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Effect of Monomolecular Films on the Underlying Ambient-Noise Field

Part 2—Low Sea State and Laboratory Tests

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SUMMARY

A series of low sea-state tests show that the reduction of surface-related ambient noise beneath monomolecular (slick-forming) films begins between 1 and 2 kHz and extends to at least 70 kHz. Although the amount of noise reduction varies between experiments, attenuations of up to 8 dB are not uncommon. Most of the experiments are conducted in the absence of whitecapping, where for wind speeds greater than 2 m/s, the ambient noise spectra beneath the films generally resemble those of nonfilmed, lower sea-state conditions.

Laboratory experiments conducted with these same films spread upon a reservoir of seawater show that the regular bubble entrainment associated with vertically falling drops can be dramatically suppressed, and the air entrainment accompanying plunging liquid jets is characterized by a conspicuous increase in the number of smaller bubbles. Preliminary studies providing simultaneous in situ acoustic and video monitoring of the ocean surface from a meter beneath it suggest that, in the absence of whitecapping, the ambient noise reduction beneath the slick results from a dramatic decrease of microbreaking events within it. The acoustic signatures of these microbreaking events are distinguished by individual oscillating bubbles.

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1.0 INTRODUCTION

"I want to know what it says... the sea...what it is that it keeps saying."—Charles Dickens

Rohr, Glass, and Castile (reference 1) have previously reported that the presence of a monomolecular film on the sea surface can dramatically reduce the ambient noise beneath it. The ambient noise quieting provided by a film was assumed to result from reducing the number of breaking whitecaps within the area over which the film spread. Noise reductions beginning around 2 kHz and extending to at least 20 kHz have been found (reference 1) in varying degrees throughout sea states 2 through 6. In some instances, maximum noise reductions of about 8 dB were observed (reference 1) beneath the slick-forming films.

Calming the ocean surface with monomolecular films is cuneiform old. There have been recent reports (reference 2) as well of the absence of breaking waves within experimental slicks. It is hypothesized (references 3 to 5) that the films' smoothing of the small-scale roughness on the sea surface loosens the wind's grip on the larger gravity waves and, consequently, decreases the probability that they will break. While in the presence of surface-active materials the damping rate of capillary waves can be increased by factors of two to four (reference 6), the film's suppression of the generation of capillary waves by the wind may be even more important. Barger, Garrett, Mollo-Christensen, and Ruggles (reference 2) have observed that when a slick is present the wind field appears to lose all knowledge of the underlying sea. Nelson (reference 7) has calculated that the components of the fluctuating Reynold's stresses in the atmosphere tangent to a film-covered ocean surface can be decreased by an order of magnitude or more.

On several occasions monomolecular films have been reported (reference 8) to have a pronounced quieting effect even when whitecaps were not present. The study of the film's quieting effects under these conditions are of particular interest since, in the absence of whitecapping, candidate sources of sea-surface sound are particularly lacking (references 8 to 14). Intriguingly, for sea states neither too low (reference 11) nor too high (reference 15), the ocean ambient-noise spectrum from 500 Hz to 25 kHz exhibits a similar -5 to -6 dB per octave slope, regardless of whether whitecaps are present or not. The deviations from this spectral shape at either end of the sea-state spectrum are not attributed to differences in the noise-generating mechanisms themselves but to effects on their propagation.

The object of this study is twofold: (1) to better establish through a series of at-sea experiments the noise-quieting effects of different films throughout a range of low sea states where whitecaps are not present or just beginning to appear, and (2) to begin to determine from laboratory and further field tests the acoustic source(s) on the sea surface that the films undermine.

Section 2.0 compares low sea-state noise spectra collected simultaneously from sonobuoys within and outside experimental slicks. Section 3.0 contains higher (70 kHz) frequency measurements obtained from individual hydrophones of a vertical array as a monomolecular film passed over them. The result of laboratory and at-sea testing of candidate sea-surface sound sources, both with and without films present, are reported respectively in sections 4.0 and 5.0. Concluding remarks can be found in section 6.0.

2.0 AT-SEA TESTS WITH SONOBUOYS AND MONOMOLECULAR FILMS

2.1 BACKGROUND

Navy sonobuoys (AN/SSQ-57A) were used to monitor underwater noise from depths of 9 (primarily), 18, and 122 m. Wind speeds were monitored from a height of 7 m for the 1988 experiments conducted from the Marine Physical Laboratory's Barge, the ORB, and from 10 m for the 1989 experiments conducted from the USNS *De Steiguer* and the David Taylor Research Center's Mobile Noise Barge (MONOB). Sonobuoys are essentially composed of a battery-operated hydrophone hanging from a balloon-encased transmitting antenna. They provide a readily available source of expendable omnidirectional hydrophones with variable depth settings. Moreover, by converting the hydrophone output into a radio frequency signal, the acoustic contamination associated with a nearby monitoring platform can be avoided.

Although an absolute calibration of the sonobuoys is unnecessary to measure the noise reduction produced by the films, on several occasions the sonobuoys were calibrated prior to deployment. A portable bench calibrator described in reference 16 provided sonobuoy sensitivities from 2 to 8 kHz. Figure 1 compares the sound-pressure levels monitored by several calibrated sonobuoys (no slick present) with the Knudson Sea Curves, which are represented as solid lines. The dotted line in figure 1 corresponds to the sonobuoy manufacturer's "maximum" allowable electronic noise level expressed as an equivalent ambient noise level. Where the ambient noise signal is greater than the noise floor imposed by the electronics, good agreement is found between the data and the Knudson Sea Curves. As expected, sporadic whitecaps began to appear around sea state 2.

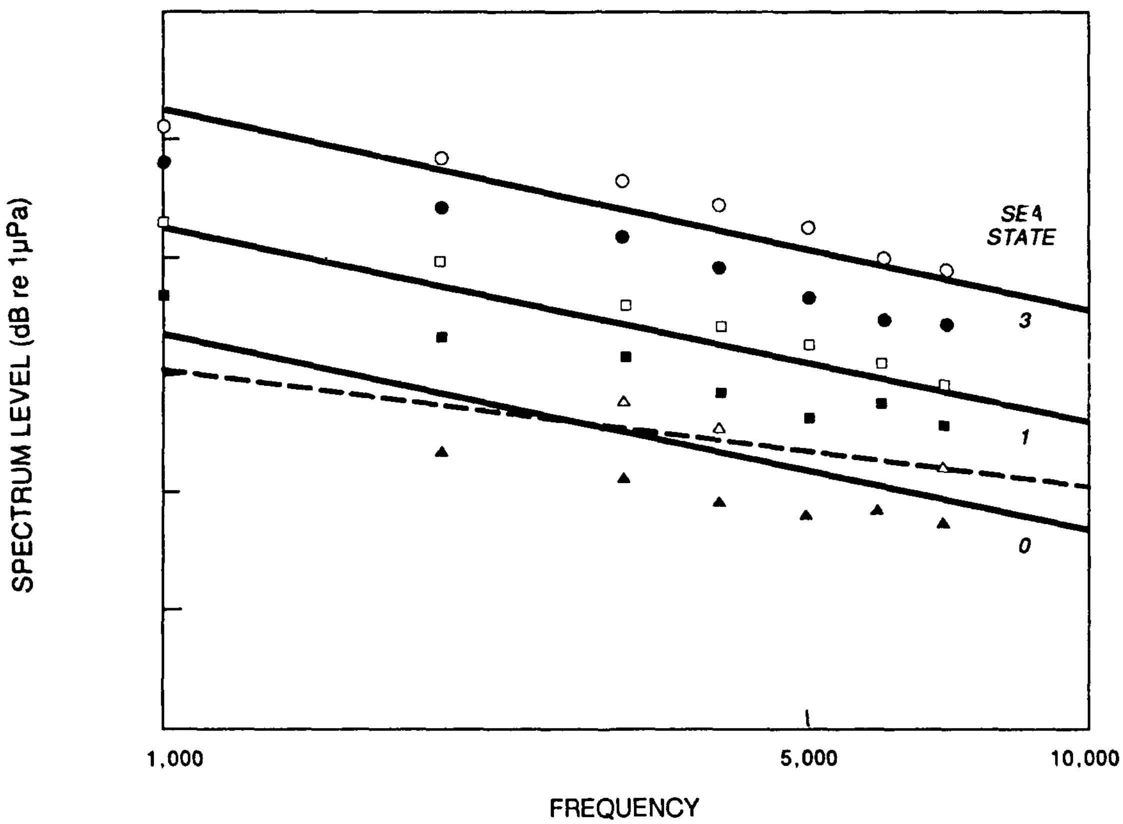


Figure 1. Symbols are typical (no slick) of underwater ambient noise spectral data. Dotted line corresponds to the manufacturer's maximum allowable electronic noise level of the sensor, expressed as an equivalent ambient noise level. Solid lines are from "Knudson Curves" for various sea states.

On several occasions the sonobuoys' output was observed to evolve through the range of spectrum levels shown in figure 1 as the wind speed increased steadily. Curiously, at the lowest sea states the ocean ambient-noise measurements did not increase steadily with wind speed but jumped discontinuously at a wind just above 2 m/s. The spectrum level suddenly appeared significantly higher than the instrument's noise floor with a form characteristic of sea-surface noise. Dramatic changes in surface activity, accompanying small changes in wind speed, are consistent with numerous references (reference 17) to ocean noise being instantly sensitive to the onset of winds. Wille and Geyer (reference 18) have previously noted that below wind speeds of about $2\frac{1}{2}$ m/s, ocean-ambient noise exhibits no systematic wind-speed dependence and this "threshold" level approximately coincides with the onset of microbreaking. Updegraff (reference 19) and Updegraff and Anderson (references 20 and 21) have also reported a similar increase in ambient noise, accompanying the commencement of microbreaking, at wind speeds around 2 m/s. As the wind speed continued to increase (the general spectral shape remaining unchanged), the recurrence of these intermittent, highly tonal events escalated, producing first a continuous babble and finally, with increasing whitecap coverage, a constant hiss.

The basic format for the sonobuoy experiments was to deploy them in pairs at identical depths about a kilometer apart. One sensor (referred to as the reference hydrophone) would monitor the true ambient noise throughout the experiment, while the second sensor (referred to as the test hydrophone) would monitor the effect of a monomolecular film spread above it. The extent to which surface-sound sources within the slick were attenuated could be ascertained through comparing simultaneous measurements from the two sonobuoys. Measurements were collected in deep water far from shipping and shore noise.

The chemicals tested were oleyl alcohol (trade name ADOL-85), oleic acid, and a double ethoxilated isosteryl alcohol (trade name AROSURF-MSF), having respective equilibrium spreading pressures (reference 22) of 31, 44, and 30 mN/m. These chemicals are nontoxic, essentially insoluble, biodegradable surfactants and bear little resemblance to crude oil, which is much less effective in damping capillary waves (reference 23). Each experiment used either 5 or 10 gallons of chemical dispensed from a small boat. The resulting slicks were estimated to be at least 36 m in diameter, four times the sensor depth. Previous modeling (reference 1) indicates that ratios of slick diameter to sensor depth greater than four are of little additional noise-quieting benefit. After creating a slick above the test hydrophone, the dispensing dinghy either returned directly to the support vessel or proceeded just outside the slick where, with its motor turned off, it monitored the position of the sonobuoy's antenna relative to the center of the slick. Hydrophone data were transmitted continuously to the support vessel located 1 to 2 kilometers away, its engines also secured.

Figure 2 is a map showing the location of the experiments described here and in the following section. Each symbol is associated with a particular measurement site and is repeated throughout the text when referring to the data collected at that corresponding location. Table 1 summarizes the environmental data collected during these experiments and is tabulated in the order in which it appears in the following text. Albeit far from complete, the table does contain significantly more ground-truth information than has been previously reported (reference 1) for experiments of this type. As is common to whitecapping measurements (references 24 and 25), surface-water temperature has been included when available. A change from 15 to 30°C will have a significant consequence on seawater's kinematic viscosity (a reduction of nearly 30%), which is known to affect bubble entrainment (references 26 and 27). Gross estimates of wave and swell heights were obtained, subsequent to the experiments, from the ship's logs.

Data processing was performed using a Spectral Dynamics SD 375 dual-channel digital spectrum analyzer. Simultaneous, 1 minute averaged spectra and spectral ratios were computed over a 0- to 20-kHz range. Due to the difficulty of even approximately duplicating sea state and film coverage over the test hydrophone, each at-sea test is to an unknown degree unique. Therefore, representative data illustrating

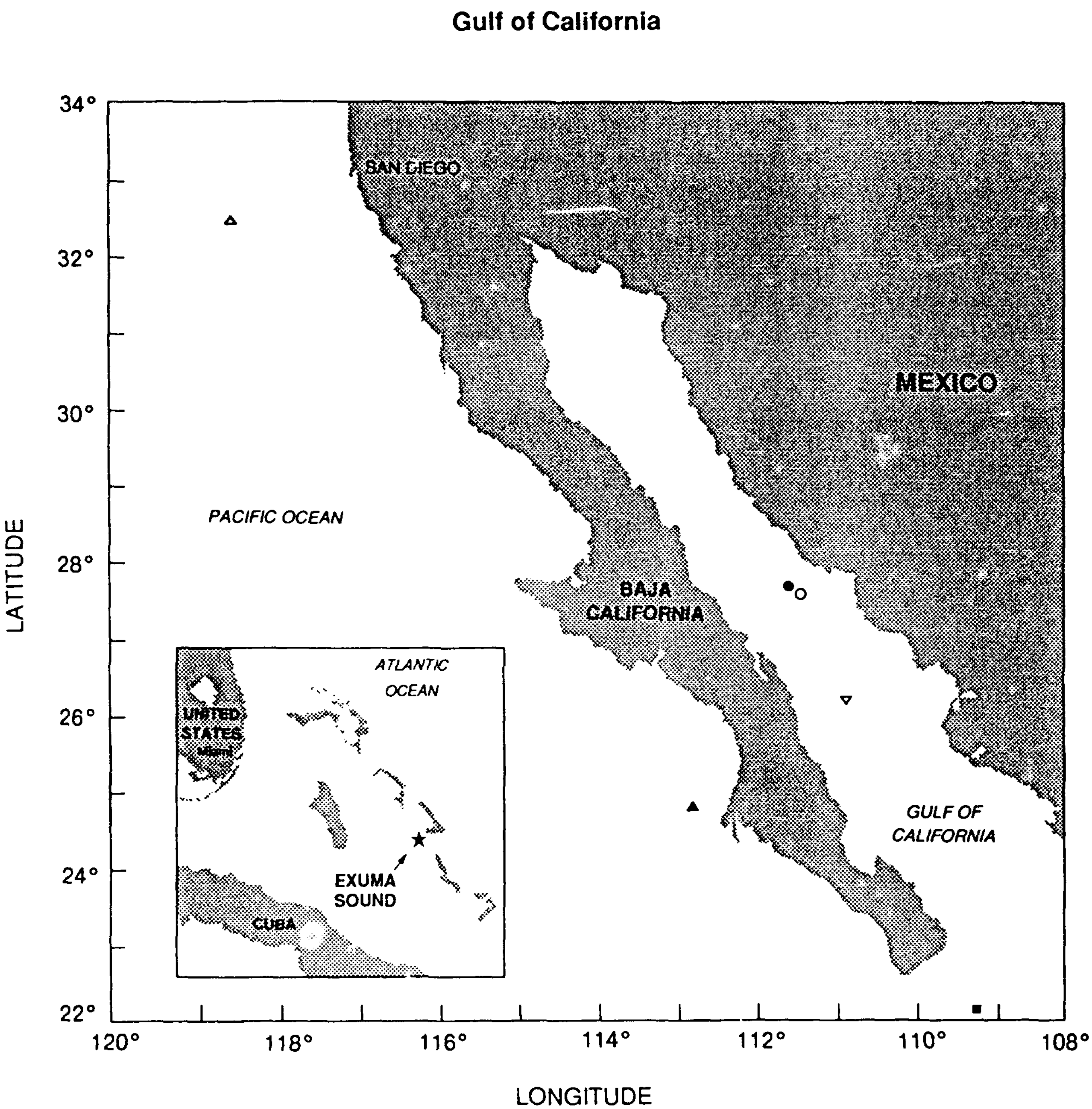


Figure 2. Locations of monomolecular film experiments.

Table 1. Summary of sonobuoy/array environmental data.

Film	Date	Longitude/ Latitude	Map Symbol	Depth (m)	Surface Water Temperature (C°)	Wind Speed (m/s)	Wave Height (m)/ Swell Height (m)
ADOL-85 (10 gallons)	2/23/89	110° 53' W 26° 22' N	▽	2,700	16°	7.0	0.3/0.9
ADOL-85 (10 gallons)	2/16/89	109° 20' W 22° 11' N	■	3,000	19°	7.0	0.3/0.9
ADOL-85 (5 gallons)	2/15/89	112° 51' W 24° 50' N	▲	3,700	17°	6.0	0.6/1.5
ADOL-85 (5 gallons)	7/4/88	118° 29' W 32° 29' N	△	1,500	—	4-6	0.3/1.2
Oleic Acid (10 gallons)	2/19/89	111° 25' W 27° 32' N	○	1,800	15°	3.5	rippled/0.6
Oleic Acid (10 gallons)	6/30/88	118° 29' W 32° 29' N	△	1,500	—	3.0	—/1.5
MSF (5 gallons)	7/1/88	118° 29' W 32° 29' N	△	1,500	—	4.0	—/.8
MSF (10 gallons)	2/20/89 (morning)	111° 38' W 27° 38' N	●	2,000	16°	3.0	rippled/0.6
MSF (10 gallons)	2/20/89 (noon)	111° 38' W 27° 38' N	●	2,000	16°	≤2.0	nil/0.6
MSF (10 gallons)	10/12/89	75° 44' W 23° 50' N	★	1,800	—	5.0	0.3-0.6/0.6-1.2
MSF (45 gallons)	10/12/89	75° 44' W 23° 50' N	★	1,800	—	7.5-8.5	0.3-0.9/0.9-1.5

the film's quieting effect are included from nearly all the at-sea experiments. It is hoped that a cursory look at figures 3 through 12 will provide a brief summary of the more salient features of these at-sea tests. Each figure is accompanied by a paragraph containing further information. The sonobuoy measurements reported in this section are first grouped by the material used to create the slick and then presented in order of decreasing wind speed.

2.2 MEASUREMENTS

2.2.1 Sonobuoy/Film Measurements with ADOL-85 (2/23/89)

Figure 3 shows the decrease in the spectral ratio of the reference to test hydrophone data, during which wind speeds averaged 7 m/s, after 10 gallons of ADOL-85 were spread over the test hydrophone (1030). Initial (1033) surface-noise quieting beneath the film begins around 1 kHz, increases monotonically with frequency to nearly 8 dB at 10 kHz, and then remains essentially unchanged to at least 20 kHz. Ten minutes later (1043) the spectral ratio has risen a nearly constant 2 to 3 dB toward its pre-slicked values, presumably as the slick either breaks up or drifts pass the test hydrophone. Although the spectral ratio format of figure 3a is how previous film data have been presented (reference 1), it is more informative to plot the spectra from each individual sensor, before and after slick deployment, separately. This is illustrated in figures 4a and b where it can now be observed that the behavior exhibited in figure 3 at 1033 is a consequence of the reference hydrophone having monitored an essentially constant increase (3 to 4 dB) in sea-surface sound (figure 4a), while the test hydrophone simultaneously measured a decrease beneath the slick (figure 4b). The decrease in sound level monitored (1033) by the slicked

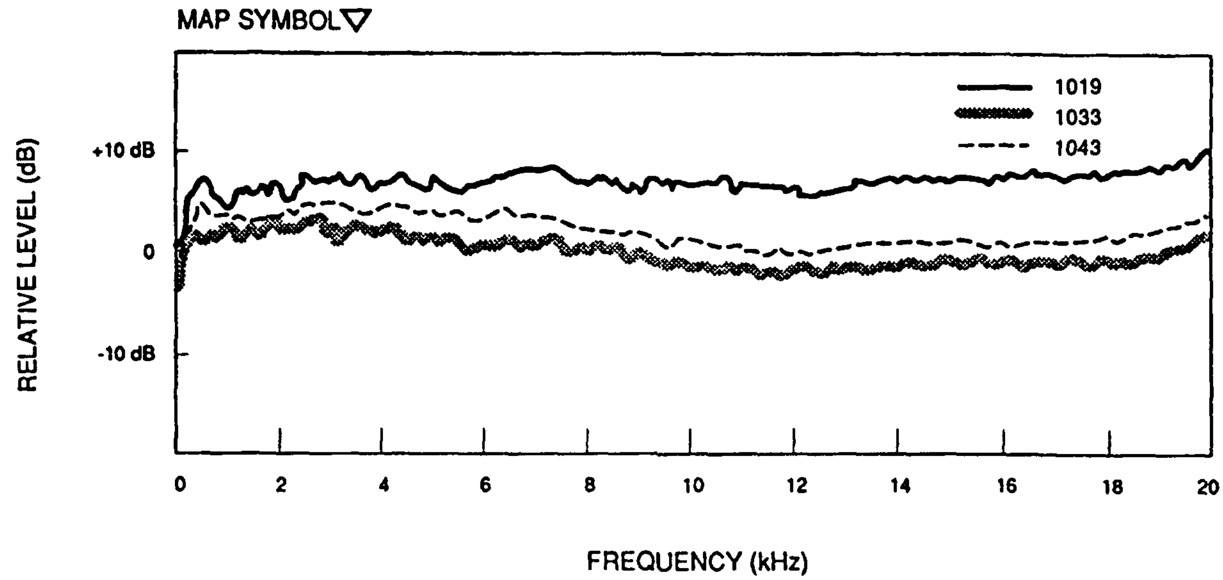


Figure 3. Spectral ratios of reference to test hydrophone data, before and after a slick (composed of 10 gallons of ADOL-85) was created over the test hydrophone. The film was dispensed at 1030 on 2/23/89, wind speed was about 7 m/s, and both sensors were 9 m beneath the sea surface.

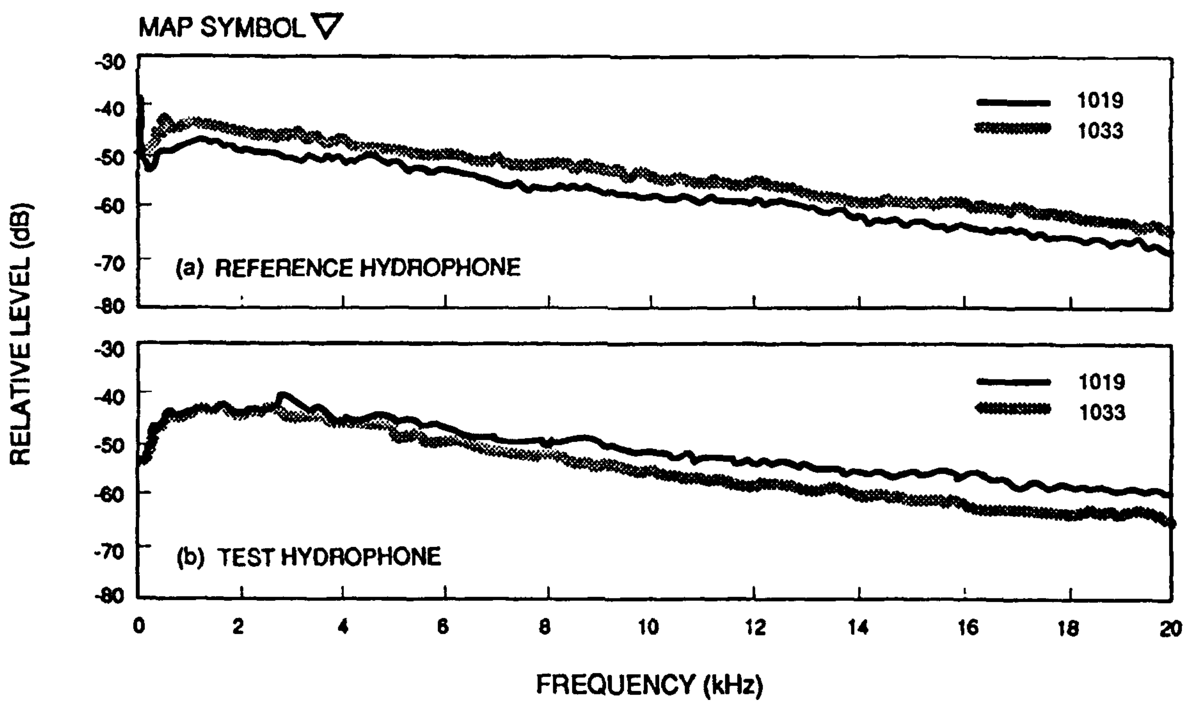


Figure 4. Simultaneous comparisons of spectral data from reference (a) and test (b) hydrophones, before and after a slick (composed of 10 gallons of ADOL-85) was created over the test hydrophone. The film was dispensed at 1030 on 2/23/89, wind speed was about 7 m/s, and both sensors were 9 m beneath the sea surface.

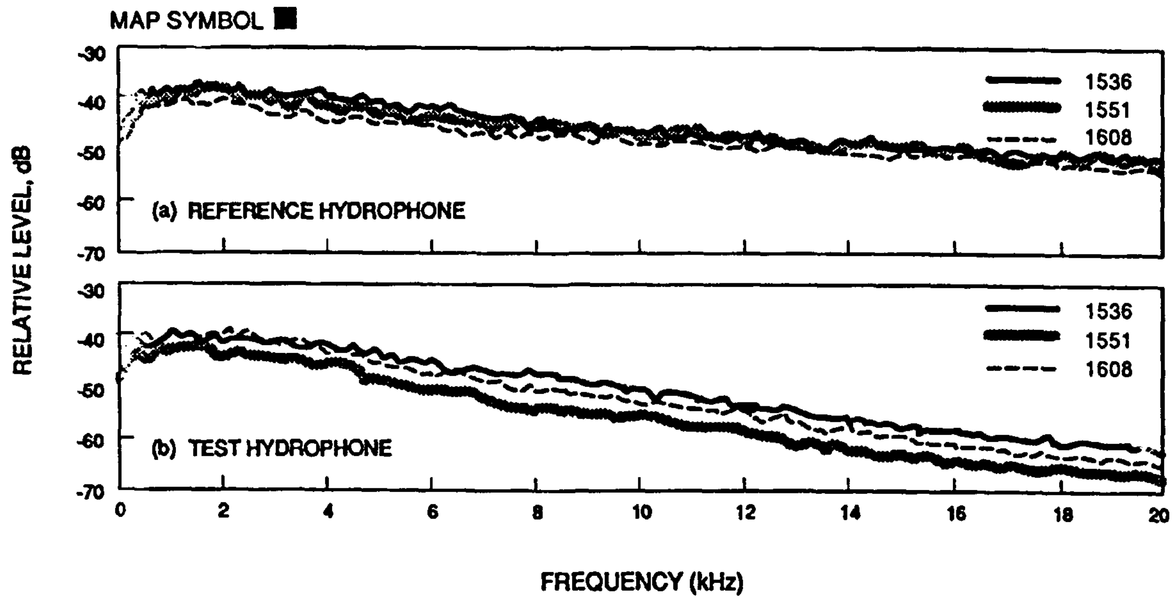


Figure 5. Simultaneous comparisons of spectral data from reference (a) and test (b) hydrophones, before and after a slick (composed of 10 gallons of ADOL-85) was created over the test hydrophone. The film was dispensed at 1545 on 2/16/89, wind speed was about 7 m/s, and both sensors were 9 m beneath the sea surface.

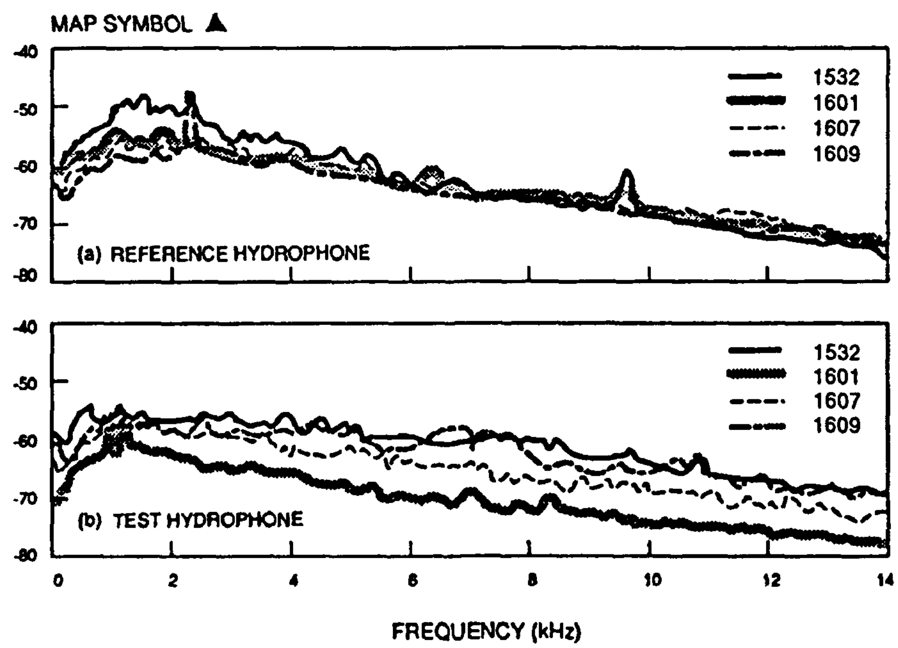


Figure 6. Simultaneous comparisons of spectral data from reference (a) and test (b) hydrophones, before and after a slick (composed of 5 gallons of ADOL-85) was created over the test hydrophone. The film was dispensed at 1555 on 2/15/89, wind speed was about 6 m/s, and both sensors were 9 m beneath the sea surface.

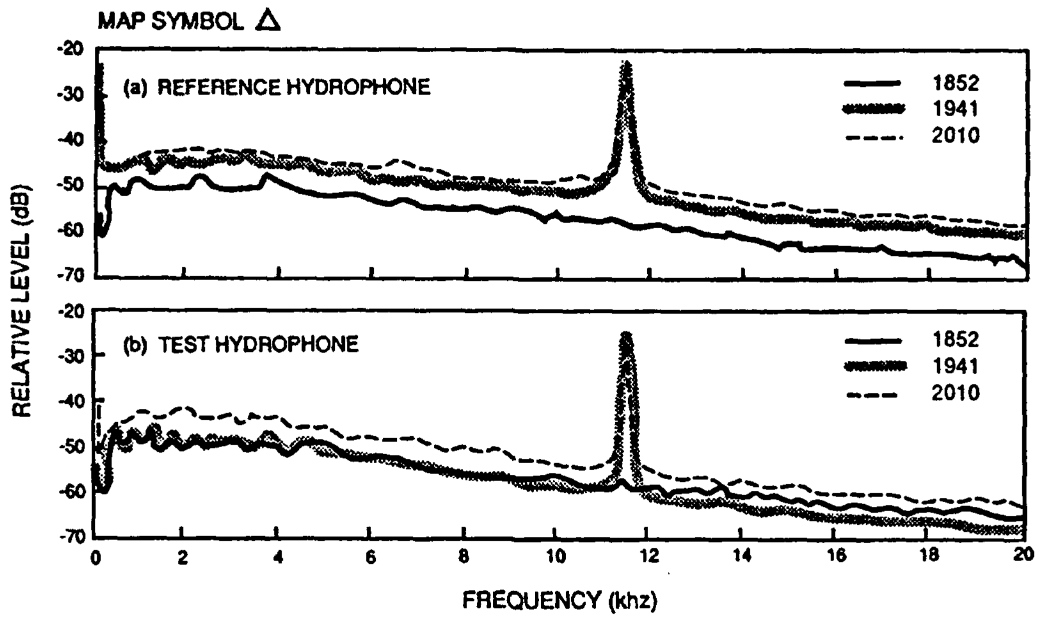


Figure 7. Simultaneous comparisons of spectral data from reference (a) and test (b) hydrophones, before and after a slick (composed of 5 gallons of ADOL-85) was created over the test hydrophone. The film was dispensed at 1900 on 7/4/88, wind speed increasing from 4 to 6 m/s, and both sensors were 9 m beneath the sea surface.

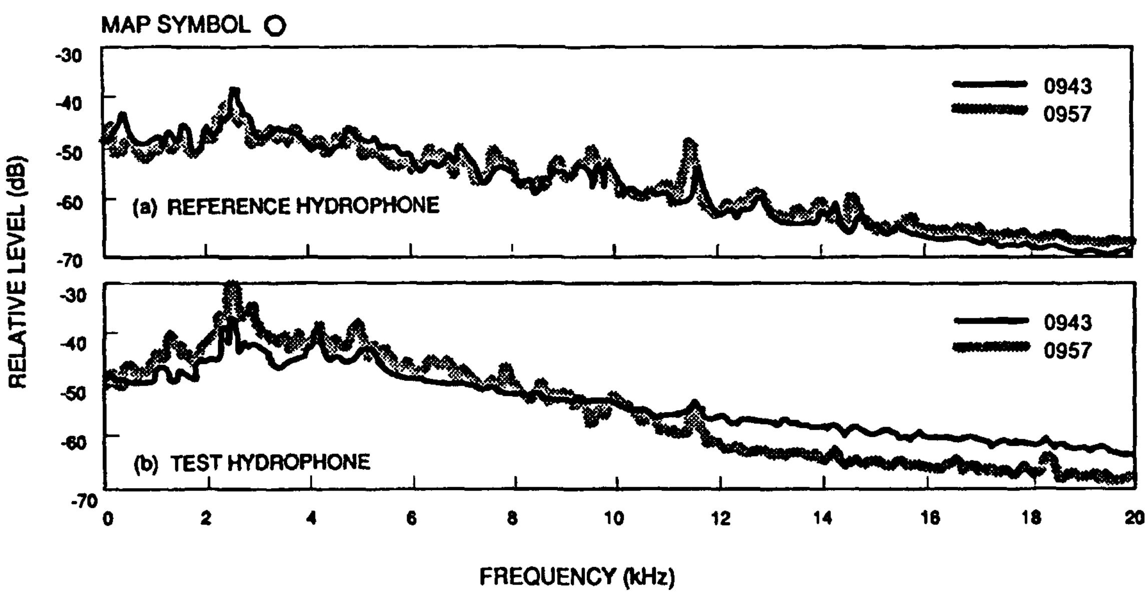


Figure 8. Simultaneous comparisons of spectral data from reference (a) and test (b) hydrophones, before and after a slick (composed of 10 gallons of oleic acid) was created over the test hydrophone. The film was dispensed at 0950 on 2/19/89, wind speed was about 3.5 m/s, and both sensors were 9 m beneath the sea surface.

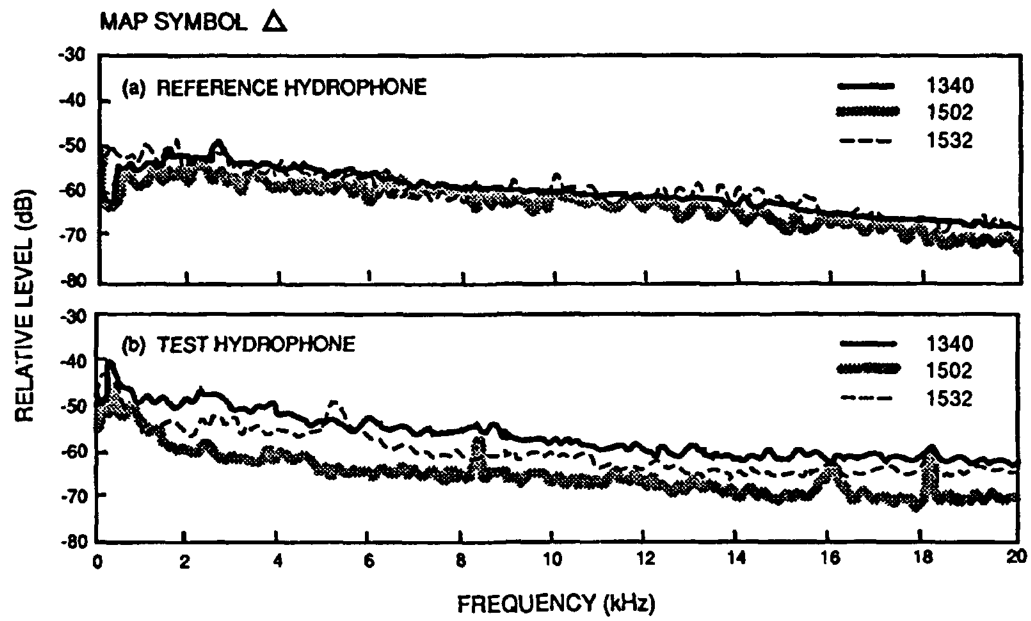


Figure 9. Simultaneous comparisons of spectral data from reference (a) and test (b) hydrophones, before and after a slick (composed of 10 gallons of oleic acid) was created over the test hydrophone. The film was dispensed at 1430 on 6/30/88, wind speed was about 3 m/s, and both sensors were 9 m beneath the sea surface.

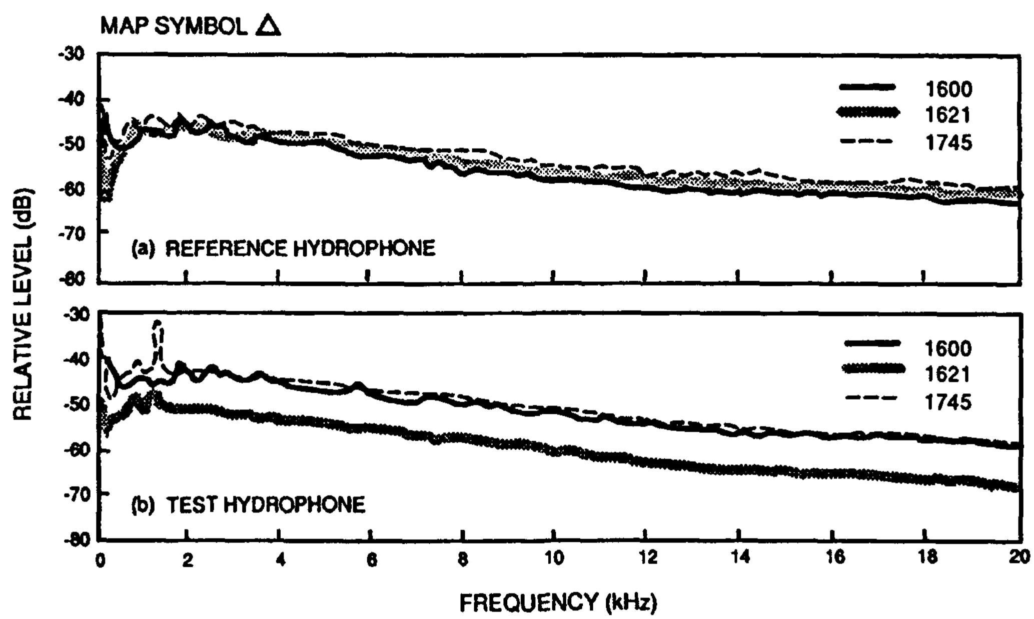


Figure 10. Simultaneous comparisons of spectral data from reference (a) and test (b) hydrophones, before and after a slick (composed of 5 gallons of MSF) was created over the test hydrophone. The film was dispensed at 1610 on 7/1/88, wind speed was about 4 m/s, and both sensors were 9 m beneath the sea surface.

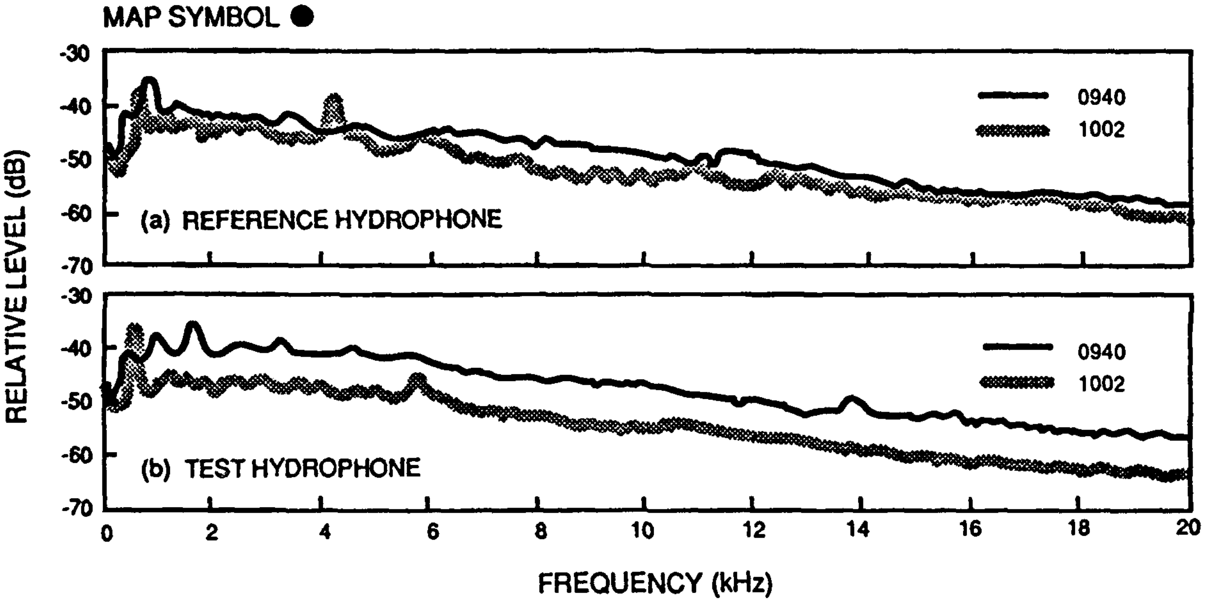


Figure 11. Simultaneous comparisons of spectral data from reference (a) and test (b) hydrophones, before and after a slick (composed of 10 gallons of oleic acid) was created over the test hydrophone. The film was dispensed at 0950 on 2/20/89, wind speed was about 3 m/s, and both sensors were 9 m beneath the sea surface.

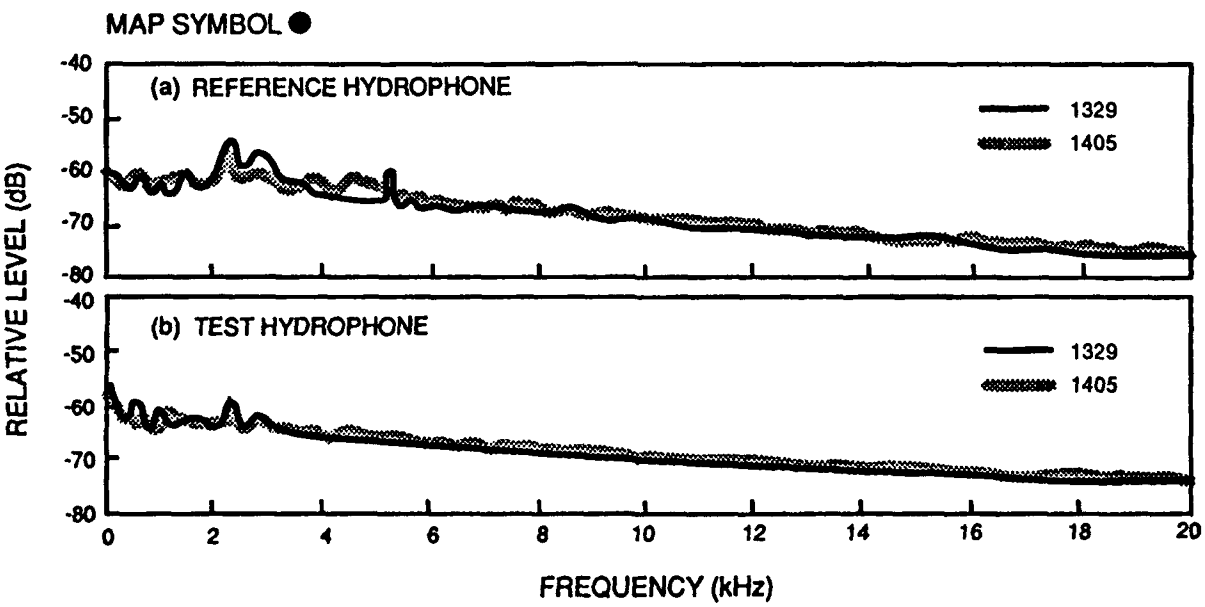


Figure 12. Simultaneous comparisons of spectral data from reference (a) and test (b) hydrophones, before and after the test hydrophone was put into the MSF slick (created at 0950 on 2/20/89). The test hydrophone was put into the slick at 1401, wind speed was about 2 m/s or less, and both sensors were 9 m beneath the sea surface.

sonobuoy (figure 4b) began around 2 kHz, increased with frequency to about a 4- to 5-dB reduction at 10 kHz, and remained constant thereafter. The wind speed measured at the support vessel inexplicably did not reflect the reference hydrophone's increasing sound levels.

2.2.2 Sonobuoy/Film Measurements with ADOL-85 (2/16/89)

Figures 5a and b show results from a similar at-sea test where 10 gallons of ADOL-85 were again used to create the slick, and wind speeds averaged about 7 m/s during the experiment. As before, the reference hydrophone measurements experienced some variability. However, sufficient data were collected to provide comparisons between the hydrophones only when the reference hydrophone levels remained nearly constant, as shown in figure 5a. As seen in figure 5b, the largest decrease in surface sound was observed at 1551, just after the experimental slick was formed (1545). Surface-sound quieting began around 1 kHz and grew with increasing frequency to about 6 dB at 6 kHz, where it continued to at least 20 kHz. By 1608, 23 minutes after the film was spread, the surface sound measured by the test hydrophone had returned halfway towards its pre-slicked values, having increased a nearly constant 3 dB from 1 to 20 kHz.

2.2.3 Sonobuoy/Film Measurements with ADOL-85 (2/15/89)

During the 2/15/89 experiment, which used only 5 gallons of ADOL-85, the test sonobuoy drifted outside the slick soon after the slick was created. Throughout this time, the wind-speed readings remained steady at 6 m/s and, except for a low-frequency transient occurring at 1532, the reference hydrophone spectral levels also remained essentially unchanged (see figure 6a). The simultaneously recorded test hydrophone data (figure 6b) exhibited quite different behavior—first (1601) showing a significant reduction in sea-surface sound just after the film was spread (1555), and then quickly returning to its pre-slicked levels (1609) as the test hydrophone drifted from beneath the slick. Surface-noise quieting began between 1 and 2 kHz and increased steadily to about 7 dB at 4 kHz, where it remained constant to at least 14 kHz (the limit of the recording instrumentation used for this test).

2.2.4 Sonobuoy/Film Measurements with ADOL-85 (7/4/88)

Five gallons of ADOL-85 also were used for this experiment where the wind speed was increasing throughout. Engine problems on the film-dispensing dinghy resulted in a delay between the pre- and post-slick measurements, during which the wind speed increased from 4 to 6 m/s. This increase in wind speed is reflected by the reference hydrophone's spectra (figure 7a), which exhibited a nearly constant 6-dB increase between 1852 and 1941. Comparing these same times for the test hydrophone (figure 7b), which was slicked at 1900, it was found that its spectral response remained approximately unchanged below 12 kHz and decreased about 2 dB at higher frequencies. Subsequent measurements taken at 2010 show that for frequencies greater than about 1 kHz, while the reference hydrophone level increased a nearly constant 2 dB, the test hydrophone level increased almost 6 dB. The spike in the post-slick data between 11 and 12 kHz was due to an on-board echo sounder. Both sonobuoys were at approximately equal distances from this underwater sound source. As anticipated, the magnitude of this tonal measured by the test hydrophone remained unchanged throughout pre- and post-slick measurements even as its signal-to-noise ratio dramatically increased.

2.2.5 Sonobuoy/Film Measurements with Oleic Acid (2/19/89)

Ten gallons of oleic acid were used while wind speeds averaged around 3.5 m/s. Both sonobuoys were deployed too close to the support vessel and, as shown in figures 8a and 8b, were consequently contaminated by ship noise at frequencies below 12 kHz. At higher frequencies the quieting effect of the film was apparent (figure 8b), uniformly reducing surface ambient noise by about 6 dB from 12 to 20 kHz.

2.2.6 Sonobuoy/Film Measurements with Oleic Acid (6/30/88)

Simultaneous measurements for the reference and test hydrophones were collected again before and after the film (10 gallons of oleic acid) was dispensed above the test sensor. Wind speed during the experiment was about 3 m/s. Throughout the test, the reference hydrophone's noise levels (figure 9a; 1340-1532) remained roughly constant. Meanwhile, immediately after dispensing the film at 1430, the test hydrophone first recorded a nearly constant 8-dB noise reduction starting around 1 kHz. By 1532, the test hydrophone's spectral level had risen 4 to 5 dB toward its pre-slicked values (see figure 9b). The bump in figure 9b's spectra around 5 kHz at 1532 is believed to be of a mechanical nature, generated by a nearby wind buoy. Curiously, when this experiment was repeated about a year later at nearly the same location under similar sea surface conditions, 20 gallons of oleic acid resulted in only a 2- to 3-db noise reduction. While the reason for this discrepancy is unknown, note that even without the added complicity of a slick, it is not especially unusual to find large differences in spectrum levels under similar sea-state conditions (references 18, 28, and 29), which may result from differences in the sound-speed profiles, surface-bubble layers, wind profiles, etc.

2.2.7 Sonobuoy/Film Measurements with MSF (7/1/88)

For this experiment, 5 gallons of MSF were used, during which the wind speed averaged 4 m/s. From 1600 to 1621 the reference hydrophone spectra remained essentially unchanged (see figure 10a). The test hydrophone during this same time conversely exhibited a near constant 8-dB decrease in spectral level, beginning between 1 and 2 kHz (figure 10b; 1621), after the slick was applied above it at 1610. By 1745, the test hydrophone's spectrum had almost returned to its pre-slicked (1600) value, while the reference hydrophone's spectrum had increased a few decibels. This suggests that a portion of the slick remained above the freely drifting test sensor while the ambient noise was increasing.

2.2.8 Sonobuoy/Film Measurements with MSF (2/20/89)

This was the first of two consecutive experiments, each using the same slick composed of 10 gallons of MSF but during different sea states. Figures 11a and 11b are measurements taken between 0940 and 1002 when wind speeds averaged 3 m/s. Immediately after dispensing the film (0950), a 5- to 6-db reduction was measured by the test hydrophone (figure 11a) for all frequencies above 1 kHz. The reference hydrophone data (figure 11b) averaged about a 1-dB decrease during this same time; consequently, the noise reduction due to the film is estimated to be between 4 and 5 dB.

The second experiment was conducted that same afternoon when the wind speed had dropped to 2 m/s or less and used the same film dispensed that morning (0950). Measurements were collected from a newly deployed sonobuoy, first (1329) positioned several kilometers from the mid-morning slick (which had now spread several times its original diameter) and then (1405) placed near the slick's center. As shown in figures 12a and 12b, the film had no measurable effect on the ambient noise beneath it. Similar experiments at these low sea states (<1) were repeated using oleic acid and ADOL-85 and, similarly, showed no noise-quieting effect. The general form and smoothness of the middle and high frequency data shown in both figures 12a and 12b reflect the electronic noise floor of the sonobuoy, as anticipated for these low noise levels. At frequencies below 4 kHz, however, where the signals from both hydrophones exhibited some intermittency, true ocean-ambient noise levels are believed to be reflected.

2.3 DISCUSSION OF SONOBUOY/FILM MEASUREMENTS

2.3.1 General Sea Conditions Prior to Film Deployment

For the experiments conducted when wind speeds were greater than 5 m/s and prior to slick application, scattered whitecaps were observed in general agreement with previous investigators (references 24, 25, and 30). For experiments executed while wind speeds were less than or equal to 4 m/s, no whitecapping was observed. When the wind speed decreased to about 2 m/s and lower, a conspicuous lack of microbreaking was noted, as has been by others (references 18 and 21). Throughout all the experiments, regardless of wind speed, capillary waves were always sufficiently present so that their absence within the film-covered area formed easily identifiable slicks.

2.3.2 Ocean-Surface Features Affected Within the Slicks

In previous high sea state (5 to 6) experiments where the films were dispensed from a helicopter, it was noted (reference 1) that less whitecapping seemed to have occurred within the slick. From the vantage point provided by sitting in a small boat at the edge of an experimental slick, and with wind speeds between 2 and 4 m/s, it also seemed there was less microbreaking occurring within them. Figures 13a and b are photographs of the ocean surface just before and after a film is applied. Figure 13c shows a close-up of a typical microbreak taken (as were figures 13a and b) from the film dispensing dinghy.

Although microbreaking has been previously recognized as being more widespread than whitecapping (reference 31), microbreaking had generally not been considered to entrain air (references 32 and 33). Simultaneous underwater video and acoustic recordings by Updegraff and Anderson (references 20 and 21) of individual microbreaking events (to be discussed further in section 5.0) have shown indisputably that bubbles are both entrained and "rung" during this process. Phillips (reference 31) had previously proposed that micro-scale breaking would be significantly reduced within a slick. Presumably, the smoothing of the small-scale, capillary-wave-type roughness, apparent in figure 13b, results in less micro-scale breaking by decreasing the wind stress at the sea surface, a quantity which has been previously proposed (reference 18) to be directly related to surface noise production.

Figure 14 is a photograph of the experimental slick's edge illustrating the presence of microbreaking (within circles) just outside the filmed area. This photograph is unusual in the sense that several microbreaking events appear. Ordinarily, the occurrence of these ephemeral events at the low sea states of interest here were spatially much more disperse. It is possible that in figure 14 the downwash from the helicopter was responsible for the increased density of microbreaking observed.

2.3.3 Ambient-Noise Reductions Beneath the Slick

Most of the previously presented at-sea measurements collected beneath monomolecular films show that a film can significantly undermine some source(s) of natural sea-surface sound. However, due to the temporal variability of ocean ambient noise, particularly when monitoring low sea states at shallow depths for periods of short duration, one must be cautioned that no single experiment can establish this quieting effect as being inherent to the presence of the films. For example, there was one experiment (not presented) where the variability of the test hydrophone's pre-slick spectra precluded comparison with its reduced post-slick spectra and, as previously noted, the magnitude of the film's noise reductions greatly varied between experiments. All the experimental data taken together, however, indicate that significant sea-surface ambient noise quieting, at wind speeds greater than 2 m/s, does occur beneath the films.

For windspeeds less than about 2 m/s, the ambient-noise spectra between 1 and 4 kHz (higher frequencies appeared to reflect the noise floor of the instrument) showed no quieting effect by any of the films. Yet at slightly higher wind speeds these same films (unless limited by ship noise) have repeatedly displayed a pronounced quieting effect starting between 1 and 2 kHz. Consequently, it is believed that the sea-surface noise sources, which the films inhibit, are absent at wind speeds below about 2 m/s. This issue will be addressed again in section 5.0 where measurements from the Synoptic Surface Noise Instrument support the same conclusion.

(a)

(b)

(c)

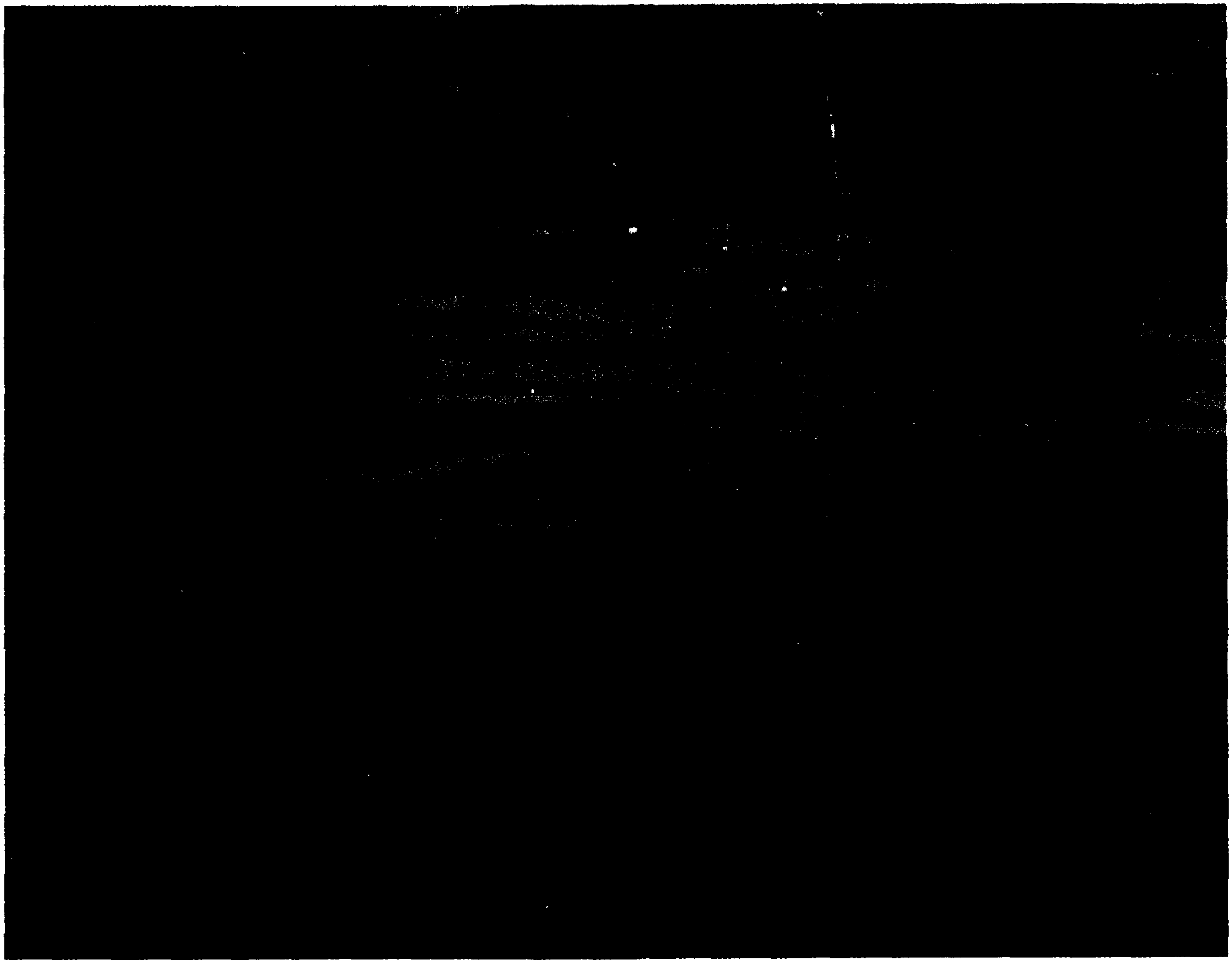


Figure 13. Photographs taken from film dispensing dinghy of ocean surface before (a) and after (b) a film was applied. Typical microbreak is shown in (c), spilling region measures about a foot across.

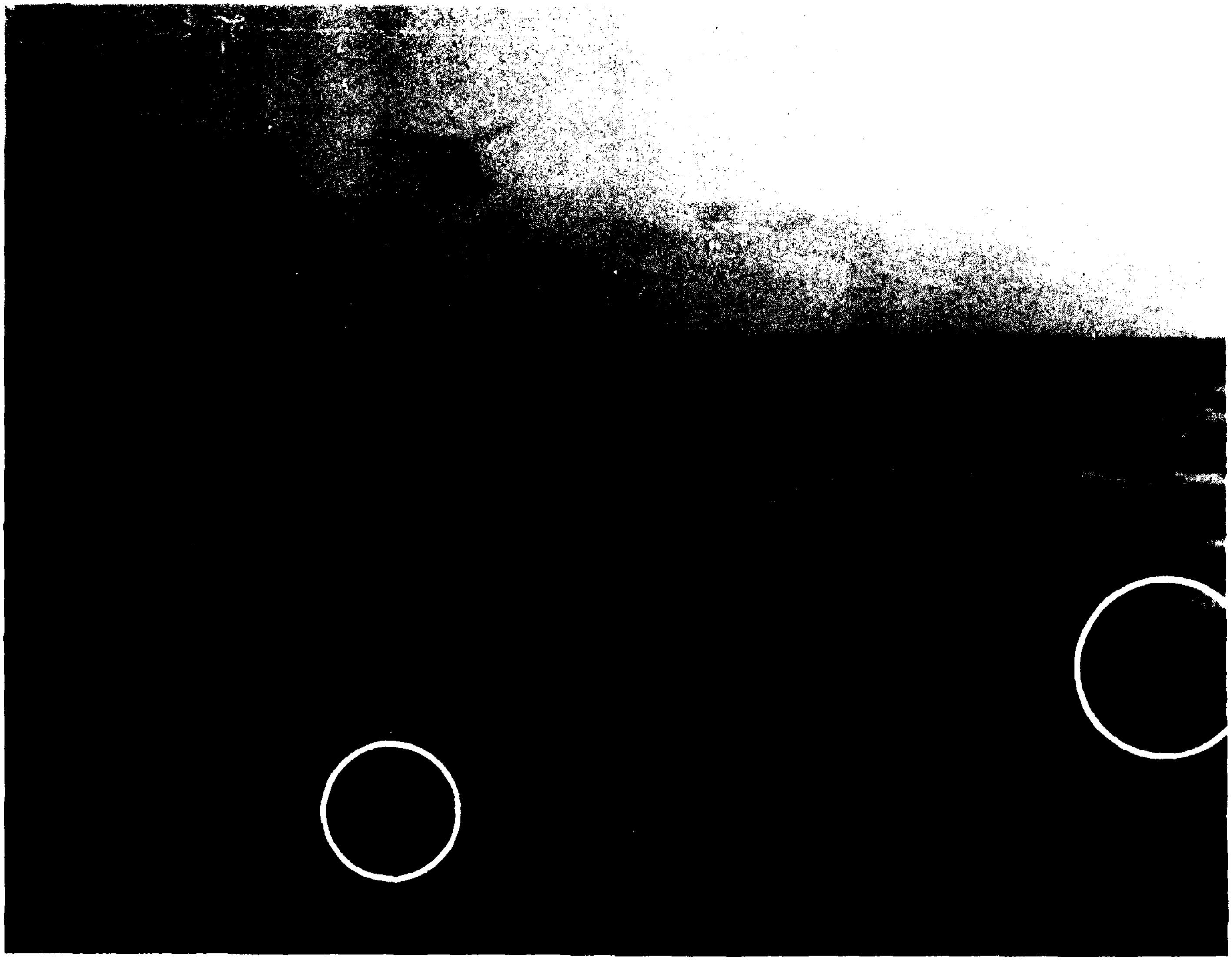


Figure 14. Photograph of microbreaking (circled) occurring outside slick.

To a first approximation, the reduction in ocean-ambient sound at wind speeds from about 2 to 4 m/s is nearly constant. In reference to the Knudsen-Sea State Curves (reference 34), this behavior is equivalent to a general decrease in sea state beneath the films. The films have produced noise reductions of 8 dB on several occasions; a difference in 10 dB in ambient noise level corresponds approximately to a tripling of the wind speed, or a change from sea state 2 to sea state 5 (reference 28). At higher wind speeds (greater than 5 m/s), sporadic whitecaps were observed, and the corresponding ambient noise reduction was generally more frequency dependent, performing poorer at the lower frequencies. Wilson (reference 9) has estimated that with the appearance of whitecaps the noise associated with the impact of spray would become significant between 50 and 1000 Hz. Whether this mechanism contributes significantly to noise levels at frequencies greater than 1 kHz is not known (though it has been argued to be unlikely (reference 35)). In any event, the film's impact on spray noise is, in the ocean scenario, not believed to be substantial for reasons discussed in section 4.0.

The conspicuous lack of greater noise reductions when twice the quantity of film material is applied (e.g., figures 5 and 6; figures 10 and 11) should also be noted. This behavior is not, however, inconsistent with both previous modeling (reference 1) and measurements (in reference 1, sonobuoys set at 18 and 122 m beneath the same slick recorded comparable noise reductions). There also does not seem to be any trend indicating that the different films behave much differently under similar ocean conditions, but as with all aspects of film quieting, further tests are desirable.

3.0 AT-SEA TESTS WITH DTRC'S MONOB AND MONOMOLECULAR FILMS

3.1 SONOBUOY/FILM MEASUREMENTS WITH MSF (10/12/89)

The following sonobuoy/film experiments were performed, for the sake of comparison, just prior to the principal experiment (to be discussed in section 3.2), which used an underwater array. The data were collected in Exuma Sound, a site just southwest of Eleuthera Island, the Bahamas. This relatively deep (1500 m) basin is almost totally isolated, acoustically, from the Atlantic Ocean. The slick was composed of 10 gallons of MSF material, and the wind speed during the experiment was about 5 m/s. For the first experiment, reference and test sonobuoys were set at depths of 18 m. The spectral levels of the reference hydrophone were observed (figure 15a), between 1119 and 1218, to slightly increase (about 1 dB) from 2 to 10 kHz and remain nearly the same at higher frequencies. The corresponding spectral levels of the test hydrophone (figure 15b), after the slick was formed at 1139, remained nearly the same for frequencies less than 8 kHz and decreased about 2 to 3 dB at higher frequencies.

The second experiment used the same slick and two hydrophone buoys set at 122 m. Wind speed anemometer readings still averaged about 5 m/s. The reference hydrophones's spectral levels, as shown in figure 16a, decreased slightly (1 to 2 dB) from 1235 to 1306. Having lost the opportunity to take pre-slick test hydrophone data, the test hydrophone measurements were instead first taken at the center of the slick (1235) and then outside it (1306). Immediately after the test hydrophone was removed from the influence of the slick, its spectra increased (see figure 16b). This change was again small, beginning between 2 and 4 kHz and increasing to about 2 dB.

3.2 ARRAY/FILM MEASUREMENTS WITH ADOL-85 (10/12/89) AND MSF (10/13/89)

Whatever the ambient-noise reduction, the previous data (figures 3 to 12, 15, and 16) show no sign of diminishing with increasing frequency, at least to 20 kHz, the limit of the sonobuoys. The principal

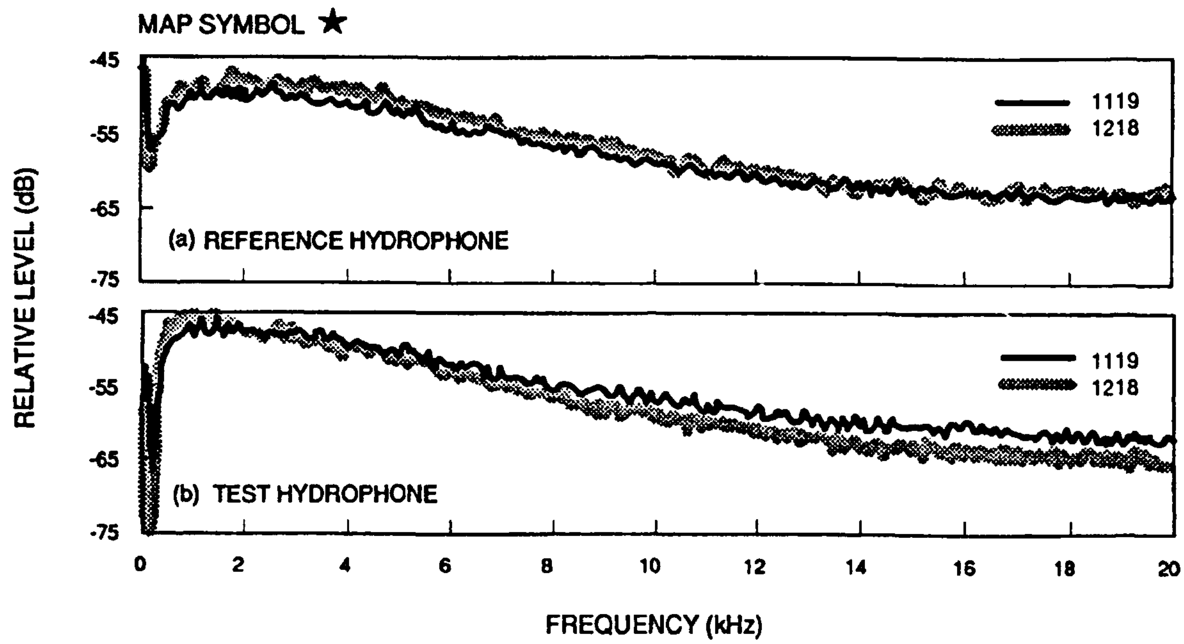


Figure 15. Simultaneous comparisons of spectral data from reference (a) and test (b) hydrophones, before and after a slick (composed of 10 gallons of MSF) was created over the test hydrophone. The film was dispensed at 1139 on 10/12/89, wind speed was about 5 m/s, and both sensors were 18 m beneath the sea surface.

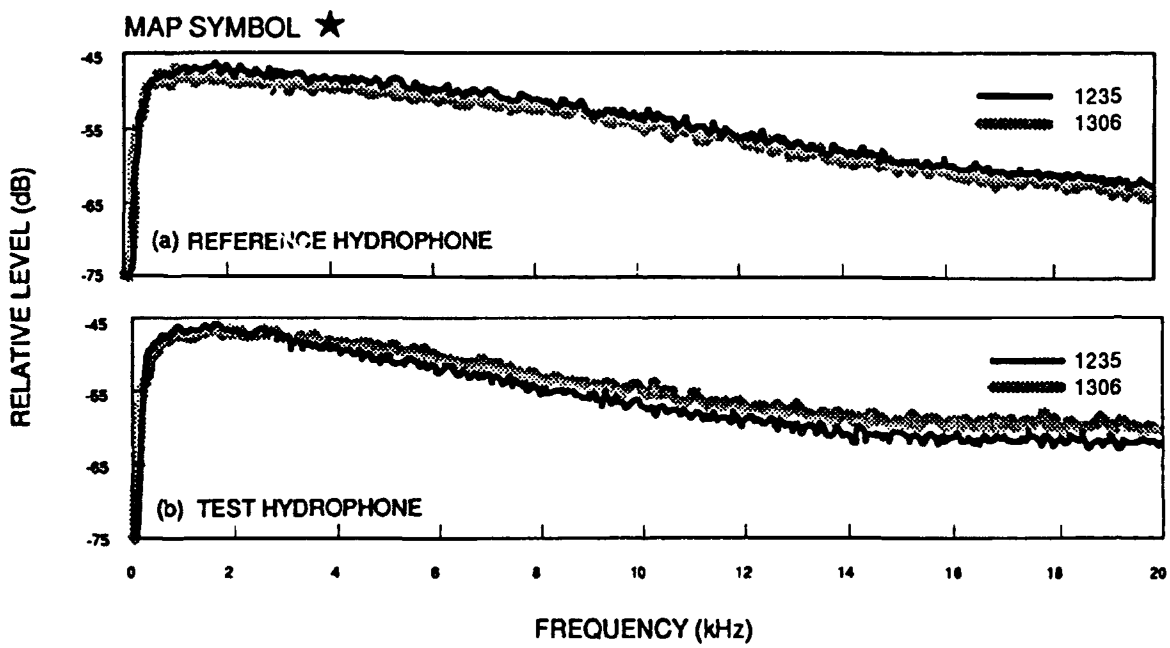


Figure 16. Simultaneous comparisons of spectral data from reference (a) and test (b) hydrophones. The test hydrophone *was taken out* of the slick (composed of 10 gallons of MSF) at 1240 on 10/12/89. The film was dispensed at 1139 on 10/12/89, wind speed was about 5 m/s, and both sensors were 122 m beneath the sea surface.

purpose of the experiments to be discussed here is to test whether the film's quieting effect continues at higher frequencies. For this purpose, the 30.5-, 61.0-, 152.5-, and 183.0-m hydrophones from the MONOB's vertical array were used individually, as they are sensitive to 70 kHz and are conveniently located (Exuma Sound) where there is minimal contamination from shipping noise.

As there was only one array, it was not possible to record simultaneously measurements from similar sensors within and outside the film's influence. Instead, data from individual hydrophones were recorded before, during, and after slicks composed of MSF and ADOL-85 passed over them. The depth of the array sensors necessitated the creation of a large slick. Mooring lines and array cables extending from the MONOB to the array's surface buoy were too shallow to permit a direct spiral application of the films above the sensors. It was, therefore, necessary to create a large slick upwind of the array. This was accomplished using two vessels, one spread the chemicals in a raster pattern, the other filled in holes appearing in the slick as necessary. Film coverage was greatly enhanced by pumping the chemicals through a nozzle, which dispersed them into a fine mist.

The first slick created was composed of 45 gallons of ADOL-85 and roughly estimated to be at least 200 by 400 m. Although the center of the slick did not pass directly over the array, nevertheless ample coverage for at least the most shallow (30.5 m) hydrophone appeared to be provided. Throughout this experiment, wind speed was steadily increasing from about 7.5 to 8.5 m/s. The film was dispensed between 1554 and 1701. Best slick coverage over the array sensors was noted at 1701; by 1726 the slick was observed to have entirely passed by the array's surface buoy. The spectral levels of the 30.5- and 61.0-m depth hydrophones, as shown in figures 17a and b, exhibited their lowest values around 1701. By 1721 (not shown) spectral levels had returned to their pre-slicked values.

Where sound reduction was evident, it generally continued throughout the frequency range monitored. However, the amount of noise reduction was, as in the accompanying sonobuoy tests, disappointedly small. Where the noise reduction was greatest (comparing spectral levels at 1554 and 1701), quieting was observed by the shallower sensor (figure 17a) to increase with increasing frequency to about 4 dB at 20 kHz, remain nearly constant from 20 to 70 kHz, and decrease (with increasing frequency) thereafter. The resonant frequency of the hydrophones are around 55 kHz; at higher frequencies their sensitivity decreases. Between 20 and 40 kHz the ambient noise spectra during the 3 days of experiments were for unknown reasons higher than expected. Otherwise, for lower frequencies and comparable wind speeds, the sound pressure spectral levels show good agreement with the composite spectra collected over previous years in this same region.

Ambient noise reductions monitored by the 61.0-m depth hydrophone, as can be seen in figure 17b, are similar but slightly diminished. Negligible effect was recorded by the hydrophones at 152.5- and 183-m depths. The following day, this experiment was repeated using 40 gallons of of MSF, while the wind speed was decreasing from 8.5 to 8 m/s. Maximum ambient-noise quieting observed by the most shallow sensor (31.5 m beneath the slick) was only 2 to 3 dB. No effect was recorded by any of the deeper sensors.

Sonobuoy measurements were collected at distances from the support vessel, both comparable and much larger than the separation between MONOB and the array, to test whether the experiments were adversely affected by noise from MONOB. No difference was found. A sonobuoy had been tethered near the array's surface buoy during the test employing the 40 gallons of MSF. The simultaneous temporal evolution of the sonobuoy and array data, as the slick passed over them, showed reasonable agreement. It is conjectured that the relatively poor performance by the films when tested in Exuma Sound may be related to the nature of the wave-breaking occurring therein. Wave-breaking may result from a host of phenomena such as the interaction of waves and currents (reference 35), direct forcing of wind (reference 30), intrinsic instabilities of the wavefield (reference 36), and from the constructive interference of a number of the wavefield's Fourier components (reference 37). Surface films are not expected to have an appreciable effect on the breaking behavior of waves, except when these waves are under the influence of the wind (reference 38). The observations of Toba and Kunishi (reference 39) indicate that waves breaking as a result of interactions with other waves, an occurrence much more likely in the Bahama basin than in the other film experiment locations, are unaffected by films.

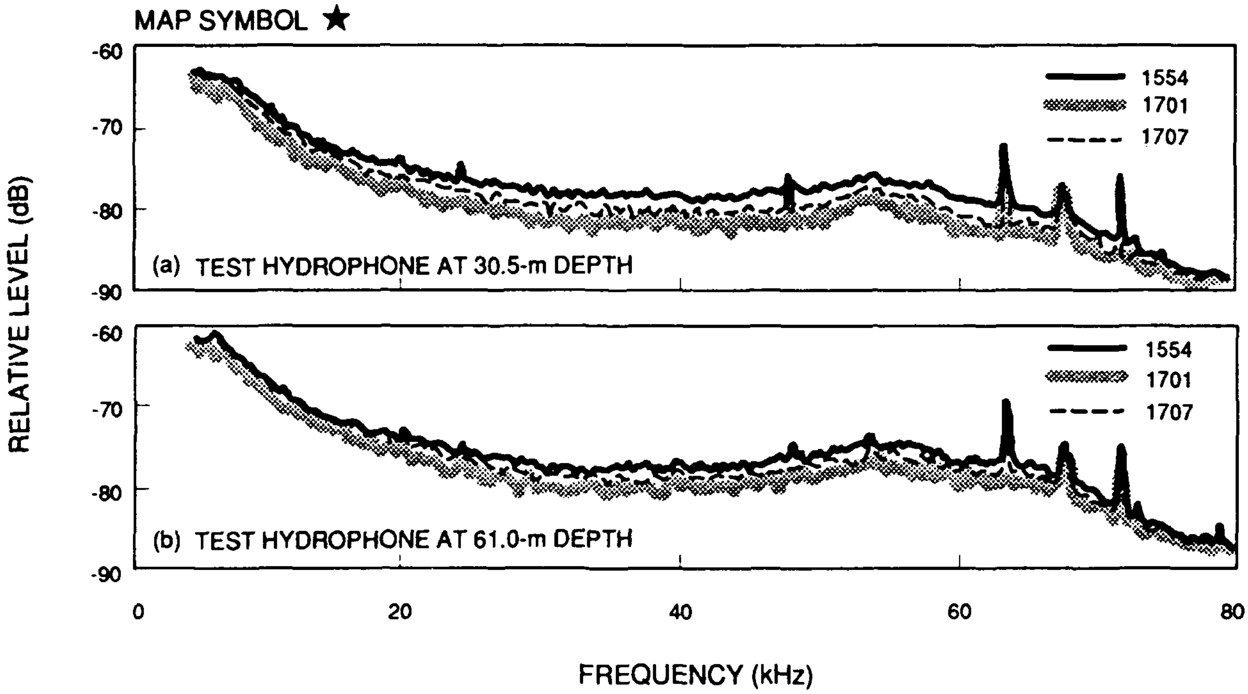


Figure 17. Simultaneous comparisons of spectral data from test hydrophones at 30.5-m (a) and 61.0-m (b) depth, from the vertical array of DTRC's MONOB, before and after a slick (composed of 45 gallons of ADOL-85) was created over them. The film was dispensed between 1554 and 1701 on 10/12/88. Wind speed was increasing from 7.5 to 8.5 m/s, and both sensors were 9 m beneath the sea surface.

4.0 LABORATORY EXPERIMENTS

4.1 SPLASHING DROPS

4.1.1 Background

Spray from breaking waves has been considered (references 10, 11, 35, 41, 42, and 43) as a possible source of underwater ambient noise in the ocean. High-speed video recordings and a series of flash photographs have shown (reference 44) that the same monomolecular films used at sea had no discernible effect on the spray resulting from splashing drops. However, the subsequent work of Pumphrey and Crum (reference 43), and Pumphrey, Crum, and Bjorno (reference 45) suggest that the effect of these films on splashing drops may be much more pronounced beneath the liquid surface. They have demonstrated that the regular bubble entrainment, associated under certain conditions with the drop impact process, can be significantly reduced by adding a soluble surfactant (Kodak Photoflow).

Pumphrey and Crum (reference 46) have experimentally determined, for a range of drop diameters, the corresponding range of drop heights where regular entrainment will occur. For these experiments, drops of water fell vertically upon a flat surface of the same liquid. The two solid curves in figure 18 outline the region where regular bubble entrainment was observed to occur by Pumphrey and Crum (reference 46). For a given drop size, the dashed line corresponds to the lowest height from which terminal velocity is reached at impact. (Pumphrey's results were originally presented (references 45 to 47) in terms of drop impact velocity versus drop diameter. The impact velocity of the drop was calculated directly from the dynamic equations governing the fall of the drop and an empirically derived formula (reference 46) relating drop size and terminal velocity.) The symbols in figure 18 mark the heights (12.5 to 22.5 cm.) where regular bubble entrainment was observed in the present experiment when 2.76-mm diameter drops of reagent grade water had fallen into a reservoir of similarly purified water. The agreement between the present results with those of Pumphrey and Crum (reference 45), as evident in figure 18, is excellent. No significant difference in bubble entrainment was found when sea water was substituted for reagent grade water.

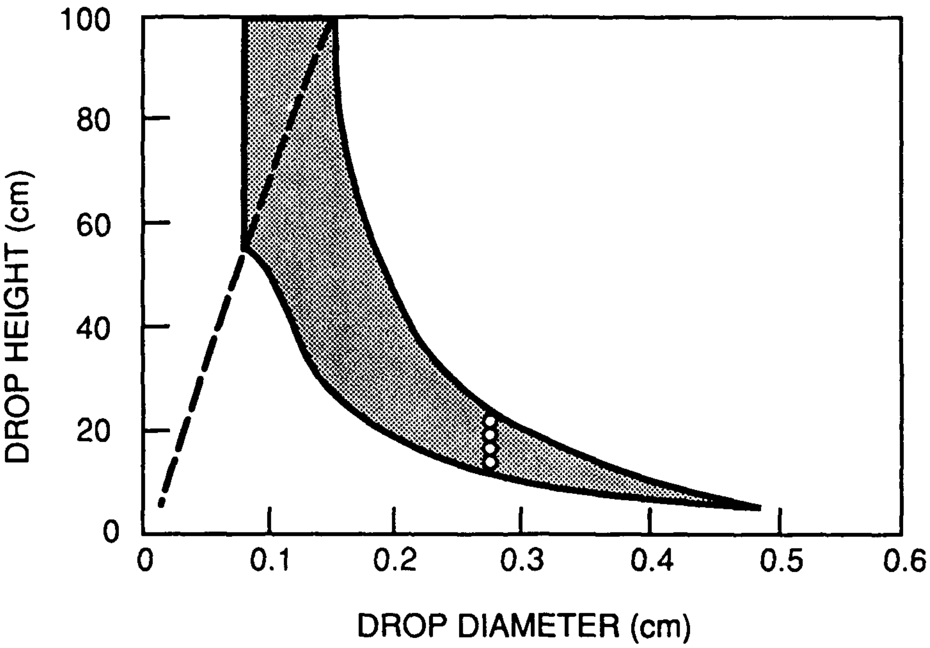


Figure 18. Stippled area shows the heights from which drops of different diameters, falling vertically, will regularly entrain bubbles as reported by Pumphrey, Crum, and Bjorno (1989). The dashed line marks the minimum height as a function of drop diameter, which results in the terminal velocity upon impact. The symbols show the present data, the heights from which 2.76-mm drops were observed to regularly entrain bubbles. Both drops and reservoir are composed of reagent grade water.

4.1.2 Seawater/Film Measurements of Splashing Drops

An entrained bubble can be identified both visually and by the sound it creates. Figure 19a shows a typical pressure-time trace produced by the impact of a 2.76-mm drop of seawater falling from a height of 21.5 cm into a reservoir of seawater. The signatures of the impact and bubble sound (exponentially decaying sinusoid) are seen at 10 and 30 milliseconds respectively. Figure 19b illustrates the outcome when the experiment is repeated after a drop of ADOL-85 is added to the surface of the seawater reservoir. While there was no effect by the film on the bubble's impact signature, the bubble entrainment process was completely suppressed. A similar result was observed (see figure 19c) when MSF was substituted for ADOL-85. Subsequent studies with the MSF film showed that the range of heights for regular bubble entrainment, by a 2.76-mm drop, was greatly reduced (from heights of 12.5 to 22.5 cm to 17.25 to 17.75 cm).

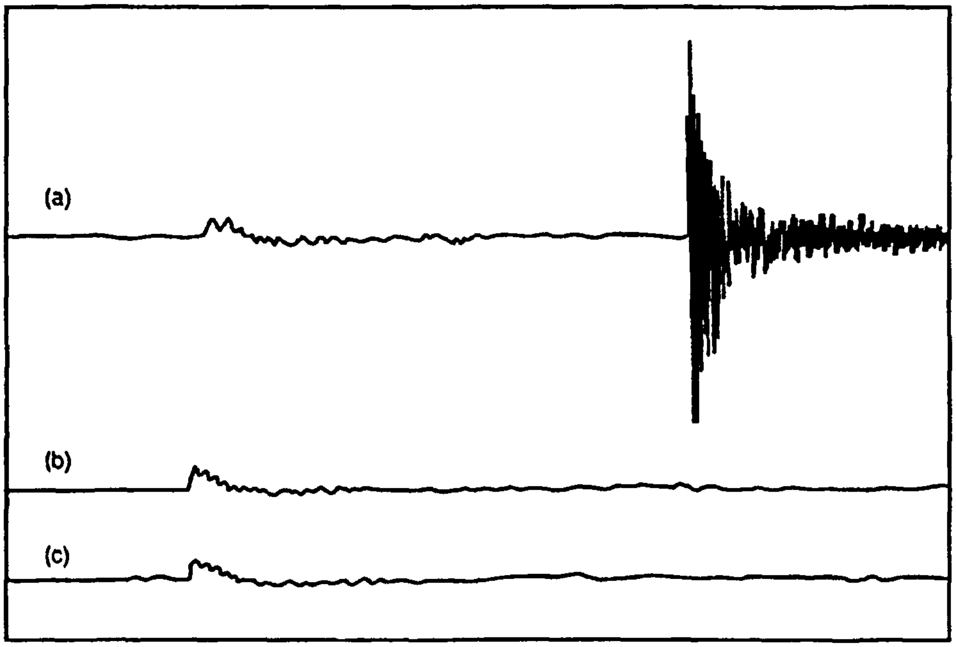


Figure 19. Typical pressure-time traces produced by the impact of a 2.76-mm drop of seawater, falling vertically from a height of 21.5 cm, into a reservoir of seawater (a), seawater with ADOL-85 spread on its surface (b), and seawater with MSF on its surface (c).

The importance of this particular phenomenon toward achieving the sea-surface sound quieting observed beneath monomolecular films is not known, as the size and impact velocity of ocean spray as a function of wind speed is not well determined (reference 10). However, there are several reasons to believe that the film's suppression of the bubbles, created by vertically falling drops, is of minimal importance in the ocean scenario. First, as seen in figures 8 through 11, the film clearly works for wind speeds between 2 to 4 m/s where there is little or no spray present. The incipient wind velocity (measured near the water surface) for droplet production, in both laboratory (reference 48) and field (reference 49) studies, has been found to be around 8.0 m/s. Furthermore, spray droplet diameters are generally thought to peak around 0.015 cm (reference 49) and rapidly drop off after 0.020 cm (reference 48). These drop diameters are probably too small (see figure 18) to regularly entrain bubbles. Moreover, theoretical studies (references 50 and 51) indicate that the mechanism responsible for regular bubble entrainment is critically dependent on the surface geometry at the moment of impact. The film's dramatic suppression of bubble entrainment and its accompanying sound, illustrated in figure 19b and c, was for drops falling at normal incidence, an unlikely occurrence at the ocean surface. Even for a flat sea, a surface wind speed of only 1.3 m/s results in a 20° inclination from normal for a terminally falling 1-mm drop (reference 52). Medwin, Kurgan, and Nystuen (reference 52) found that as the angle of incidence increased, the probability of bubble formation decreased rapidly. Drops of 0.083-, 0.091-, and 0.098-cm diameter, falling at terminal velocity, were studied. The percentage of these drops, which entrained bubbles nearly 100% of the time at normal incidence (in agreement with figure 18), decreased to about 10% at 20° from normal.

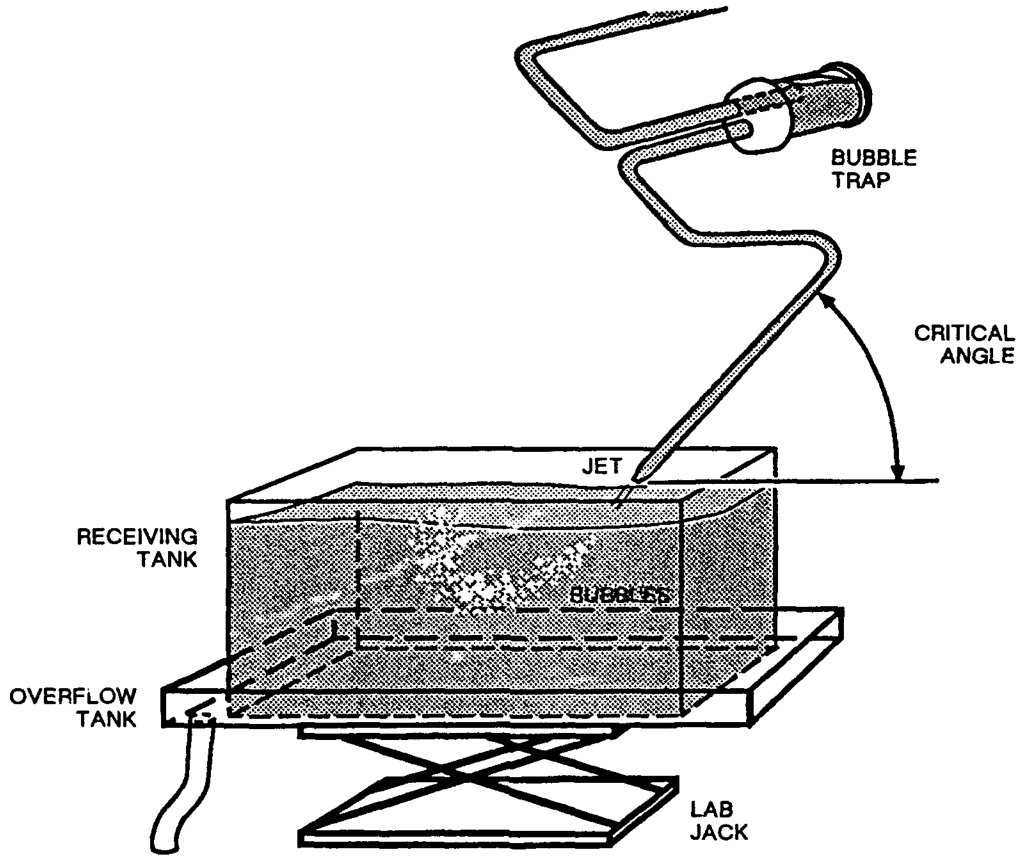


Figure 20. Diagram illustrating experimental arrangement for gas bubble entrainment study by plunging liquid jets.

Nystruen (reference 53), applying this information to rain noise, was able to successfully predict its spectral character in the presence of wind. For winds exceeding 3 m/s, Nystruen concluded that most of the sound generated by light rain is due to the impact of raindrops on the water surface rather than to the creation of bubbles. If a similar situation holds for ocean spray, the films would be ineffectual as spray noise would be due principally to the sound associated with drop impact, which the films have found to have no influence (as seen in figures 19a–c).

4.2 PLUNGING LIQUID JETS

4.2.1 Background

The object of these experiments was to begin to study the influence of films on waves that do break within the slick. Wind-wave tank studies (references 54 and 55) have indicated that the primary mechanism of bubble formation in "breaking" short wind waves is intermittent bubble entrainment, by an ordered downward flow, at the leading slope near the crest. Plunging liquid jets subsequently have been used (references 27 and 54) to model some aspects of bubble production at the ocean surface. Note that there already exists a large body of work addressing the phenomenon of air entrainment by liquid jets (see reference 27), which have determined a host of entrainment mechanisms dependent on jet turbulence, velocity, breakup, and length. The purpose here is to determine the impact of the films on jet experiments, which were most relevant to the ocean scenario (e.g., Detsch and Sharma (reference 27) and Koga (reference 55)). In these experiments, the likeliness of bubble production by the jet impinging the reservoir's surface was characterized either by a critical velocity (impinging angle, θ, remains fixed) where air entrainment begins or by a critical angle, θ_c, which is the maximum angle (velocity kept constant) measured from the horizontal for which bubbles are still entrained. At angles larger (or velocities lower) than critical no air entrainment occurs, while smaller angles (or larger velocities) increase air entrainment.

While a detailed description of the apparatus and experimental procedure can be found in reference 27, a brief summary follows. A nozzle, which delivered a constant flow of water from a pressurized tank (providing nonpulsing flow), was oriented so its tip was 1 cm above the surface of the liquid in an 11-liter receiving tank (see figure 20). To reduce jet instability, a bubble trap was placed between the pressurized tank and the nozzle. The receiving tank was constantly overflowing to assure a clean surface. The nozzle, which could be rotated about its tip, was fabricated from a 5-mm pipette ground down to provide a 1.5-mm inner diameter. All apparatus was carefully cleaned with chromic acid and then rinsed assiduously with reagent grade water. The liquid surface in the overflowing receiving tank was kept clean by frequent "sweeping" with a hydrophobic rod.

Previous experiments (reference 27) have shown that for the nozzle geometry and flow speeds used here, θ_c is insensitive to small changes in the distance between the nozzle tip and the surface of the reservoir. The range of measured jet mean velocities was between 100 and 600 cm/s, providing Reynolds numbers of 1500 to 9000. As has been found by previous investigators (references 27 and 55), this range was imposed by several constraints. At too low velocities, where the effect of gravity is more pronounced, the trajectory of the jet deviated substantially from a straight line making it difficult to measure θ. At too high velocities, θ_c could not be measured because the bubble entrainment process became highly unstable.

In measuring θ_c, the jet was slowly rotated from large to small angles. Two angles were recorded: one just above critical (no bubbles entrained) and one just below (bubbles just beginning to be entrained). These two angles were separated typically by less than 3°. The average angle was calculated and reported as θ_c. Repeating this procedure for the same operating conditions, after the apparatus was taken apart, cleaned, and reassembled, resulted in values of θ_c that varied by less than 5°. Figures 21a–d are photographs illustrating the effect of the jet impingement angle on bubble production; both jet and reservoir are composed of reagent grade water. Here the jet speed remained constant at 500 cm/s, while the angle increased from 35° to 65° in 10° increments. The critical angle, θ_c, for this set of measurements occurred around 58°. Repeating this procedure for jet velocities from 150 to 600 cm/s resulted in a curve of critical angle versus velocity similar to that previously reported (reference 27).

A wedge-shaped cavity would appear on the water surface if the incident jet angle was not too large. This cavity was formed at the convergence of the surface flow around the side of the jet making an obtuse angle with the reservoir's surface (see figure 22). With the jet's impingement angle fixed and increasing the velocity of the jet to critical and greater, bubbles appeared to be pulled from this cavity. Photographs illustrating this bubble entrainment process for a jet of reagent grade water plunging into a reservoir of the same, at an angle of 25° and increasing flow speeds of 70, 150, 230, 340, 440, and 550 cm/s, are presented respectively in figures 23a-f. Repeating this process at smaller injection angles resulted in both a larger wedge-shaped cavity and the entrainment of larger bubbles. Increasing the injection angle would reduce both the cavity and the average size of the entrained bubbles (see figures 24a and b) until θ_c is reached, whereupon entrainment ceased. Koga (reference 55) has reported similar findings.

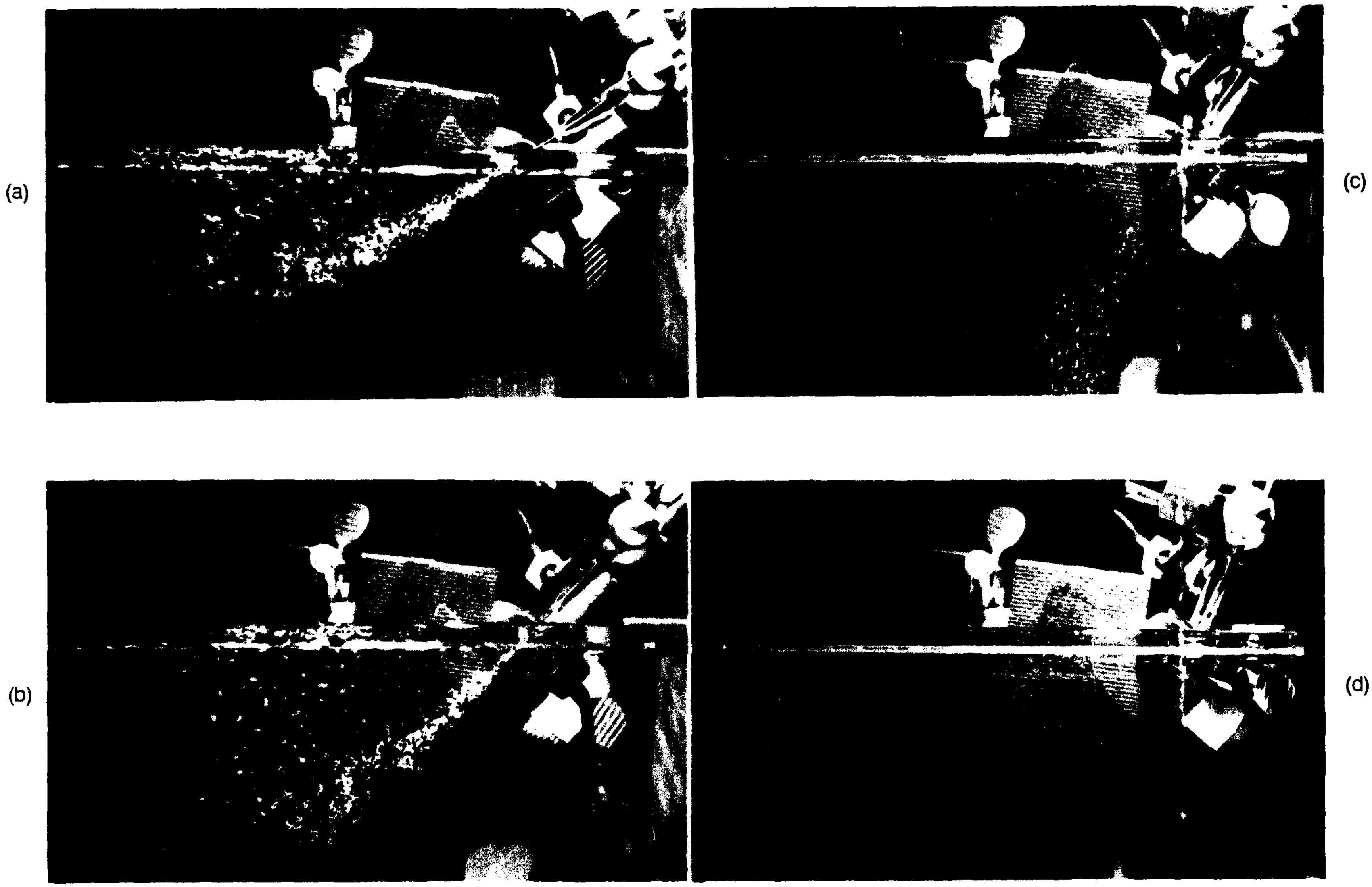


Figure 21. Photographs of bubble entrainment for incident jet angles of 35° (a), 45° (b), 55° (c), and 65° (d). Jet speed was 500 cm/s. Jet and reservoir are composed of reagent grade water.

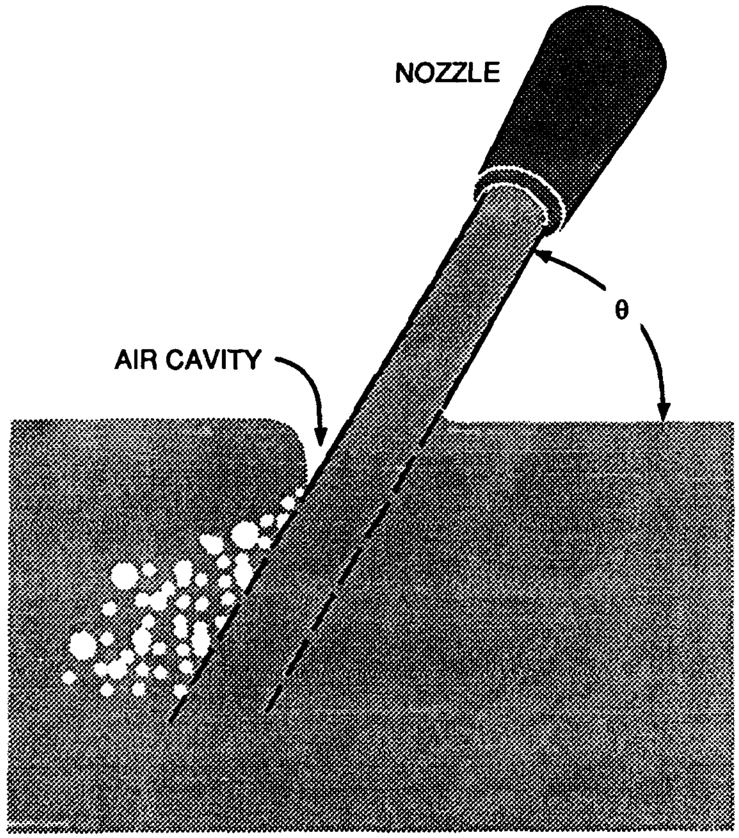


Figure 22. Schematic of air cavity formed by jet of water (or seawater) plunging into reservoir of water (or seawater).

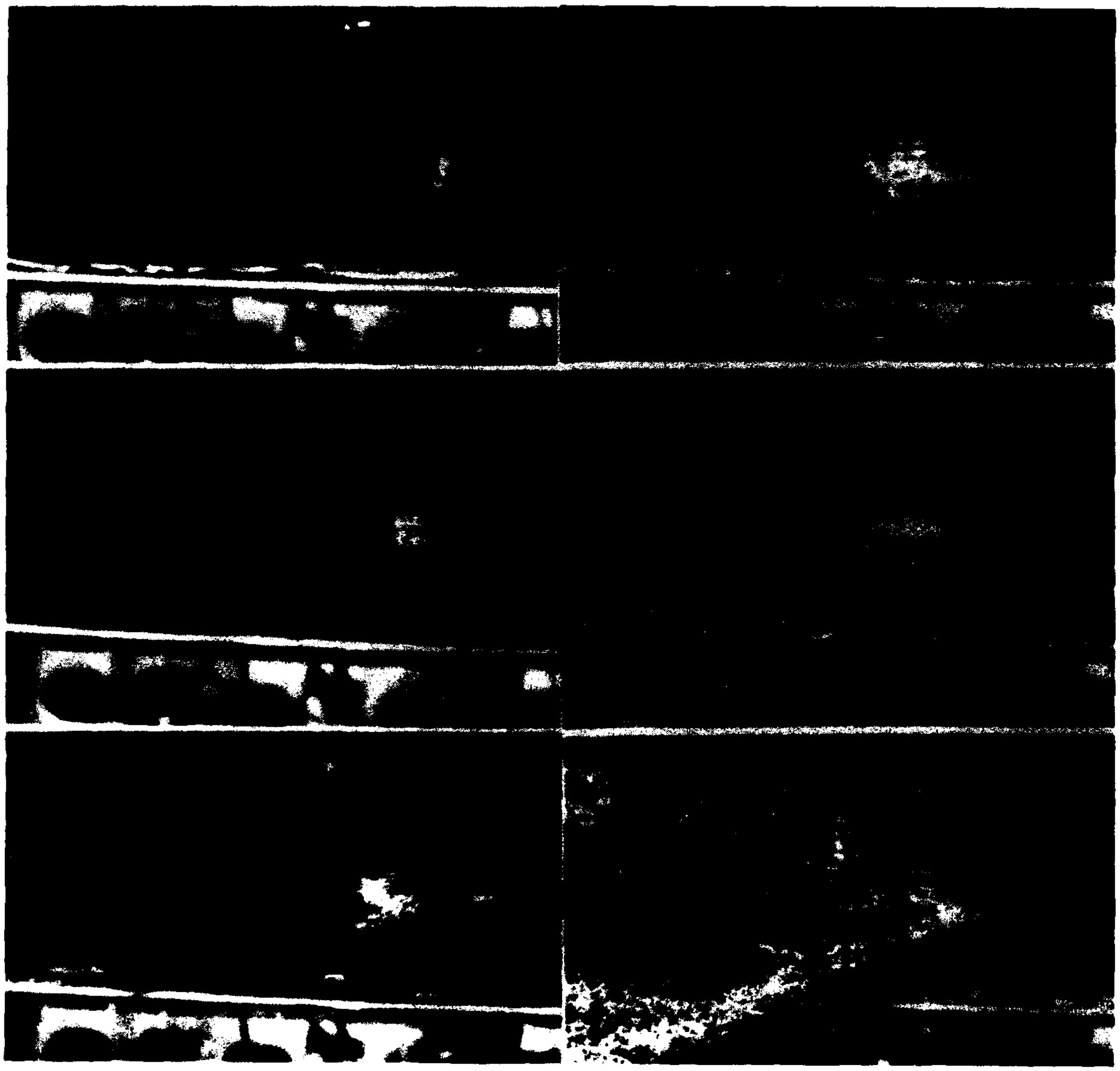
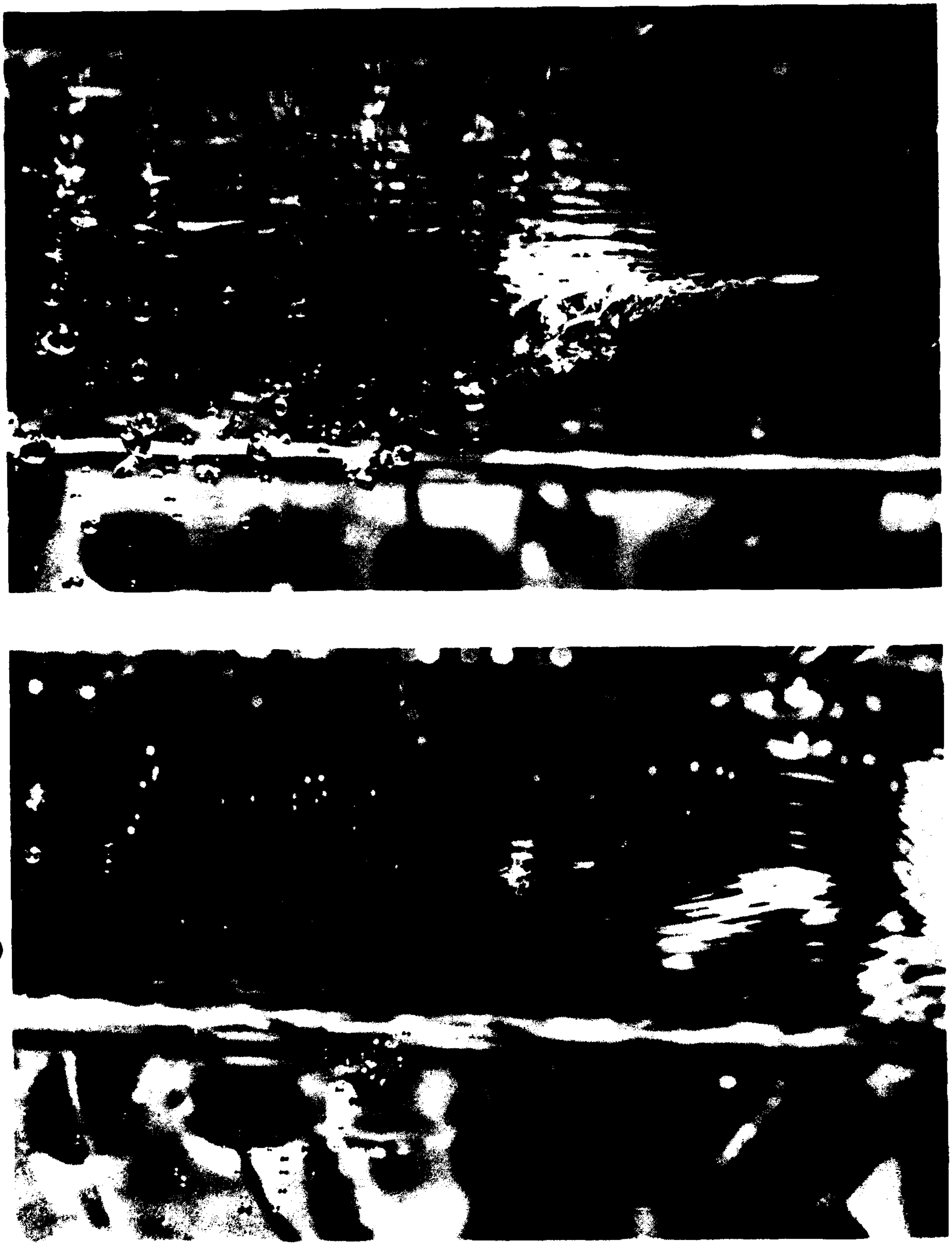


Figure 23. Photographs (taken from beneath the surface) of air cavity and bubble entrainment for jet speeds of 70 (a), 150 (b), 230 (c), 340 (d), 440 (e), and 550 (f) cm/s. Incident jet angle was 25°. Jet and reservoir are composed of reagent grade water.



(a)

(b)

Figure 24. Photographs (taken from beneath the surface) of air cavity and bubble entrainment for incident jet angles of 25° (a) and 50° (b). Jet speed was 340 cm/s. Jet and reservoir are composed of reagent grade water.

4.2.2 Seawater/Film Measurements of Plunging Liquid Jets

Figures 25a–c show the critical angle as a function of jet velocity for seawater plunging into (a) seawater, (b) seawater covered by a film of ADOL-85, and (c) seawater covered by a film of MSF. As in the splash experiments, the seawater was always fresh, taken just prior to performing the experiment. The presence of the films on the continually overflowing reservoir surface was assured by adding drops of film material as needed to maintain micelles in the corner of the reservoir that was not overflowing. Since the films are autophobic, they tend to form these tiny reservoirs when applied in excess. Figure 25d contains fits from the previous plots for comparison sake. The effect of the films on the critical angle (throughout the range measured) is not thought to be particularly significant, considering the spread in the data for any given experiment.

What was particularly striking (see figure 26) when the films were present was a dramatic increase in the number of smaller bubbles. Figures 26a1 and b1 are photographs of the bubble plumes produced by a 1.5-mm diameter jet of seawater, with a mean speed of 280 cm/s and θ equal to 28°, plunging into reservoirs of seawater (figure 26a1) and seawater coated with a film of MSF (figure 26b1). Figures 26a2 and b2 are complementary close-ups of the surface where bubble entrainment occurred, for identical flow conditions. Figures 26c and d show a similar increase in small bubbles when reagent grade water was substituted for seawater (figure 26c) and the same film was applied (figure 26d).

Lin and Donnelly (reference 26) have reported for vertically plunging laminar jets (Reynolds numbers less than 2000) that the presence of a surface-active agent resulted both in an increase in bubble formation and a decrease in the the average bubble diameter. William Garrett (personal communication, 1990), during his studies of forced breaking waves in the laboratory, also observed a significant increase in the number of smaller bubbles after these same films were applied. Detsch, Stone, and Sharma (reference 56) recently have begun quantifying the effect of films on the bubble size distributions produced by plunging liquid jets in seawater. Bubble density peaks at diameters of 100 and 375 microns were observed regardless of whether a film of MSF was present or not. However, with the addition of the film, the 375-micron peak was reduced by about half while the 100-micron peak increased nearly five-fold.

A similar increase in the number of smaller bubbles can be found when comparing air entrainment in water (figure 26c) and seawater (figure 26a2), without the introduction of a monomolecular film. The reason for this, as Scott (reference 58) has shown, is that small bubbles are expected to be less likely to coalesce in seawater than in fresh water. This phenomenon results in greater whitecap coverage on the ocean than on fresh water lakes for the same wind conditions (references 24, 25, and 57). Scott (references 39 and 58) notes that surface active material will also stabilize thin films against rupture, thereby also increasing the number of smaller bubbles. Comparing the bubble-size distributions close to where the jet impinges on a clean (figures 26a2, c) and filmed (figures 26b2, d) surface, it is tempting to speculate that the greater number of smaller bubbles observed with a film present is at least partially due to their increased production at the cavity. Further work is necessary to substantiate this.

The increase in smaller bubbles was accompanied by a noticeable sound reduction at higher frequencies. The fact that a bottle of bubbly liquid gives a dull sound when struck is common. This phenomenon has been attributed to the excessive dissipation of sound (reference 61), due primarily to the smaller bubbles, as well as to the lowering of the eigenfrequencies of the system (reference 62), a consequence of the greatly reduced sound velocity. Farmer and Lemon (reference 15) perhaps have noted a similar effect in the ocean. At high wind speeds they have reported a decrease in the high frequency noise spectra, which they attribute to the scattering and absorption by a thin layer of entrained bubbles occurring near the surface.

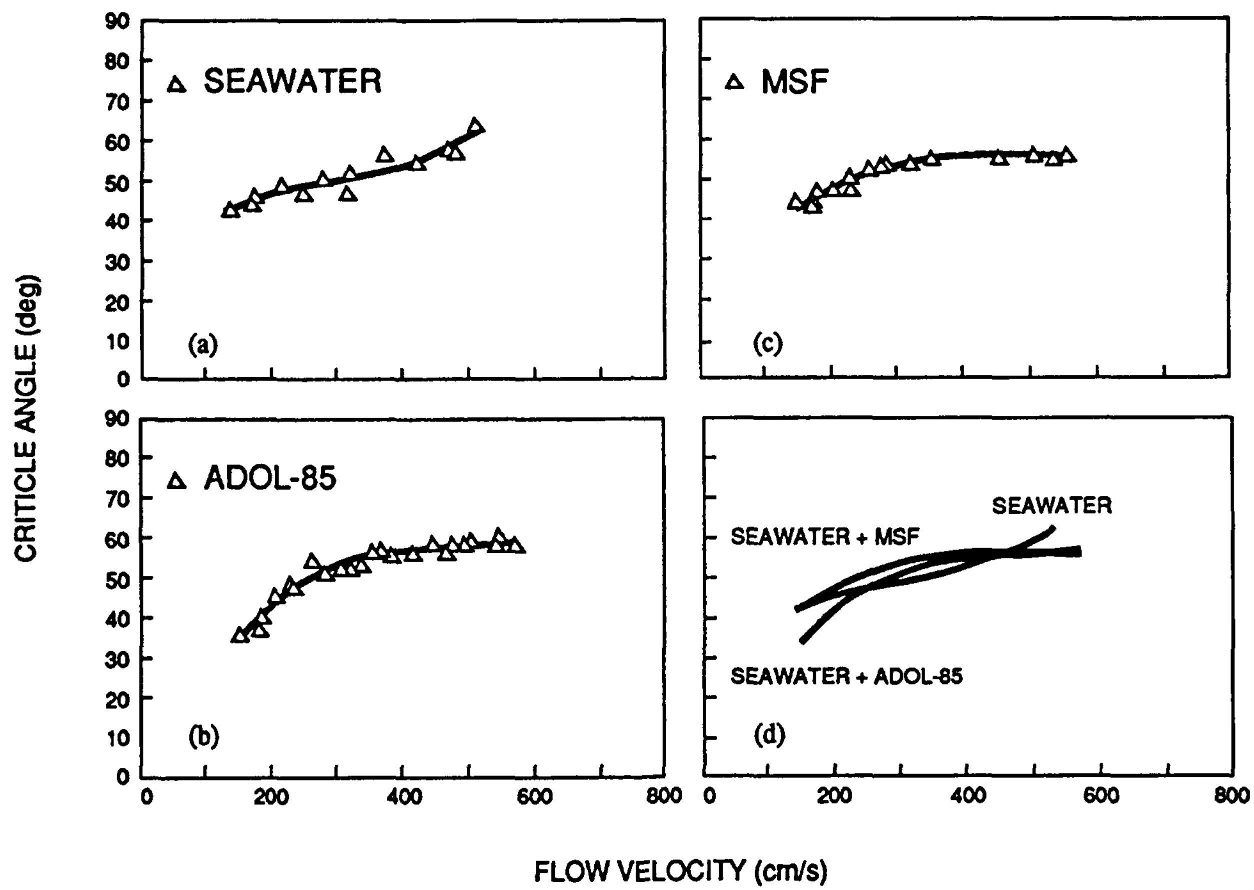


Figure 25. Critical angle versus velocity data for jets of seawater injected into seawater (a), seawater with ADOL-85 spread on its surface (b), and seawater with MSF spread on its surface (c). Complementary curve fits are superimposed in (d).

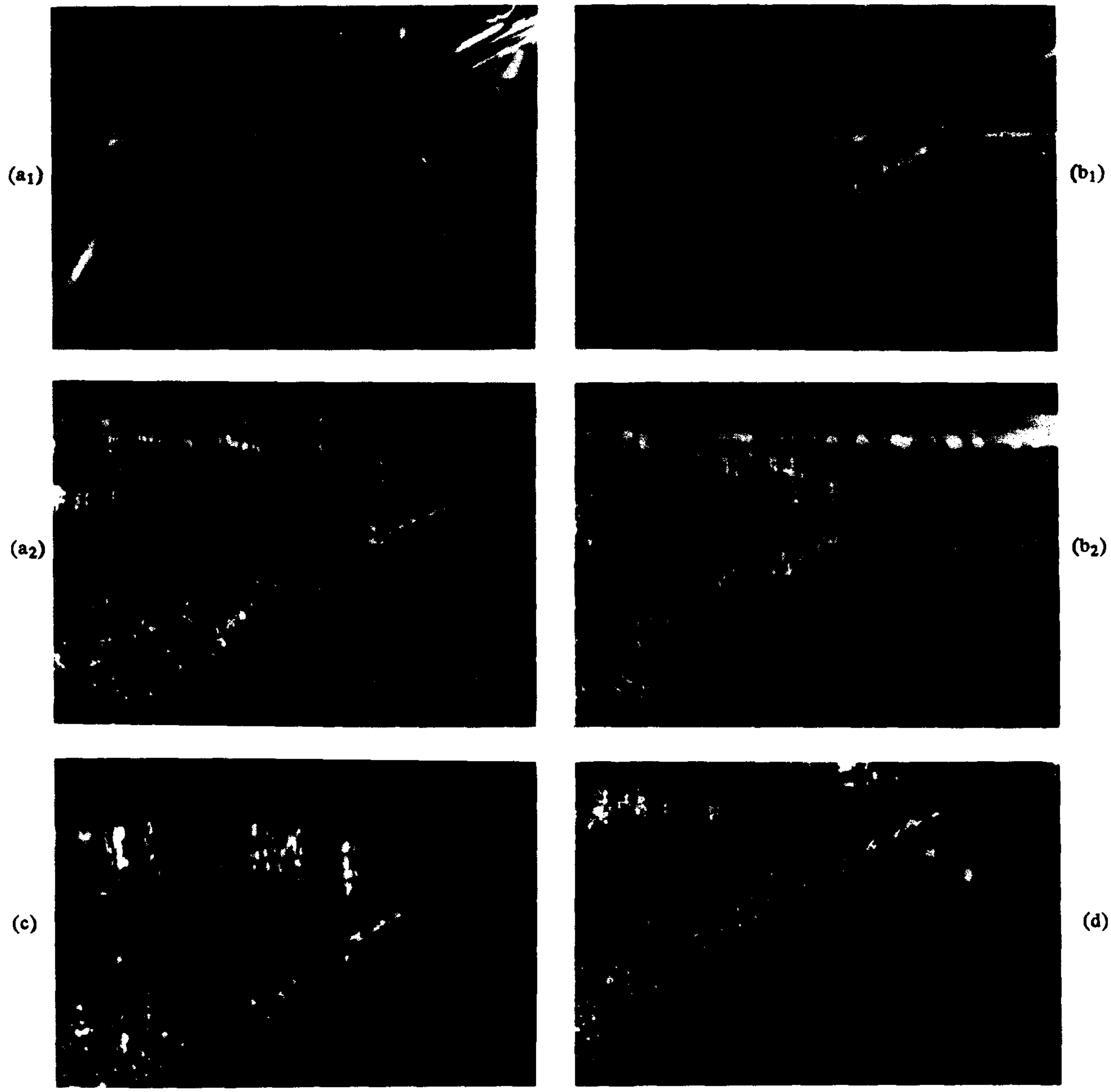


Figure 26. Photographs of bubble entrainment for jets of seawater plunging into seawater (bubble plume (a1) and close-up of cavity (a2)), and seawater with MSF spread on its surface (bubble plume (b1) and close-up of cavity (b2)). Photographs of cavity for jets of reagent grade water plunging into reagent grade water (c) and reagent grade water with MSF spread on its surface (d). Jet speed and incident angle was 280 cm/s and is 28°.

When the jet angle was just below θ_c and few bubbles were being generated (e.g., figure 23c), the unmistakable signature of individual bubble oscillations was evident whether a film was present or not. However, with the film present the pressure amplitude of the bubble oscillations was much reduced, 1/2 to 1/4 of their nonfilmed values. The small size of the tank precluded further study of whether this effect continued at smaller impingement angles and greater jet velocities (where air is continually entrained), as tank reverberation was a problem. Glazman has predicted that a surfactant-film coating (depending on the amount of surfactant transport between the bubble wall and the bulk solution) may result in both smaller bubble diameters (reference 59) and greater bubble damping (reference 60). Unfortunately, the present work is too crude to apply Glazman's theories, though the approach seems promising.

5.0 AT-SEA TESTS WITH THE SYNOPTIC SURFACE NOISE INSTRUMENT AND MONOMOLECULAR FILMS

5.1 BACKGROUND

The Synoptic Surface Noise Instrument (SSNI), built by G. E. Updegraff and V. C. Anderson (reference 20) and pictured in figure 27, was designed to provide simultaneous in situ acoustic and video monitoring of the ocean surface from a depth of 1 meter. The instrument is tethered 1 kilometer from a support vessel to provide acoustic isolation. The housing contains a surface-pointing video camera, along with sensors to measure the instrument depth, tilt, roll, and compass orientation. The depth of the SSNI is remotely controlled by extruding a piston to change its buoyancy. Four clevite hydrophones, each sampled at 20 kHz, are mounted on the instrument's three arms so the position of individual noise sources can be triangulated relative to the camera's view of the surface, which roughly covers 1 square meter. A surface buoy, tethered 30 meters from the SSNI, provides a continuous record of wind speed and direction at 1.5 m above the ocean surface.

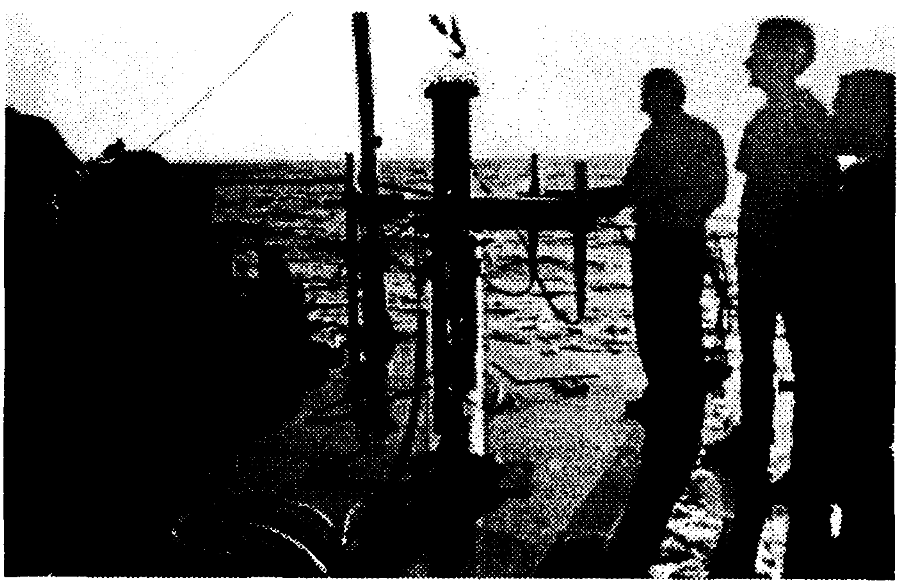


Figure 27. SSNI, built by G. E. Updegraff and V. C. Anderson.

As mentioned in section 2.0, simultaneous acoustic and video recordings collected from the SSNI show that the surface noise generated at low sea states in the absence of whitecapping is produced by bubbles entrained by small wavelet spills referred to as microbreaking. (A word of caution—the present study does not intend to suggest that small-scale whitecapping and microbreaking are fundamentally of different nature. Microbreaking is used here for convenience to distinguish between air entrainment processes associated with small waves that, unlike whitecapping, are not readily observable.) The time series recorded by the instrument's hydrophones show that a microbreak's sound is actually composed of distinct sinusoids, which start abruptly and then decay within milliseconds—the unmistakable signature of freely resonating air bubbles. Unfortunately, these bubbles measure a few millimeters or less and are too small to be individually resolved by the instrument's camera. The sounds of similar resonating bubble oscillations also have been discerned in the babble of brooks (reference 63) and in the breaking of laboratory waves (references 64 and 65).

5.2 SSNI/FILM MEASUREMENTS WITH ADOL-85

On one occasion, a test was conducted during sea state 2 conditions, during which the SSNI recorded data before and after a 2-gallon ADOL-85 slick was applied above the instrument package. This quantity of film material provided a slick whose diameter was estimated to be at least 10 times greater than the depth (around 1 m) of the SSNI. A conspicuous reduction in the visual and aural observation of small-scale wavebreaking was immediately evident within the slick. This is illustrated in figures 28a–c, where some representative sections of the pressure-time series data recorded by one of the SSNI's hydrophones before (figures 28a and b) and after (figure 28c) the film is applied are plotted. The creation of bubbles near the SSNI, evidenced by their sinusoidal oscillations (figure 28b), are much more prominent before the slick is applied. However, the bubble entraining noise associated with the small-scale wavebreaking comprised only a small part of the total record. Unfortunately, the time-averaged acoustic power was more dependent on the propeller cavitation noise of distant shipping, which was increasing during most of the experiment (compare figures 28a and c).

In an effort to objectively quantify the film's effect on the naturally occurring, intermittent surface noise, the following procedure was adopted. First, root-mean-square levels from 1 to 2 minutes of videotape audio were averaged to estimate the steady shipping background noise. Then, a threshold was set at twice this value. To discriminate against short-duration sounds of unknown origin (presumably biologics) in favor of the generally 1-second microbreak sounds, a 6-millisecond hold time was employed. Using this approach, it was found that the slick reduced the number of intermittent noise events by nearly 80%. Regrettably, neither a reference sonobuoy nor a calibrated wind anemometer was available during this test. (When this experiment was attempted to be repeated 1 year later with the aforementioned equipment, its completion was interrupted by a distress call. To respond promptly, the SSNI was set adrift. Several weeks later it was found by a Mexican fisherman and, after a somewhat circuitous route, was eventually returned.)

5.3 SSNI/SONOBUOY EXPERIMENTS

Fortuitously on several occasions, the SSNI had recorded 30 minutes of continuous data (no slick involved) at the same location and often within 1 hour of a sonobuoy/film experiment, the results of which were presented in section 2.0. These records provide environmental information near the ocean surface and, more importantly, a measure of the frequency of microbreaking events, which can be contrasted to the effectiveness of the films. Table 2 briefly summarizes the most important aspects of this comparison. Further details can be found in references 8 and 19. The wind speeds referred to in table 2 for the SSNI experiments were measured 1.5 m above the sea surface and for the sonobuoy experiments (as previously mentioned) either 7 (1988) or 10 m (1989) above the ocean surface.

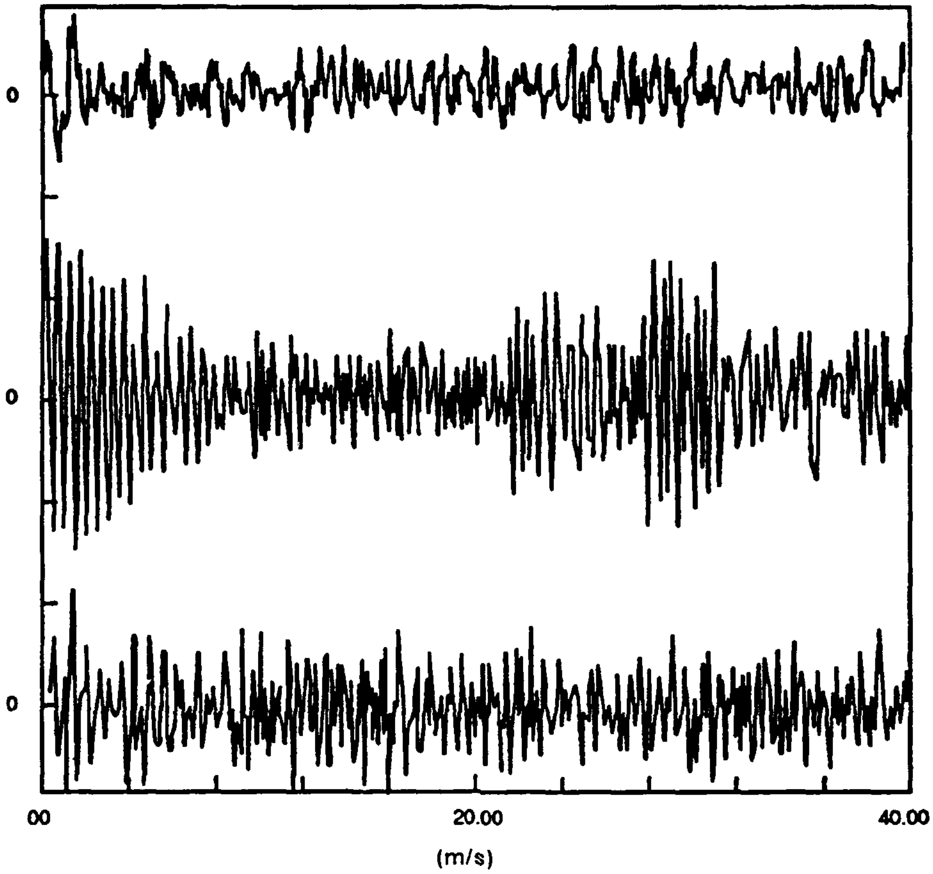


Figure 28. Pressure-time traces before (a, b) and after (c) a slick was created over the SSNI, during which ship traffic noise was increasing. Examples of bubble entraining sounds associated with microbreaking are shown in (b).

Microbreaking was determined by the magnitude of the mean-square acoustic pressure spikes in the hydrophone time series, the position of noise sources relative to the instrument, and by audio playback of videotape to eliminate obviously mechanical (thunk) and biological (belch) noises. Figures 29a and b show a representative segment (250 seconds) of the wind speed and corresponding mean-square pressure data collected by the SSNI on the morning of 20 February 1989. Figures 29c and d show two consecutive 1/30-second sections of the SSNI's acoustic time-series data collected while microbreaking was occurring in the previous record (figures 29a and b). Individual bubble oscillations are clearly recognizable. In more energetic spills, the individual oscillations overlap to the extent that they can no longer be singly identified.

Summarizing table 2, at lower sea states (1/2) where the films had no acoustic consequence there was, as previously conjectured, essentially no microbreaking activity to suppress. For sea states between 1 and 2, single microbreaking events could be discerned, their rate of occurrence increasing with windspeed. During these conditions, the films have been found to perform best in reducing surface ambient noise, apparently by greatly decreasing the number of these air-entraining microbreaking events. When whitecaps were present (sea states 2-3), the sea-surface ambient noise was continuous so only the larger wavebreaks could be individually identified. Under these conditions, the noise-quieting by the film appeared to be more frequency dependent, increasing with increasing frequency.

Table 2. Summary of SSNI/sonobuoy experiments.

Measuring Instrument	Sea State	Time	Number of Microbreaks	Noise Reduction by Film
SSNI $U_{1.5}$ = 1.3 m/s Sonobuoy U_{10} = 2 m/s	~1/2 ~1/2	2/20/89 1159 – 1229 2/20/89 1329 (began)	1	No effect (10 gallons of MSF) See figure 12
SSNI $U_{1.5}$ = 1.6 m/s Sonobuoy U_{10} = 2-3 m/s	1-1/2 ~1	2/20/89 1041 – 1111 2/20/89 1002 (ended)	30	About a constant 6-dB noise reduction starting around 1 kHz (10 gallons of MSF) See figure 11
SSNI $U_{1.5}$ = 1-3 m/s Sonobuoy U_7 = 3 m/s	~1 ~1	6/30/88 1255 – 1325 6/30/88 1340 (began)	63	About a constant 8-dB noise reduction starting around 1 kHz (10 gallons of oleic acid) See figure 9
SSNI $U_{1.5}$ = 2-3.5 m/s Sonobuoy U_7 = 4 m/s	~1 ~1	7/1/88 1357 – 1423 7/1/88 1500 (began)	107	About a constant 8-dB noise reduction starting around 1 kHz (5 gallons of MSF) See figure 10
SSNI $U_{1.5}$ = 7 m/s Sonobuoy U_7 = 5 m/s	~3 2-3	7/4/88 2054 – 2124 7/4/88 2022 (ended)	Continuous background noise, 50 large wave-breaks recorded	Overall about a 6-dB noise reduction (5 gallons of ADOL-85) See figure 7

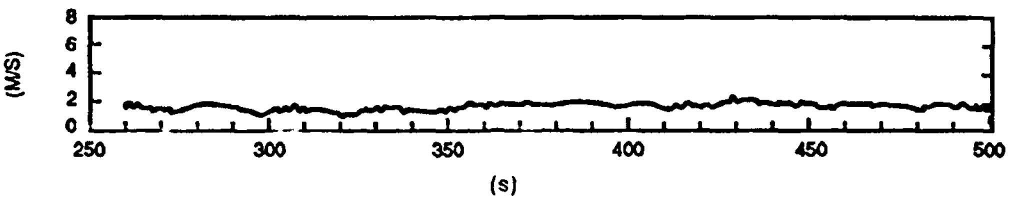


Figure 29a. Sample of a 4-minute time series of wind speed (1-s averages, obtained 1.5 m above the ocean surface) during an SSNI deployment on the morning of 2/20/89.

Figure 29b. Sample of a 4-minute time series of mean square acoustic pressure (1-s averages, obtained 2 m below the ocean surface) during an SSNI deployment on the morning of 2/20/89.

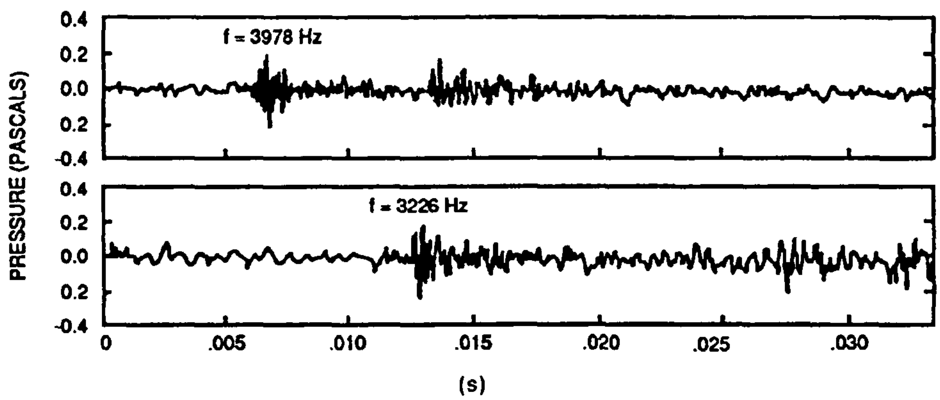


Figure 29c. Two consecutive 1/30-s sections of the acoustic time series occurring about 378 s into the previous (figure 29a,b) recording. Where possible, the frequency of the larger oscillations have been marked.

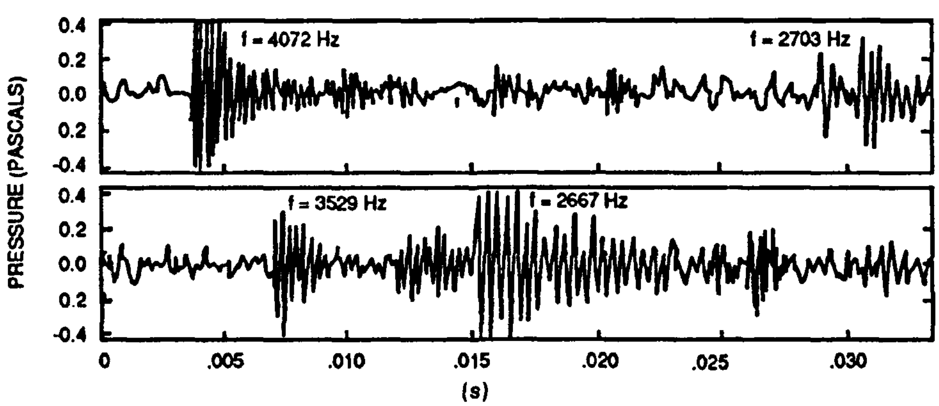


Figure 29d. Two consecutive 1/30-s sections of the acoustic time series occurring about 438 s into the previous (figure 29a,b) recording. Where possible, the frequency of the larger oscillations have been marked.

5.4 BUBBLE ENTRAINMENT BY "BREAKING" CAPILLARY-GRAVITY WAVES

There has been proposed (references 66 and 67) another source of bubble production, which may be important at low sea states. It has been shown theoretically for capillary (reference 68) and capillary-gravity (references 67 and 69) waves that as the wave profile steepens the troughs become more and more curved until the sides of the trough touch, pinching off a bubble of air. Schooley first reported (reference 70) wave profiles similar to those predicted but did not recount bubble entrainment. Toba (reference 71) first documented the production of bubbles at the troughs of capillary waves. Extrapolating his results (attained in a 21-m wind flume) Toba conjectured that a wind speed corresponding to 13 m/s (at a height of 10 m) would be necessary for this phenomena to occur in the ocean. He also remarked on the profound consequences that a surfactant would have on this mechanism.

Recently Kolaini, Roy, and Crum (reference 72) have measured the sound produced by bubbles generated by "breaking" capillary waves in a wind-generated wave tank of 2.1-m fetch. The spectra of radiated frequencies ranged from a few kHz to over 100 kHz, with a broad peak centered around 25 kHz. There was evidence of a wind speed threshold of 10.6 m/s for bubble production to occur. Curiously, at wind speeds greater than 10.6 m/s, the addition of a soluble surfactant (Kodac Photo-Flo) always resulted in the production of more bubbles and, consequently, greater noise.

Although the SSNI could not visually confirm whether bubble production via "breaking" capillary waves was (in addition to the microbreaking) also occurring, there are several reasons to believe it was not. First, the wind speeds measured during most of the film experiments were greatly below those found in the relevant laboratory experiments (references 71 and 72). Granted, laboratory fetches are many orders of magnitude less than those experienced at sea; nevertheless, high-frequency wave spectra collected with fetches as short as 1 m, have been thought previously (reference 73) to be fairly representative of the field conditions. Moreover, the spectral form of ocean surface waves in the gravity-capillary range has been found by Mitsuyasu (reference 74) to be unaffected by the presence of large dominant waves in the gravity range and, hence, largely independent of fetch. Secondly, the average of individual bubble events did not result in a spectrum reminiscent of the ocean. Note that Medwin and Beaky (reference 64) have reasonably duplicated the character of ambient ocean noise in the laboratory by measuring individual bubbles produced by the spilling breakers. Finally, the results of Kolaini et al. (reference 72), suggest that the addition of a film would increase surface ambient noise (through an increase in bubble production). This clearly was not observed and deserves further investigation. There is no question that the dilational elasticity, which the films provide the ocean surface, tend to oppose capillary wave motion (references 4, 5, 6, and 75). However, if air entrainment occurs in spite of this, as in the case of the plunging liquid jets (section 4.1), it is not inconsistent that a greater number of bubbles would be produced when a monomolecular film is present.

6.0 CONCLUSIONS

"The sea never changes and its works, for all the talk of men, are wrapped in mystery."—Joseph Conrad

Over the past 3 years, some 30 monomolecular film experiments (reported here and in references 1 and 44) have been performed throughout a variety of sea state conditions with wind speeds varying from about 1 to 25 m/s. A significant reduction in ambient noise beneath the films was observed throughout most of these experiments, normally beginning between 1 and 2 kHz. It was hoped that through studying the quieting effects of the films, especially at low sea states where whitecapping is absent but the characteristic -5 to -6 dB per octave spectral slope still prevails, a better understanding of the nature of the ocean-surface noise sources might be achieved. Albeit the character of the film's quieting impact, both in magnitude and frequency dependence, exhibits a large amount of variability between tests. Moreover, it is not known how much of this disparity results from causes independent of the presence of the film, or are rooted in poor slick coverage, or how the films interact with a particular wave field. Nevertheless, several trends have been noted in the data that we believe add to our understanding of the nature of sea-surface noise, particularly at low wind speeds.

There have been many candidate sound sources proposed to account for the -5 to -6 dB per octave portion (kHz range) of the ocean ambient-noise spectra. These include wave-wave interaction (reference 76), ocean spray impact (references 10 and 11), cavitation (references 66 and 77), freely oscillating bubbles (references 11, 21, 35, 64 and 78), bursting of bubbles on the ocean surface (reference 66), and the sound of cosmic rays (reference 12). Ironically, surface-active films have been found to affect most of the mechanisms proposed (references 4, 5, 6, 58, 59, 79, and 80). However wave-wave interaction, cavitation, and bubble bursting respectively can be eliminated since sound produced by wave-wave interaction has been now determined (reference 81) to be only relevant to much lower frequencies (< 10 Hz), cavitation has been shown (reference 82) to be physically impossible in the ocean environment, and it is presently believed that the underwater sound of bursting bubbles is too weak to be of any significance (reference 82). Moreover, by focusing on low sea-states, which still exhibited a -5 to -6 dB per octave slope, the presence of spray can be discounted (reference 49), as can also the noise contribution due to cosmic rays (reference 12). Without introducing any new mechanisms for surface-noise production, the sound of freely oscillating bubbles is the sole remaining candidate to be examined as the sea-surface sound source the films undermine. A similar conclusion (without regard to the quieting effects of monomolecular films) as to the source of ambient noise at low sea-states has recently been deduced by Pumphrey and Williams (reference 83).

It is proposed that the number of bubble-entraining microbreaking events is greatly reduced within the slick. This number appears, in the absence of whitecapping, to be the operative parameter determining the level of the -5 to -6 dB per octave slope of the spectrum. Consequently, the ambient noise level beneath the slick suggests a sea-state significantly lower than observed outside it. Updegraff and Anderson (reference 21) have found that the spectra produced by both a single energetic microbreak, as well as the addition of some 81 individual bubble oscillations taken from smaller breaks, exhibit close to a -5 dB slope beginning around 1.0 kHz and continuing to the upper range of their instrument (8 kHz). Theoretical arguments by Prosperetti (reference 35) indicate that the noise levels from oscillations of newly formed bubbles would become important above 1 to 2 kHz. The fact that the noise reductions observed beneath the films have always continued throughout the highest frequencies recorded by the sensor is also indicative of the films interrupting some bubble entraining process.

None of the films had ever been observed to have any acoustic consequence if the wind speed was less than about 2 m/s (e.g., figure 12). We believe this is due to the natural absence of bubble-producing microbreaking events, which the films would otherwise oppose. With the appearance of whitecaps (wind speeds greater than 5 m/s), the present film data indicate some loss in noise-quieting effectiveness, which increases with decreasing frequency. It is not known whether this is a consequence of the increasing difficulty of applying a large slick centered above the test hydrophone, or that other noise sources insensitive to the films begin to become important.

Laboratory experiments have shown that a filmed surface of seawater can completely suppress the regular entrainment of bubbles by vertically falling drops, as well as increase the number of smaller bubbles produced by an air entraining jet. The acoustic implications of the latter in the ocean scenario are as yet unknown. As argued previously (section 5.1) because slight deviations from a vertical impact trajectory (as would be expected under field conditions that would ordinarily produce spray) would precipitously reduce bubble entrainment (reference 48), a decrease in bubble production by spray is not thought to be integral to the noise reductions observed beneath the films. On the contrary, it may be anticipated that as impact noise, which has been found (section 4.2.2) to be insensitive to the films, becomes increasingly important the lower-frequency noise reductions beneath the films would decrease. Pumphrey et al. (reference 45) have shown, for example, that by adding detergent to a tank of water, the acoustic power spectra of real rain (presumably falling vertically) is unaffected below 5 kHz but dramatically reduced at the higher frequencies (about a 10-dB reduction at 14 kHz) associated with regular bubble entrainment by drops.

Given the dramatic noise reductions often observed beneath artificial slicks the question arises of whether the possible noise quieting of natural slicks could significantly impact our assessment of "natural" ocean-ambient noise. It is noteworthy that natural film-forming molecules of biogenic origin are present to some degree at all times at the sea surface (reference 84). Therefore, the potential exists (if these molecules come into contact with one another) for the formation of natural organic slicks wherever the ocean is unfrozen. Furthermore, natural sea slicks, which are not unlike ADOL-85 in their physicochemical behavior (reference 85), have been observed (references 22 and 75) to withstand sustained wind speeds of up to 5 to 7 m/s. Studies of oceanographic phenomenon conducted from the Space Shuttle Challenger (reference 86) have shown the presence of slicks, thought to be primarily of natural origin, to be ubiquitous over large portions of the world's oceans.

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A series of low sea-state tests show that the reduction of surface-related ambient noise beneath monomolecular (slick-forming) films begins between 1 and 2 kHz and extends to at least 70 kHz. Although the amount of noise reduction varies between experiments, attenuations of up to 8 dB are not uncommon. Most of the experiments are conducted in the absence of whitecapping, where for wind speeds greater than 2 m/s, the ambient noise spectra beneath the films generally resemble those of nonfilmed, lower sea-state conditions.

Laboratory experiments conducted with these same films spread upon a reservoir of seawater show that the regular bubble entrainment associated with vertically falling drops can be dramatically suppressed, and the air entrainment accompanying plunging liquid jets is characterized by a conspicuous increase in the number of smaller bubbles. Preliminary studies providing simultaneous in situ acoustic and video monitoring of the ocean surface from a meter beneath it suggest that, in the absence of whitecapping, the ambient noise reduction beneath the slick results from a dramatic decrease of microbreaking events within it. The acoustic signatures of these microbreaking events are distinguished by individual oscillating bubbles.

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