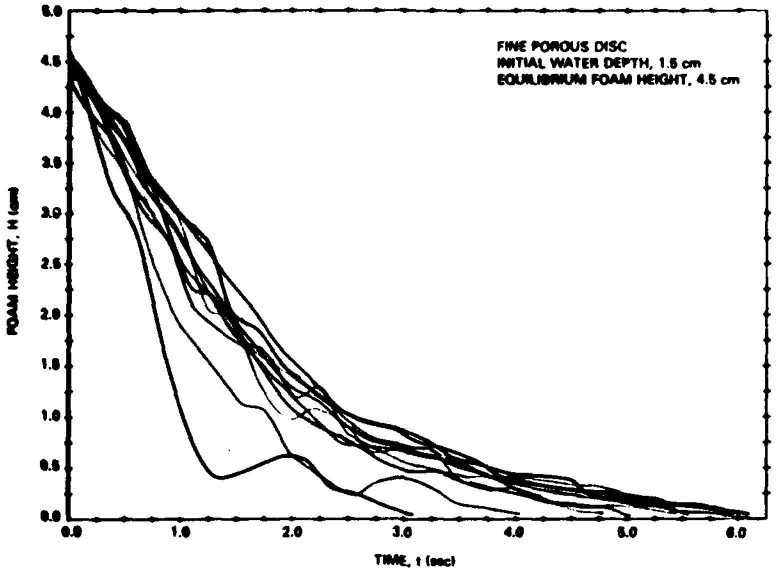


Fig. 23 — Influence of salt content on the decay properties of an equilibrium foam column

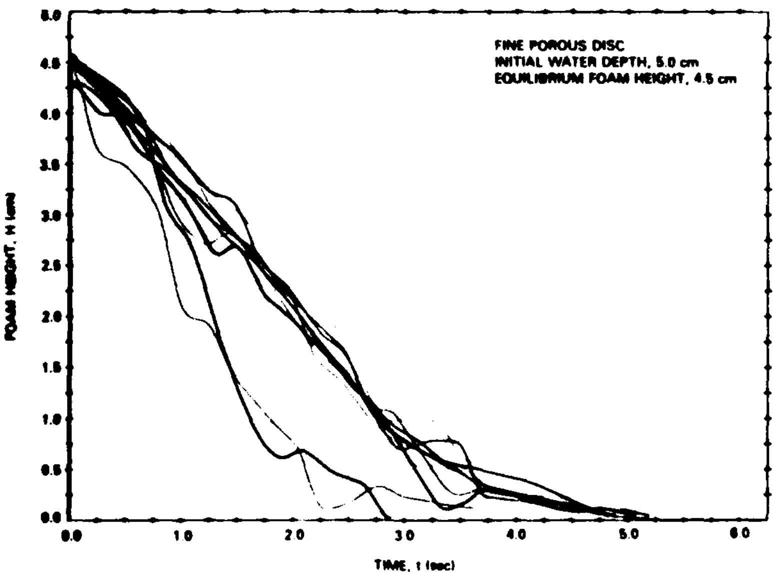


Fig. 24 — Influence of salt content on the decay properties of an equilibrium foam column

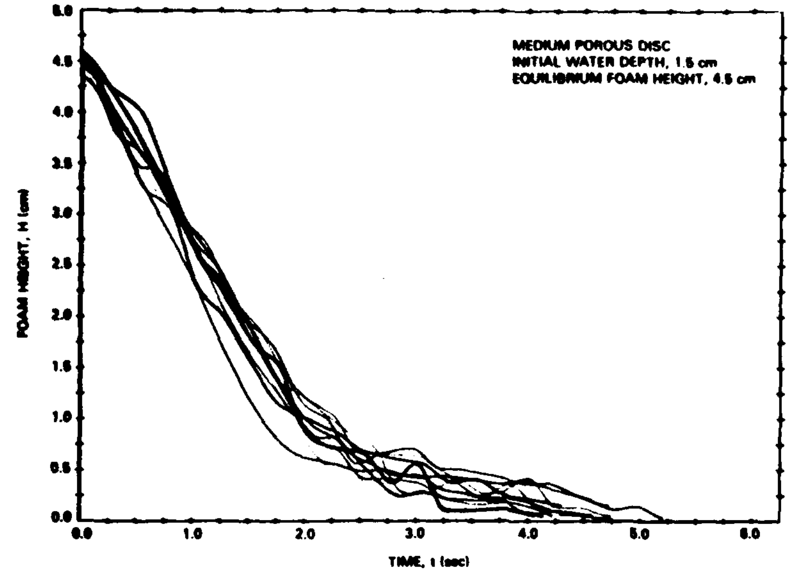


Fig. 25 — Influence of salt content on the decay properties of an equilibrium foam column

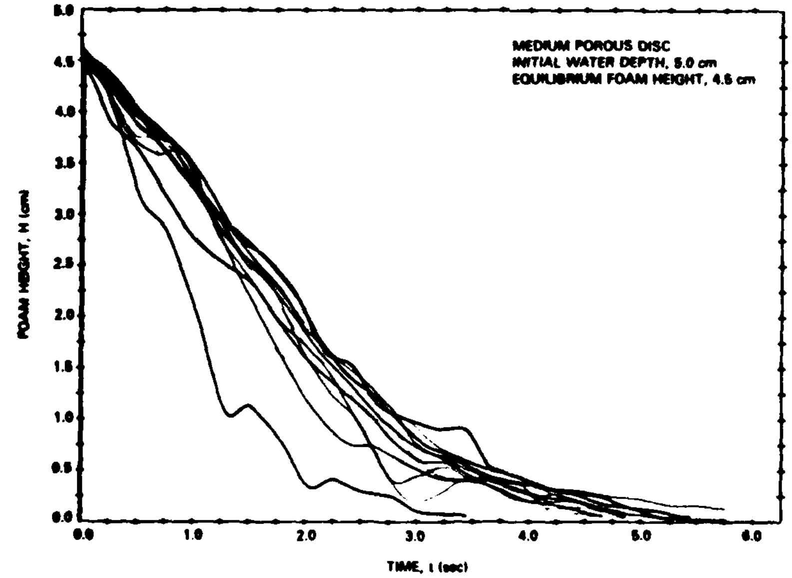


Fig. 26 — Influence of salt content on the decay properties of an equilibrium foam column

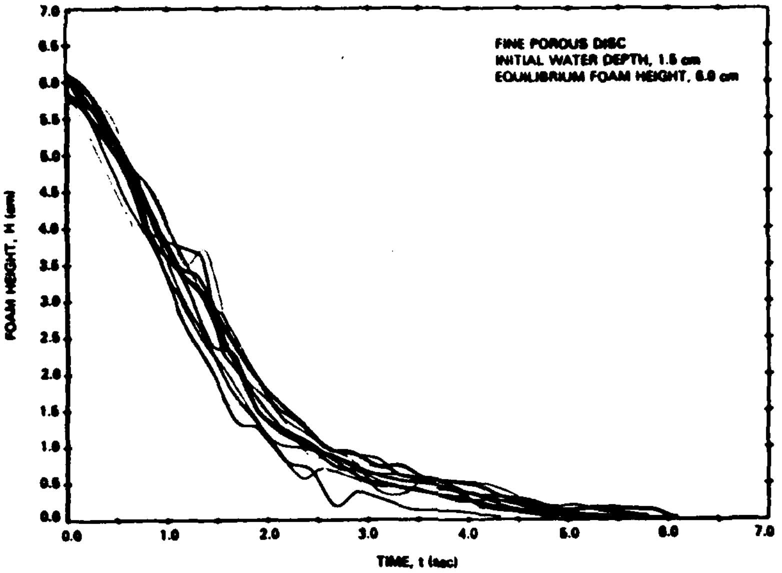


Fig. 27 — Influence of salt content on the decay properties of an equilibrium foam column

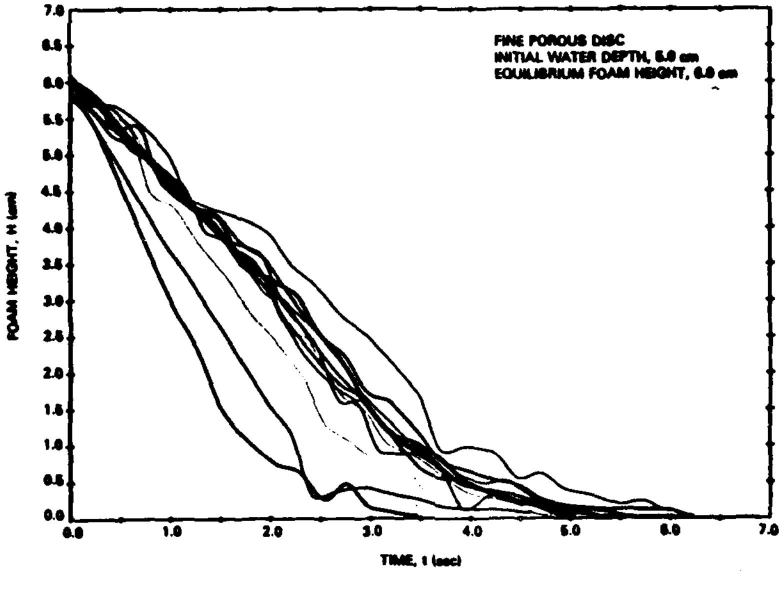


Fig. 28 — Influence of salt content on the decay properties of an equilibrium foam column

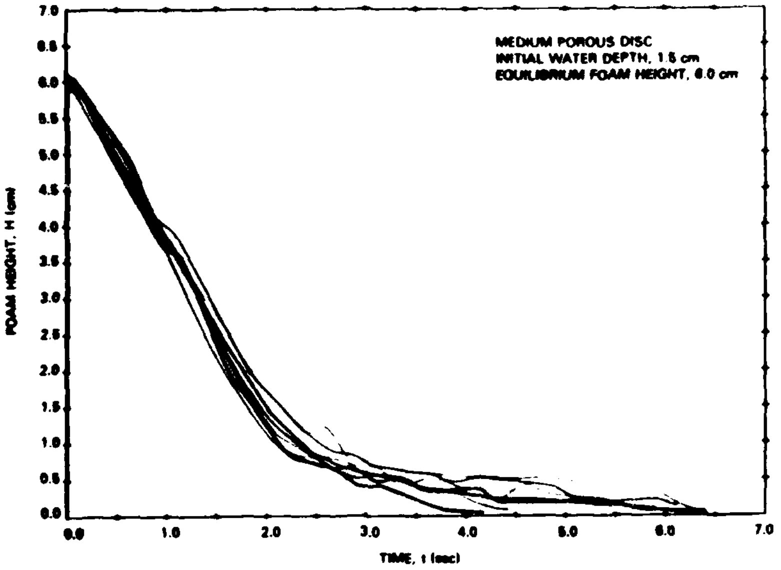


Fig. 29 — Influence of salt content on the decay properties of an equilibrium foam column

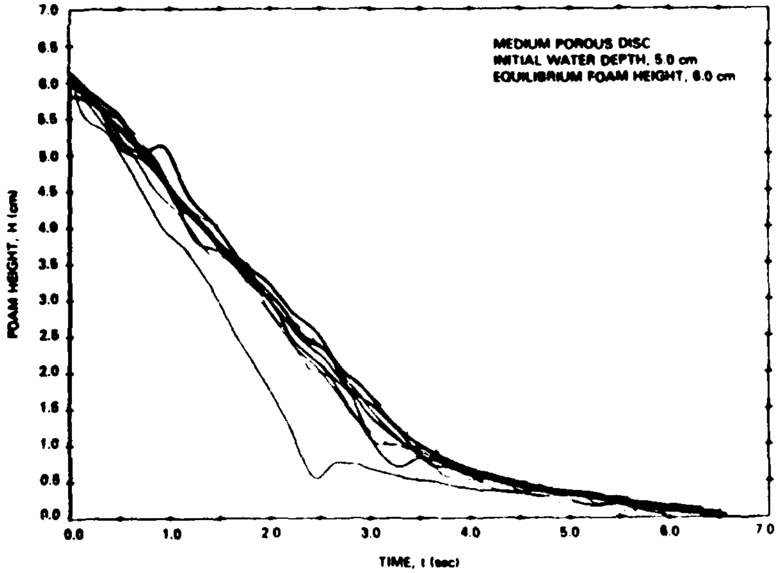


Fig. 30 — Influence of salt content on the decay properties of an equilibrium foam column

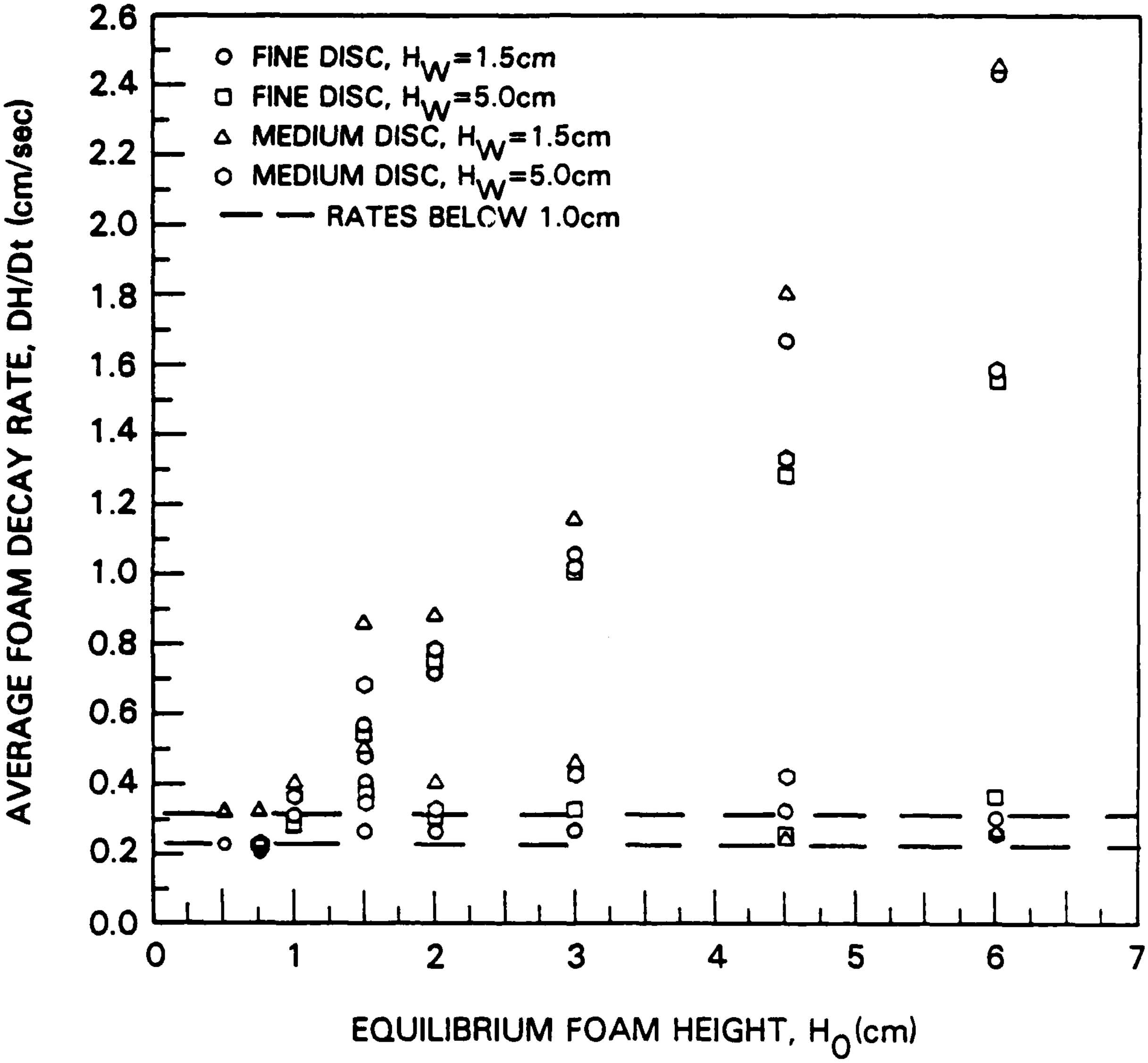


Fig. 31 — Summary of the average foam layer linear decay rates for salinities between 16 and 36 ppt as a function of the equilibrium foam height

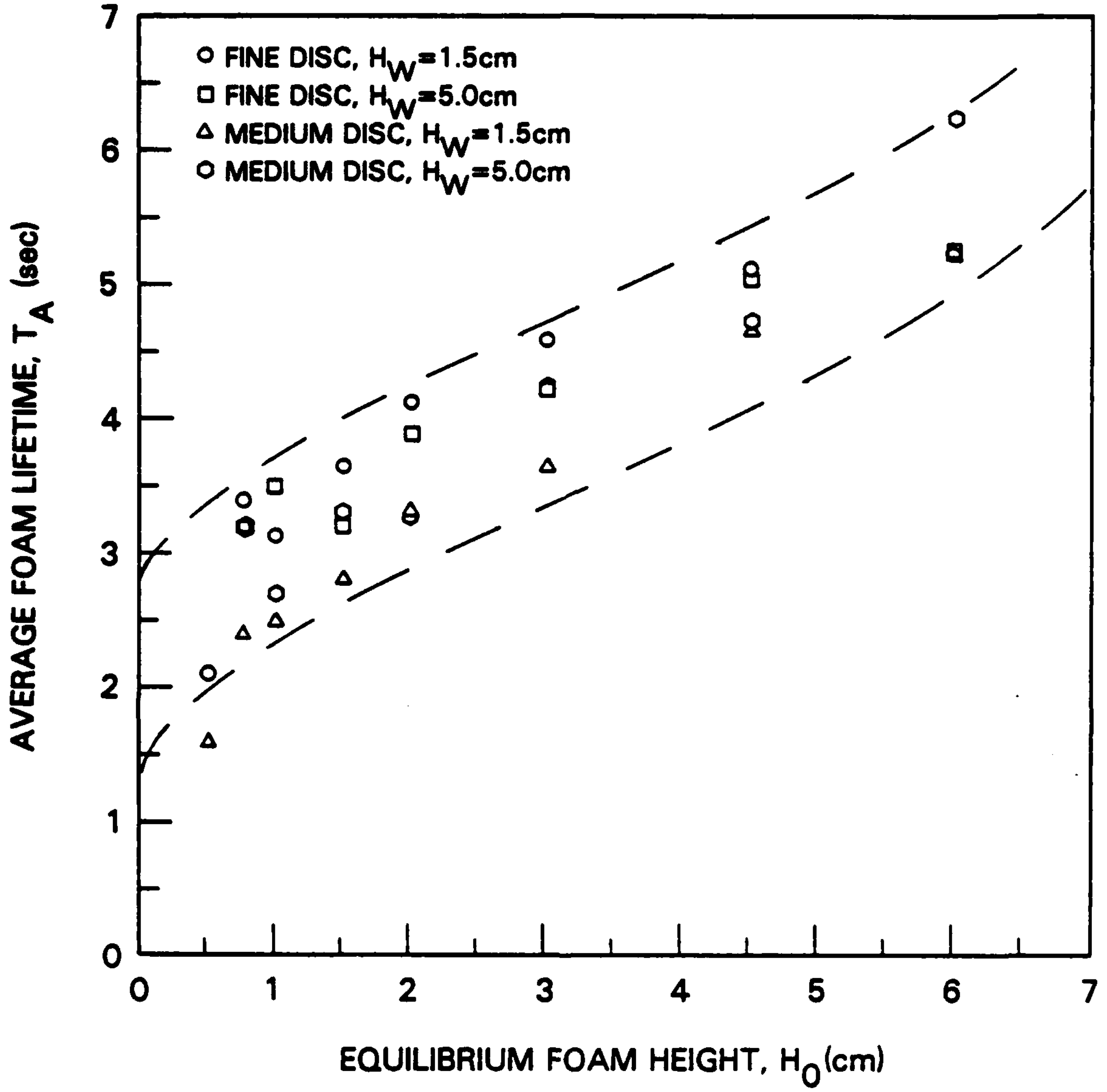


Fig. 32 — Summary of the average foam layer lifetimes for salinities between 16 and 36 ppt as a function of the equilibrium foam height

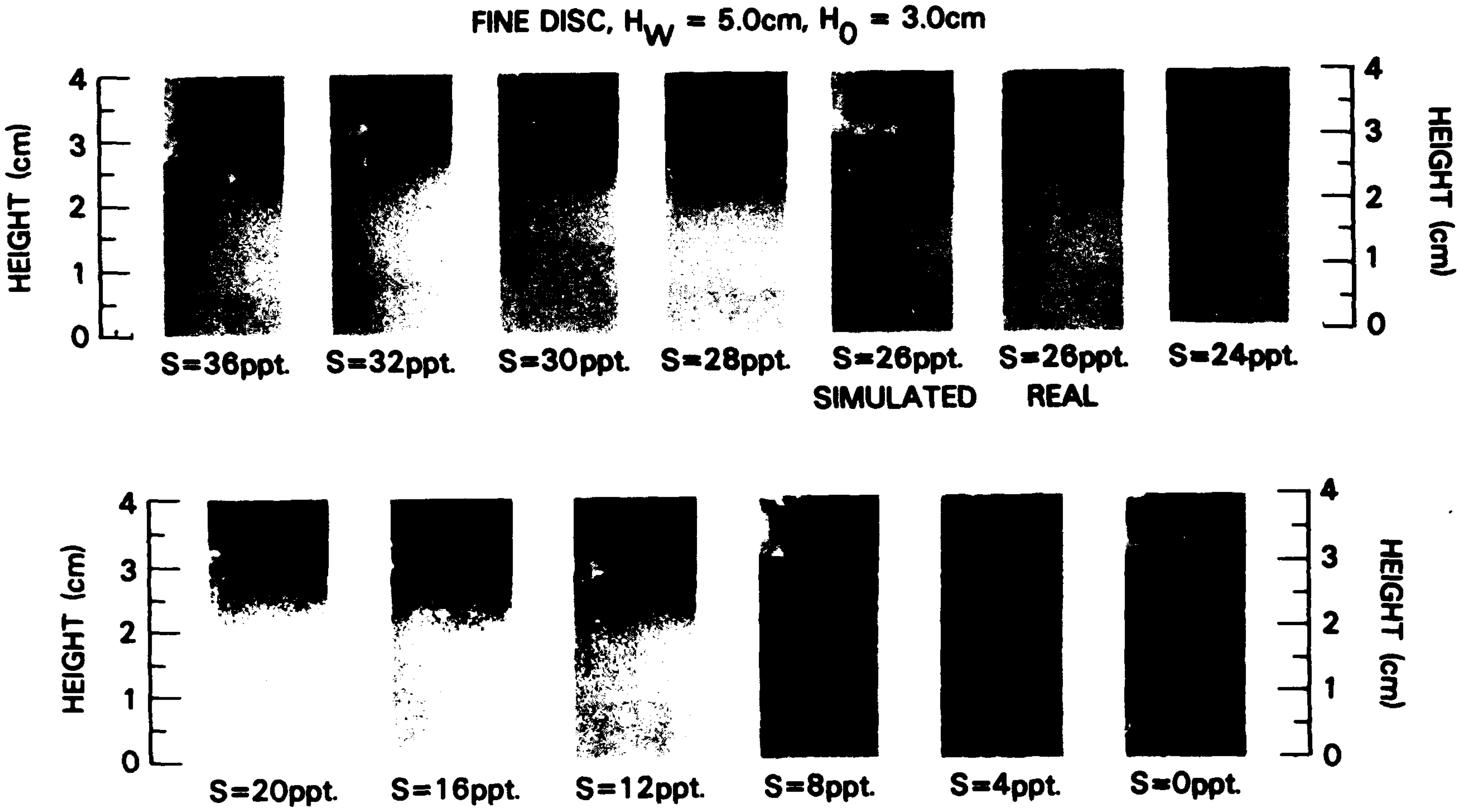


Fig. 33 — Photographs showing the influence of salt content on the bubble size distribution within the 3.0 cm equilibrium height foam columns

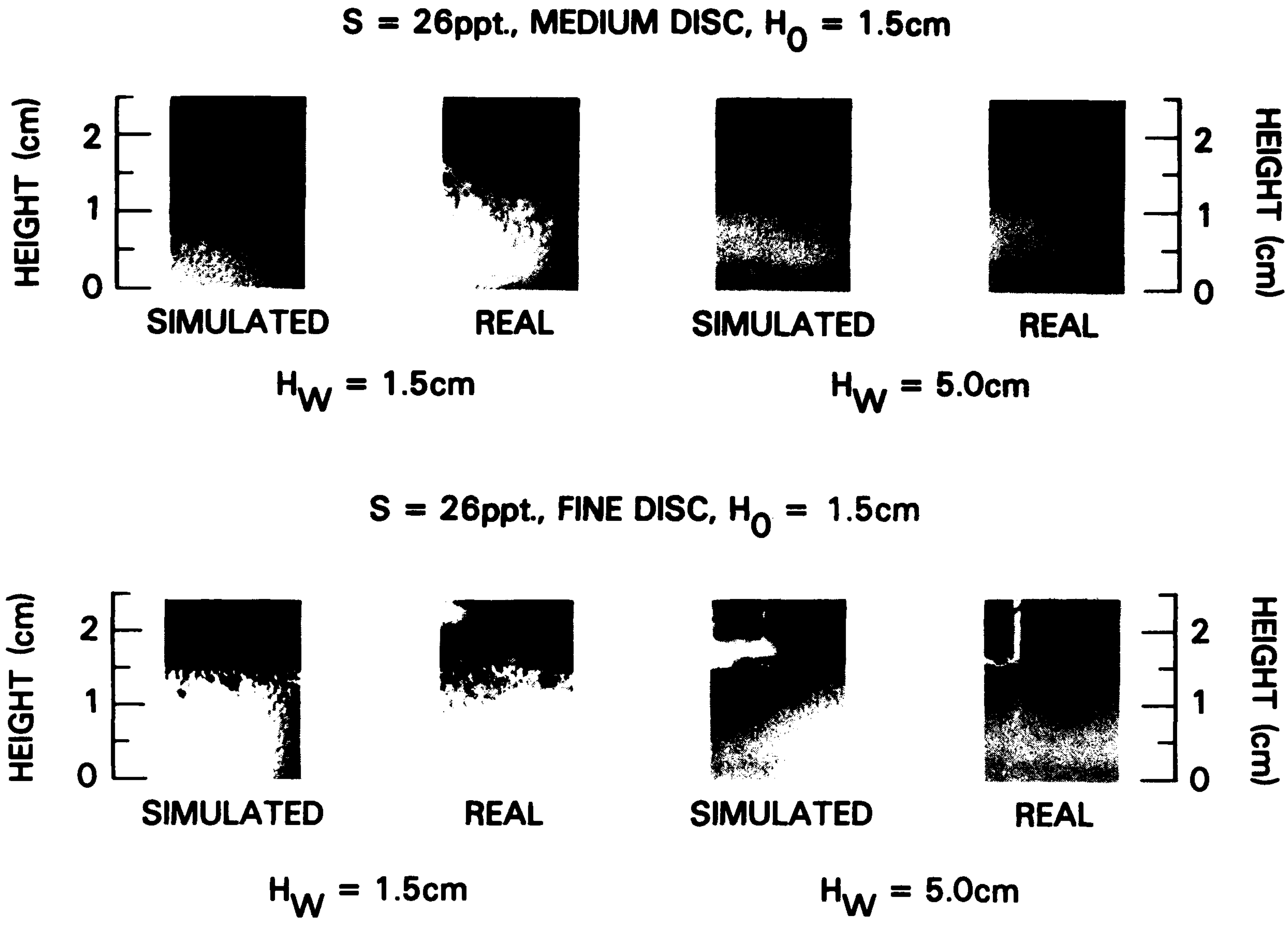


Fig. 34 — Photographs comparing the bubble size distribution within the real and simulated seawater foam columns at an equilibrium height of 1.5 cm

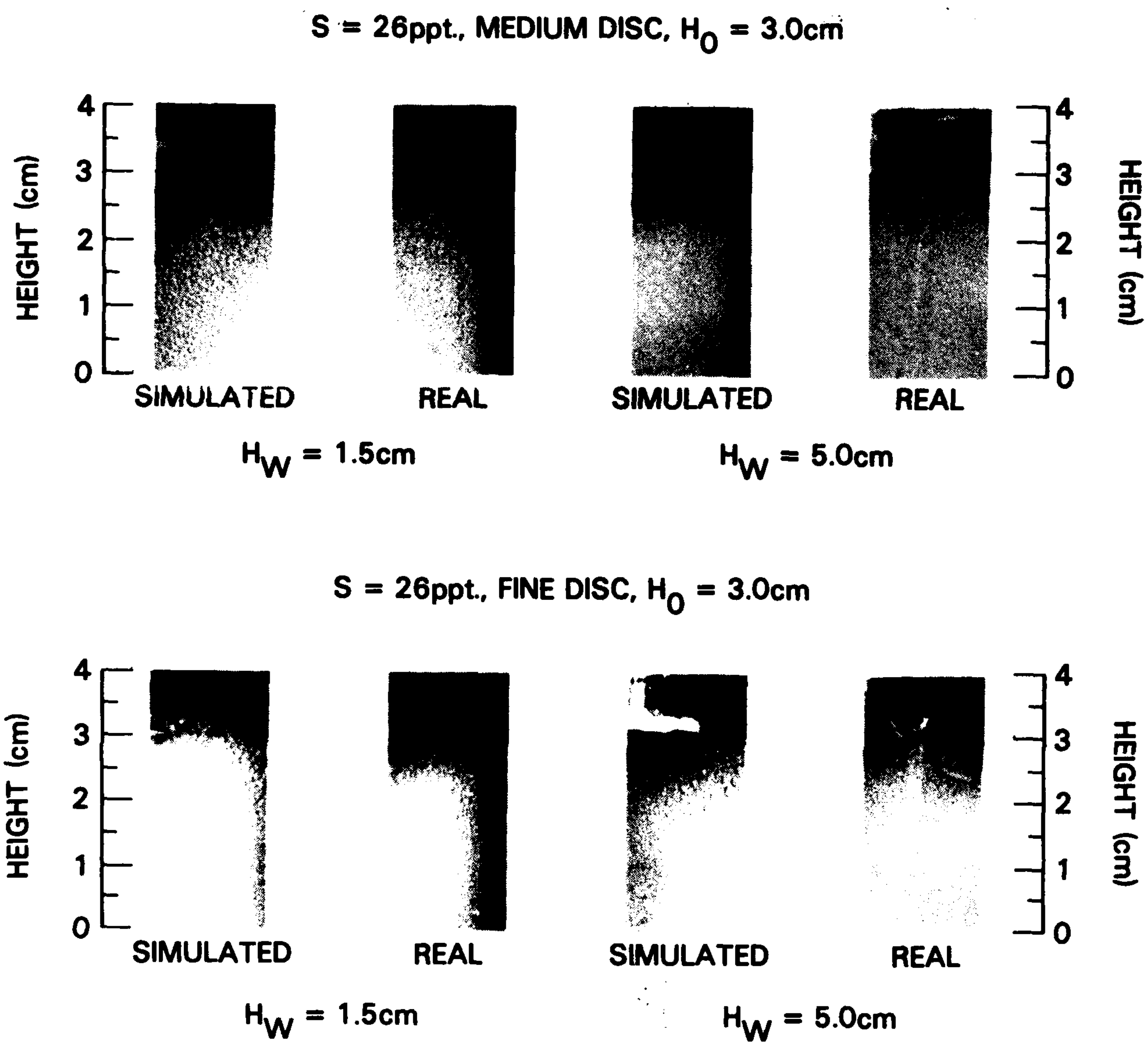
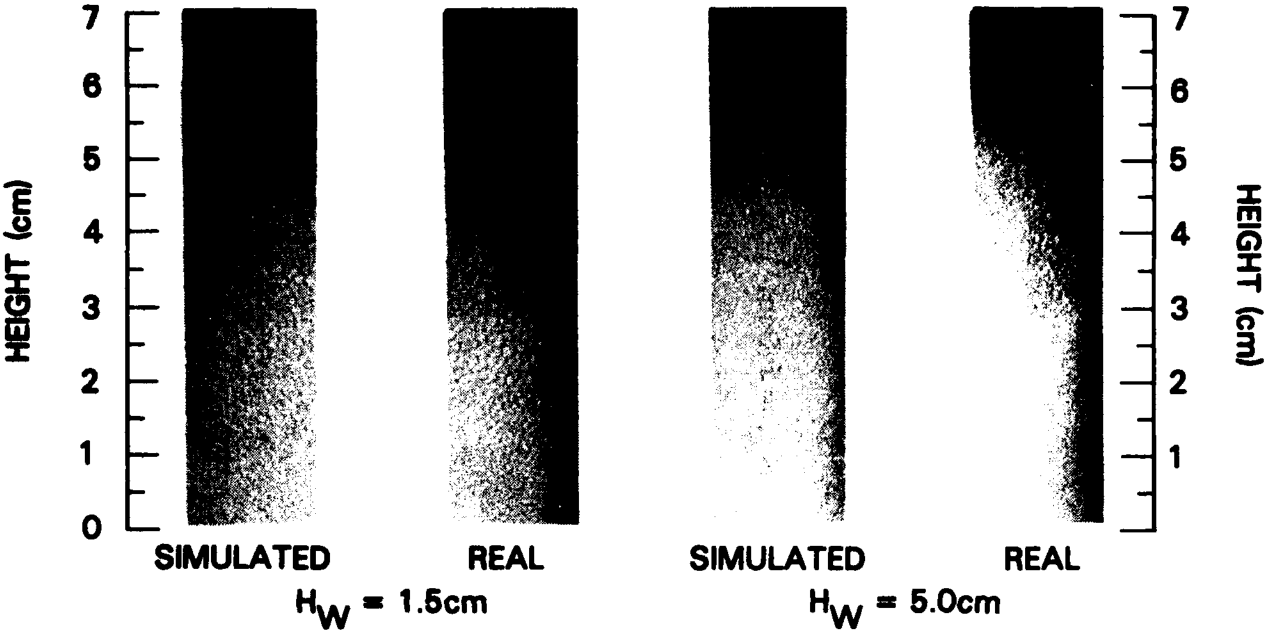


Fig. 35 — Photographs comparing the bubble size distribution within the real and simulated seawater foam columns at an equilibrium height of 3.0 cm

S = 26ppt., MEDIUM DISC, H_O = 6.0cm



S = 26ppt., FINE DISC, H_O = 6.0cm

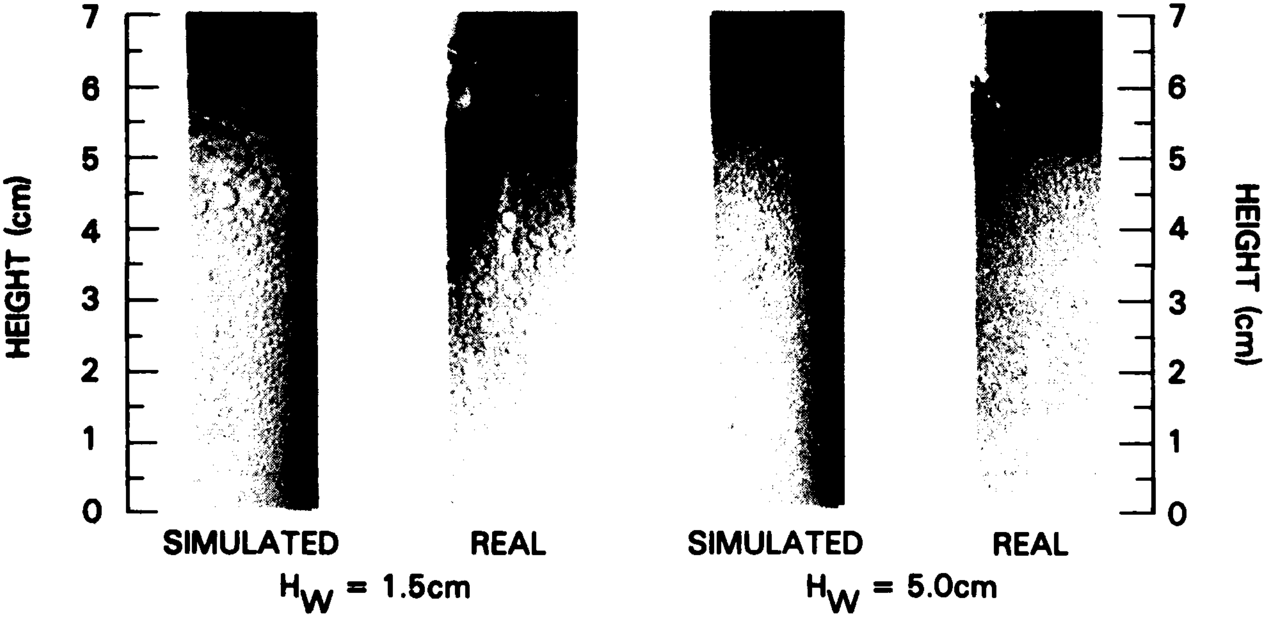


Fig. 36 — Photographs comparing the bubble size distribution within the real and simulated seawater foam columns at an equilibrium height of 6.0 cm

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