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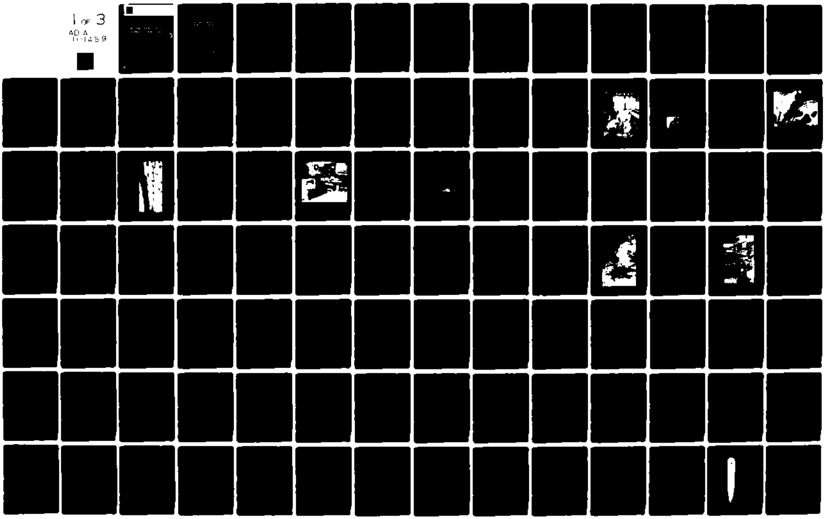

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Proceedings of a Symposium and Workshops February 11-12, 1980

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Ocean Instrumentation to Serve Science and Engineering

WATER SAMPLING WHILE UNDER WAY

Proceedings of a Symposium and Workshops February 11-12, 1980

Convened by the
Steering Committee for
Underway Water Sampling Technology
for the
Marine Board
Assembly of Engineering
National Research Council

N00014-80-G-0034

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PREFACE

Ben C. Gerwick
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Among the subjects granted priority consideration by the Marine Board is improved technology to meet the needs of ocean science and engineering. Many activities in ocean science and engineering demand underway water sampling: collection, measurement, and analysis of various constituents of seawater while in transit. The samples collected may, of course, be analyzed further on shore.

The purposes of underway water sampling are diverse and numerous, dictated by the needs of oil and gas exploration, of marine biology (e.g., to understand the nutrients in seawater at various locations and depths), of environmental monitoring, and of oceanography. These needs have been met, for the most part, by systems built to the specifications of each activity, or by adapting off-the-shelf technology for particular applications.

While all the requirements of underway water sampling may be too various to admit of a single technological solution, several could perhaps be served by a set of systems and procedures.

The Ocean Science and Technology Division of the Office of Naval Research, U.S. Navy, seeing that an exchange of information among the scientists and engineers engaged in underway water sampling could be most productive at this stage of development, asked the Marine Board to convene such a group. The Marine Board agreed to this request. Among the Marine Board's stated functions is to "foster communication among the professional engineering community in the United States and scientists, engineers, government officials, and the public on national ocean engineering problems, and to provide a forum to facilitate the exchange of information and data." Early in 1980, the National Research Council appointed a steering committee under the board's direction to plan and convene a meeting with the purpose of effecting exchange of information among the community of interests, and of gaining technical insights into the range of characteristics required of underway water sampling.

About 60 scientists and engineers from academic institutions, government agencies, and industry met for three days in February 1980 to present and hear papers on one another's work, and to develop lists of existing and projected needs for sampling, the principal technological requirements for meeting those needs, and the technical difficulties demanding attention in the near term.

The proceedings of the resulting symposium and workshops constitute this publication. It should be understood that the opinions expressed by the participants are their own, and may not necessarily represent those of their organizations, the steering committee, the Marine Board, or the National Research Council. The proceedings are offered to broaden the exchange of information pertinent to continuous improvement in the equipment and techniques of underway water sampling.

CONTENTS

INTRODUCTION

Marshall P. Tulin
Chairman
Steering Committee for Meeting on
Underway Water Sampling Technology

To gain greater knowledge of the oceans, scientists are turning to more sophisticated instruments of measurement. Chemical oceanographers, for instance, are employing various types of chromatographs and spectrometers (flame, photo, fluorescent, infrared, ultraviolet, and mass), and encouraging the adaptation of other instruments for use at sea. But instrumentation is only one aspect of measurement. Another is sampling.

In the course of scientific research and resource exploration using advanced instrumentation, critical needs for new sampling technology have come to the fore. Oceanographers typically take samples at a station. The stations are widely spaced, and do not provide sampling on spatial or temporal scales adequate to detection of the microfluctuation, variability, and other data in frontal zones of particular interest.

The needs of scientific research and exploratory ventures for new oceangoing sampling equipment and techniques are diverse and numerous. Engineering efforts to meet them must take into account the characteristics of available ship platforms and their modes of operation. The complications of designing a sampling system to meet the research needs of a single project present so formidable a challenge that the problems inherent in designing a single system to meet many needs seem insuperable. Nevertheless, the search for unique solutions is expensive, and could doubtless benefit from sharing the experience gained in various quarters.

The Office of Naval Research, U.S. Navy, asked the Marine Board to investigate these issues with a view to organizing such an exchange. Discussions between members of the Marine Board, scientific and industrial users of underway water sampling systems, technologists, and suppliers indicated a distinct and exigent need for exchange of information.

These proceedings constitute a report of the meeting, organized by a Marine Board steering committee, consisting of about 60 scientists, engineers, technologists, suppliers, and representatives of government agencies. As indicated, the meeting had two objectives: to exchange information, and to elaborate a single set of criteria, if possible, for the underway water sampling systems of near- and longer-term applications. To meet the first objective, the meeting opened with presentations of recent work. The participants then developed short statements of their needs and requirements, both for prevalent problems that demand near-term solutions, and for the projected course of research in their fields, with a view to the second objective. The statements were discussed in two workshops, one concentrating on present and future needs for sampling and analysis, and the other on present and future technology to meet those needs.

The wealth of details in the presentations and discussions, and the range of applications described for underway water sampling may swamp the agreement that began to emerge during the meeting about a few simply stated considerations and requirements of primary importance. A brief summary of these points is offered here to help keep the reader afloat in the sea of particulars that follows.

SUMMARY

Denzil C. Pauli
Member
Steering Committee for Meeting on
Underway Water Sampling Technology

Underway water sampling systems find a number of applications in:

- Understanding the chemical processes in the ocean, particularly in ocean fronts;
- Determining background levels of dissolved gases and chemicals in the ocean, and their variability;
- Measuring types, concentrations, and variations of planktonic populations;
- Investigating the movement, mixing, and fates of pollutants, and
- Detecting offshore energy resources, and understanding the history and patterns of their deposition.

Underway water sampling for most of these applications can be divided into two categories: those requiring relatively low flow rates (4 to 30 l/min), and those requiring larger flow rates (100 to 500 l/min). The latter are typical of the sampling required by organic chemistry or biology. Sampling depths for the measurements of interest range from near the surface to near the bottom.

Considerable work has been undertaken to produce technologies appropriate to these sampling requirements, with specific attention to shipboard winches and handling equipment, composite sampling hoses that incorporate cables to conduct electricity and to add strength, cable fairing, underwater depressors, submersible pumps, and sensors.

One aspect of this work of particular importance to much underway water sampling is the development of parts and techniques to prevent contamination of the samples by the equipment itself. Measurement of the low-level background values and variability of some dissolved chemicals demands strict control of contact or interaction with the sampled seawater.

Among the critically needed components of underway water sampling are non-contaminating systems with submersible pumps that can provide sufficient head to overcome the flow losses of long hoses. Other needed components, such as faired composite sampling hoses, are available by special order.

Multiple-depth sampling can be easily engineered for maximum depths of 100 meters or so, but for depths of 1000 meters, the size of the components, and the shipboard handling and storage the systems require, make the systems less flexible and more difficult to move from ship to ship. Pumping techniques are likely to be critical in these larger systems.

SYMPOSIUM

WELCOME

Marshall P. Tulin

It is my pleasure to welcome you here on behalf of the National Research Council and the Marine Board of the National Research Council, convening this meeting at the request of the Office of Naval Research, U.S. Navy.

I have had the pleasure of serving as chairman of the steering committee to organize this meeting, in collaboration with the Marine Board.

Speaking for the steering committee, I want to thank all of you for your enthusiastic response to the idea of this workshop, and for the time and labor represented by your participation.

Each of you has been invited because of your experience and expertise in one or more area of science or engineering. Our purpose in meeting is to provide a summary opinion on the technical requirements for future underway water sampling systems, the extent to which the requirements can be met with current technology, and the technological developments that may be necessary.

We are asking you to provide that summary opinion through the workshops. The first--a short one--will take place later today; the longer workshops will occupy tomorrow's program.

We will have a very full day today of tutorials, or reports on recent work in underway water sampling. At their conclusion, we will meet in workshop sessions for about an hour to develop individual statements of existing and projected technical requirements. These will be taken up and discussed in detail in two workshop sessions tomorrow. Our intention is to conclude our work tomorrow afternoon with as much of our product in written form as possible. I want to thank you again for your time and effort, and wish you a lively and successful two days of work.

Now I would like to call on Edward Green, from the Office of Naval Research, whose interest in underway sampling systems led to this meeting.

KEYNOTE PRESENTATION

Edward J. Green
Office of Naval Research

One does not have to look very far in the history of federal funding of oceanography to find examples of disasters and failed programs which came about largely because the programs were driven from Washington by the federal bureaucracy, and did not spring from the motivating needs and desires of the scientific community. So I believe it is appropriate as we begin this seminar and workshops to ask three questions: First, are there first-order scientific problems that cannot be addressed unless we develop the sort of technology that we are going to be discussing here today? In other words, are there problems that cannot be faced unless we have rapid, synoptic, underway, short time-scale, short space-scale chemical analyses?

Second, let us ask, is the chemical oceanographic community sufficiently motivated to aggressively pursue these scientific questions if we can and do provide them with the technological development? And third, can the federal programs afford it? Is the scientific payoff likely to be commensurate with the cost of developing these kinds of systems?

My immediate response is "yes" to all three questions, but I have very little more than intuition on which to base it. I am here today among you to be educated in the views of the scientific community and to find out what your needs, desires, and motivations are. But, as I say, I do have a hunch that the answer to those questions is yes, so let me explain the basis of that hunch. Let's look at some recent developments in physical oceanography.

The ocean exhibits fluctuations over a broad range of time and space scales. The spatial scales extend from the oceanic-basin scale of fluctuations in the general circulation all the way down to the microstructure at the centimeter scale; the time scales extend from years to possibly decades for the former to seconds for the latter. The types of motion in the ocean can be grouped very broadly into four categories: general circulation at one extreme, fine and microstructure of the other, and mesoscale phenomena in between--phenomena that have really come to be viewed as important by physical oceanographers only in the last decade--and the internal wave regime.

We know a lot about the general circulation. For many years, the tools and techniques available to physical oceanographers made it almost impossible to study any other sort of phenomena in the ocean. We know, for example, that these very large scales of motion, the general circulation, are set by very large phenomena, by the large-scale wind-stress pattern, by the large scale of solar heating and cooling, and by the broad bathymetry of the ocean basins.

However, as physical oceanographers developed the techniques and tools that allowed them to measure on finer grids and on shorter time scales--tools such as the expendable BT, towed thermistor chains, profiling devices of various kinds, the use of aircraft for rapid synoptic surveys, and recently, satellite imagery--they found that the mesoscale fluctuations are much more energetic than the general circulation. We know that the great bulk of the energy supply to the ocean does not drive the general circulation, but rather, drives the finer-scale fluctuations in the ocean, with horizontal space scales of tens to several hundreds of kilometers, and time scales, not of decades or years, but of many days to several months.

As a matter of fact, one can make a rather good analogy between the way physical oceanography has developed and the way meteorology has developed. In meteorology, you can think of studying climate by looking at records accumulated over many years and considering the broad, long-scale length patterns, whereas to study weather you need synoptic maps; you need to look at the changing instantaneous patterns; you need to look at the passage of fronts. It is not surprising that physical oceanographers have taken over meteorological terms such as "fronts" to describe the sort of phenomena to which they have turned their attention. But we chemists are still largely confined to studying the chemical climate. We are not yet looking at the analogous "weather" of marine chemistry. We do not have the tools that would allow us to look at the same time and space scales the physical oceanographers have developed.

We are making breakthroughs in some areas. In regions where there are very strong chemical fronts, such as in the California coastal upwelling region, strong chemical variability extends all the way to the surface. There, underway surface pumping can be an effective way to obtain rapid sampling rates.

At Texas A&M, David Schink, who is with us today, has used a towed fish device with an armored hose--an industrial off-the-shelf device--to try to make progress with somewhat deeper water sampling. I also want to show you some of the work Gene Traganza has done at the Naval Postgraduate School. Let me say that all the credit for any of this work goes strictly to him; any of the blame for the mad ravings of a program director should be attributed to me, and no blame should accrue to him for any of the things that I say today.

Gene has been studying the California upwelling area, where cyclonic eddies occur. In particular, he observed in a satellite image a mushroom-shaped plume of colder upwelled water in the Monterey Bay region, the detailed structure of which would have been almost impossible to ascertain without the use of satellites, and which he used to actually set his ship track to be able to sample the different water masses. This is the first example that I know of in which satellite imagery has actually been used interactively to assist a chemical oceanographic study. The prospect has been discussed, but so far as I know, this is the first time it has been employed in such a close, interrelated fashion.

In Gene's data you see the expected close correlation of temperature and nutrient chemistry: the cold water high in nutrients, the warm water low in nutrients. In a later study, Gene looked at ATP and chlorophyll to get an idea of biomass concentrations so he could determine where the blooms are occurring. His data show very strongly that the blooms are occurring not in the cold nutrient-rich water, but rather on the gradients. Well, this is an idea that biologists have speculated about for a long time. So far as I know, this study provides the first hard data to indicate that it is in fact true, and that the biological patchiness may be set initially by the chemical patchiness which itself is a consequence of the physical oceanography.

I find this work very exciting. I think it is an indication of what we can do if we are able to make rapid synoptic underway measurements.

In conclusion, let me reiterate that I believe that most of the fundamental change that has taken place in oceanography in the past few years can be attributed to the rate at which data can be collected. Chemists, by and large, have not kept pace with this oceanographic revolution, and the question I think we should address here is, should chemists turn their attention to this sort of problem, and if so, how should we proceed?

OPENING REMARKS

Richard S. Stevens
Office of Naval Research

Several months ago, I had a fascinating discussion with an investigator about the research he was conducting in the region of the shelf/slope water front off the New England coast. From XBT, CTD, satellite imagery, and high-frequency acoustic observations, he was able to discern oceanic features such as the interleaving of cold shelf water and warm slope water in the region of the front, internal waves, internal wave bores impinging on the front, and resuspension of sediments in the bottom boundary layer.

It appeared that he had an excellent data base, except for short time-scale and short space-scale chemical and biological data. These are the types of data that one can acquire with an efficient underway water sampling system, which, as you know, is the subject of this two-day seminar and workshops.

The first session this morning consists of five presentations. The first three will concentrate on the capabilities and problem areas of present-day underway sampling systems, as well as requirements for future systems; the remaining two will cover the hydrodynamics of towing and pumping systems technology.

These five presentations will provide a framework for subsequent papers and the discussions that will take place this afternoon and tomorrow.

CONTINUOUS MEASUREMENTS OF INORGANIC SUBSTANCES IN THE OCEAN

Dana R. Kester* and Mary F. Brown**

Three principal points will be made in this paper. First, each time we have increased the resolution of ocean measurements, we have increased our knowledge of ocean processes. Second, continuous sampling analysis systems have given us unique information about chemical distributions in the upper ocean. Third, a versatile pumping system is needed to improve our knowledge of ocean phenomena. Some tentative design requirements for such a sampling system will be presented.

High-Density In Situ Sampling

Much of our information about chemical distributions in the ocean has traditionally been acquired by making observations at standard depths. These generally include spacings in the water column on the order of 10 to 50 meters in the upper couple of hundred meters, then 100-meter intervals, followed by 200-meter intervals, and eventually, deep-ocean sampling at 1000-meter intervals.

In the past ten years, there has been an emphasis on increasing the density of sampling for better definition of chemical gradients and the processes associated with them (Spencer, 1972). By increasing the density of sampling, one can resolve maxima and minima in the distributions of chemical parameters and identify new boundaries in the ocean between major water masses, such as the benthic boundary layer and the benthic thermocline (Broecker, et al., 1976; Craig, et al., 1972).

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* Presenter

** Our studies related to in situ oxygen sensor measurements in the ocean and to Gulf Stream rings have been supported by the Office of Naval Research under ONR Contract No. N00014-76C-0226. Our research related to the pumping of wastes in the ocean, which has utilized continuous pumping and analysis systems, has been supported by the Ocean Dumping Division under NOAA Grant NA-79-AA-D-00033. We thank Richard Legeckis of the NOAA National Environmental Satellite Service for providing the color-enhanced image used to produce Figure 4.

In addition to high-density discrete sampling, there has been increased use of continuous in situ sensors. The mechanical BT (bathythermograph) was the first widely used in situ water column sensor. With advances in the field of electronics, the BT was refined to provide the expendable BT (XBT). More sophisticated in situ sensors such as the CTD-O systems now yield measurements with a precision comparable to those of discrete analyses (Lambert, et al., 1973).

Some of the results that can be obtained with in situ sensors are illustrated in Figure 1. This station was located in the Venezuelan Basin of the Caribbean Sea. The temperature profile shows a fairly smooth decrease with depth. The structure of the water masses in this region begins to emerge in the salinity profile. The salinity of the surface waters is diminished by the fresh-water discharge of the Orinoco River. At about 100-200 meters depth a layer of Subtropic Under Water (SUW) is evident as a salinity maximum. The salinity minimum at about 750 meters represents the northwestern extension of Antarctic Intermediate Water (AAIW). In the deep waters, one encounters the relatively homogeneous waters originating in the North Atlantic which spill into the Caribbean basins. The oxygen profile reveals a broad minimum zone from 300 to 900 meters and an especially large gradient at an interface between SUW and AAIW. The detailed character of the oxygen distribution could not have been established by traditional discrete sampling. In some cases, we have observed complex maxima and minima within the main oxygen minimum zone of the ocean (Kester, et al., 1973). Continuous chemical measurements in the ocean are needed to define the gradients that exist, and the gradients that are important in establishing the chemical transport associated with physical mixing and advection.

The sampling system used in our studies of continuous oxygen measurements in the ocean is illustrated in Figure 2. It consists of an STD system for in situ measurements of temperature and salinity with depth, to which a Beckman oxygen sensor has been added. An electronic rosette sampler allows collection of up to 12 five-liter samples on command.

A second application of in situ sensors has been in the investigation of Gulf Stream rings, which are bodies of water that spin off from meanders in the Gulf Stream. This phenomenon is illustrated in Figure 3. The top portion of this figure shows, in sequence, the Gulf Stream, the meander, and a ring. The center part illustrates the structure of the waters associated with these rings. There is a large contrast between the water inside the ring (in this case, from the Sargasso Sea),

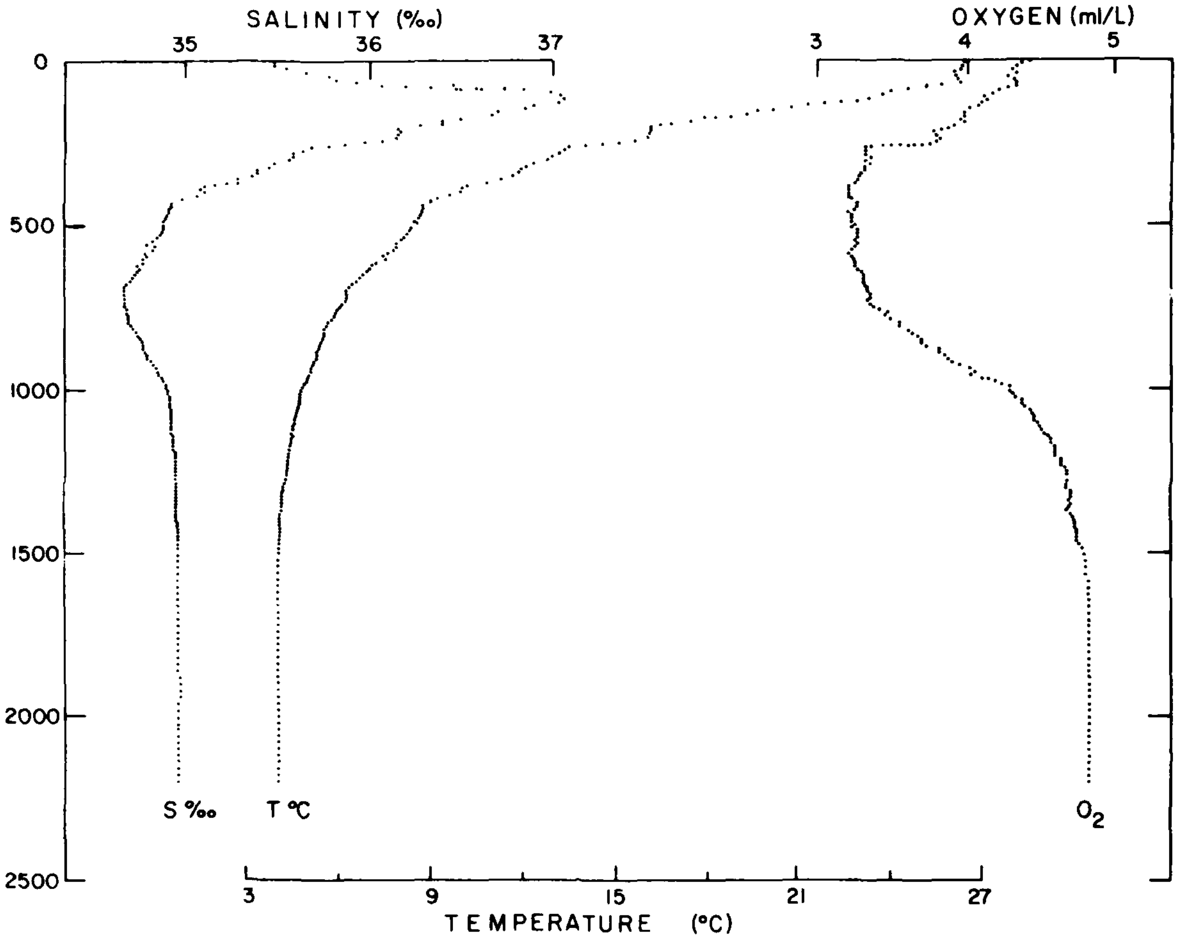

Figure 1 Profiles of salinity, temperature, and oxygen, based on continuous <u>in situ</u> measurements with an STD-O_2 system. This system was located in the Venezuelan Basin of the Caribbean Sea.

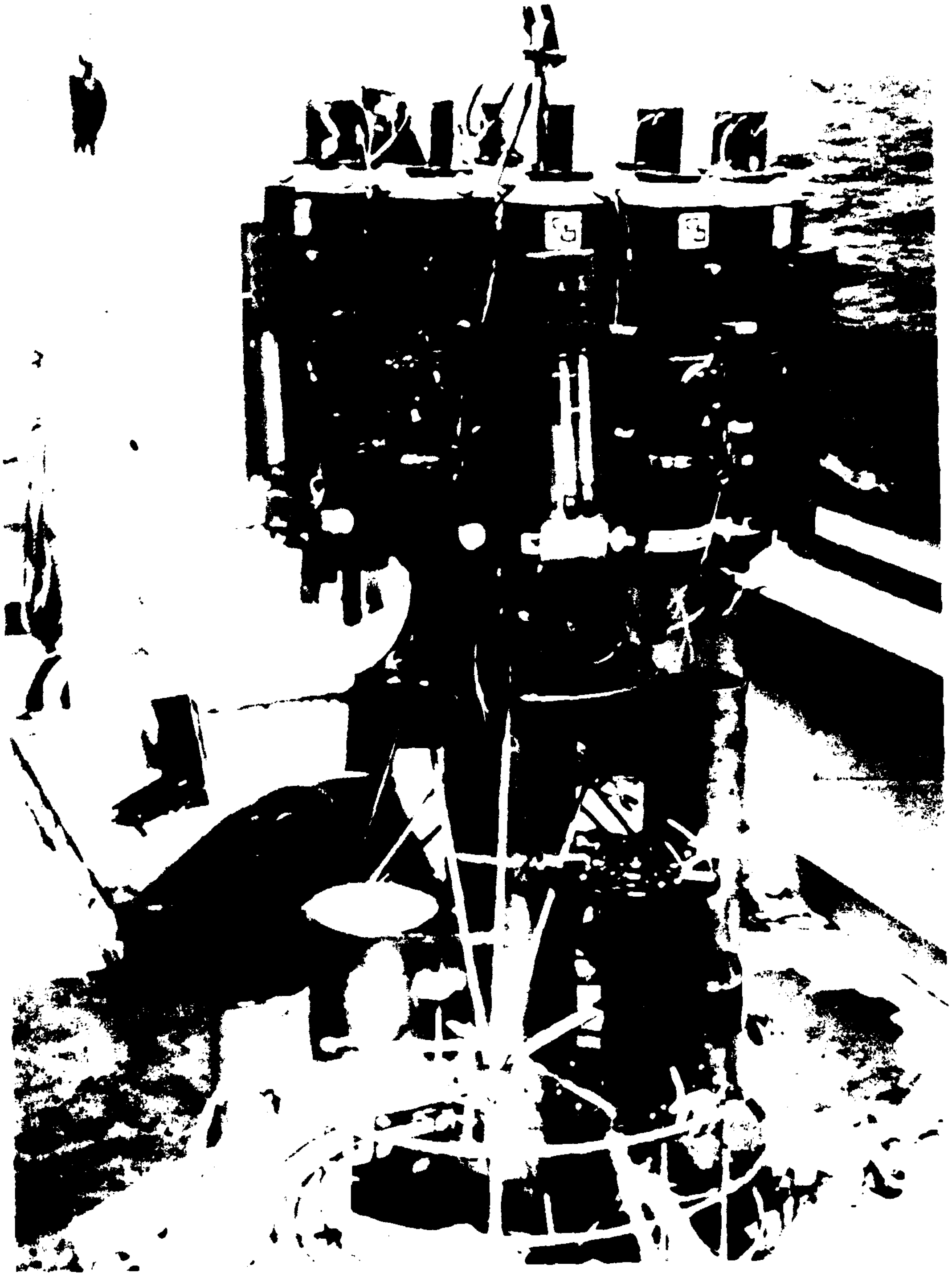

Figure 2 The STD-O_2 system with a 12 five-liter rosette sampling system.

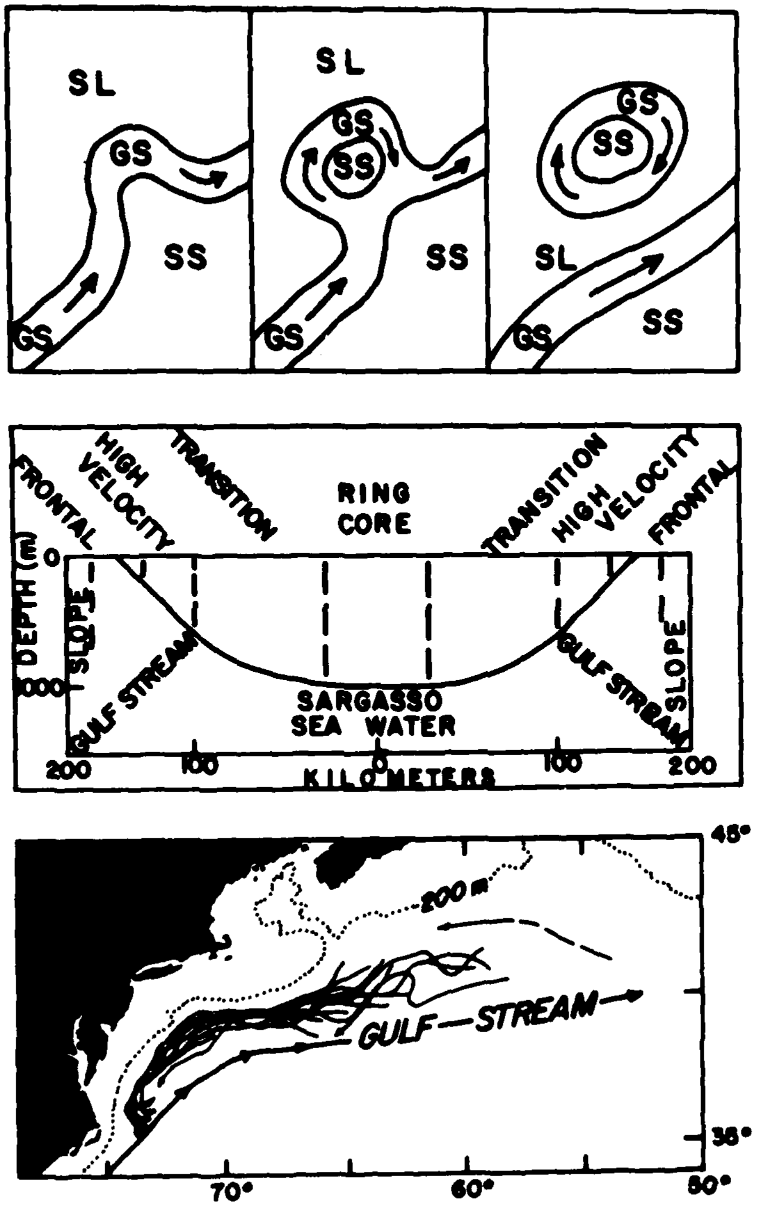

Figure 3 Characteristics of warm core Gulf Stream rings. The upper panel illustrates three stages in the formation of a ring from a meander in the Gulf Stream (GS). The core of the ring traps Sargasso Seawater (SW) and after detachment the ring drifts in the Slope Water (SL) region. The center panel represents a cross-section of a warm core ring which appears as a lense of warm Sargasso Seawater surrounded by a high-velocity remnant of the Gulf Stream. The lower panel (after Lai and Richardson, 1977) shows trajectories of a large number of warm rings.

and the water surrounding the ring, known as slope water. These differences are evident in physical properties, in chemical distributions, and in biological populations (Backus, et al., 1980). The boundary of the ring represents a continuous frontal zone through which exchange can occur. And finally, the lower illustration is a summary of many of these rings. They migrate for periods of months up to a year through the northwest Atlantic.

Infrared satellite imagery provides a very good indication of variability of surface conditions in examining these features. We received a color rendition of sea-surface temperature from infrared satellite imagery for an area containing a cold-core Gulf Stream ring that we were investigating in April 1977 (Figure 4). The distribution and variation of temperature at the surface is evident: warm, intermediate, and cold waters, and the Gulf Stream are clearly shown (in striking contrast in the color-enhanced version of this image).

This variability at the surface is also evident from distributions within the water column around the boundary of one of these rings. Temperature, salinity, and oxygen profiles taken near the edge of a Gulf Stream ring generally show an interleaving of waters of different properties. The gradients that are associated with this phenomenon are very large, and could not be determined by discrete sampling.

Discrete samples were collected for other chemical measurements, to complement measurements of the parameters for which we have sensors. These are illustrated by the example in Figure 5. On the left side is the distribution of nitrate through the water column in the center of the ring. On the right side is the distribution in the surrounding Sargasso Sea. While there are large differences in the nitrate profiles, discrete sampling probably does not reveal the true gradients or distribution in this system.

Our experience with in situ sensors, as summarized in the foregoing examples, can be briefly stated: There are chemical gradients in the ocean that can be understood only by continuous measurements. In situ sensors are available or feasible for measurements of temperature, salinity, pressure, oxygen, pH, suspended materials (by light scattering), and chlorophyll (by fluorescence).

In situ sensors are not available, and are not likely to be developed in the next several years, for chemical measurements of various dissolved gases, nutrients, trace metals, organic substances, and radionuclides.

Figure 4 This satellite-produced image of sea-surface temperature is based on a NOAA-5 color-enhanced very high resolution radiometer (VHRR #3192) photograph. The U.S. coastline is evident from the mouth of Chesapeake Bay to Long Island. The image was obtained at 1400 GMT, 13 April 1977. The medium-gray band extending from the middle of the lower edge to the upper-middle of the right edge is the Gulf Stream. The light gray elliptical feature to the right of the Gulf Stream is cold core ring "Bob" which was being investigated by the Research Vessel KNORR at the time this image was obtained (see Backus, et al., 1980 for more details). The nearly white region north of the Gulf Stream is a warm core ring.

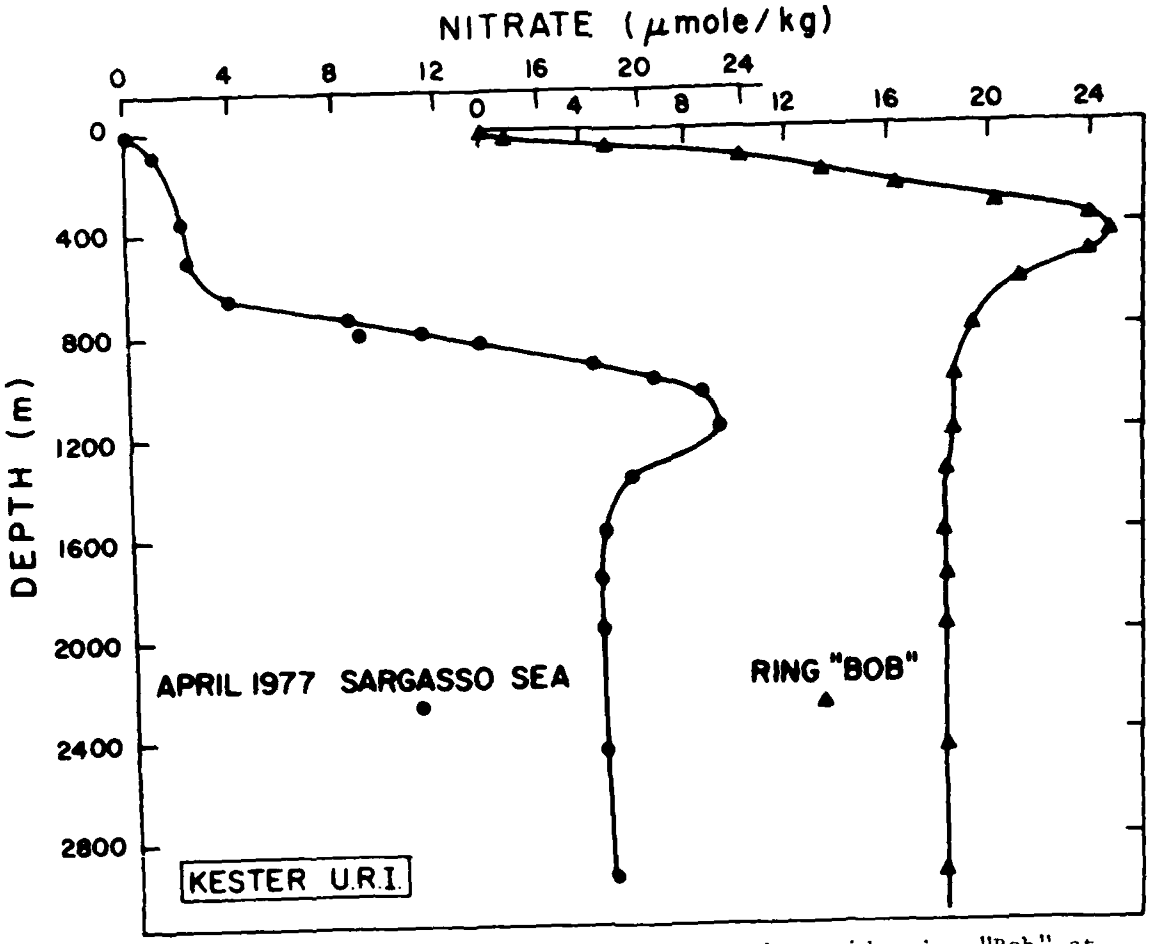

Figure 5 Vertical profiles of nitrate inside and outside ring "Bob" at the time when the image in Figure 4 was obtained. The large differences in nitrate concentrations in the upper 1200 m imply large horizontal gradients across the ring.

Continuous Sampling and Chemical Analysis in the Ocean

If knowledge of the continuous distribution of these constituents in the ocean is to be increased, a pumping system or continuous sampling system must be considered. During the past couple of years, we have been involved in a research program in which this need became acutely apparent. The program addresses the behavior of industrial wastes discharged into the surface waters at a particular location (Deepwater Dumpsite 106) off the coast of New Jersey and the continental shelf, south of the Hudson Canyon.

Several times a week, a barge with four million liters of liquid wastes steams to this site and discharges the material in the ocean. The particular waste we have been investigating is about 0.5 molar hydrochloric acid and 0.5 molar ferric chloride. When this waste mixes with seawater, a precipitate is formed that produces the discoloration of the surface water evident in the wake of this barge (Figure 6).

There are several ways we can view this event. It can provide an analogue to a chemical disturbance left by the wake of a moving vessel; we can consider it a chemical plume associated with a frontal region of the ocean, or it can represent a large-scale chemical experiment in which the scavenging of material by hydrous ferric oxide can be investigated. Finally, we can consider it an opportunity to study the effect of a particular set of chemicals on the oceanic ecosystem. The future management of waste disposal in the ocean requires a better understanding of the impact of these wastes on the marine environment.

Our initial approach to studying and sampling these chemical plumes consisted of using a pump that was guided by acoustic scattering, and positioning that sampling device in the plume to collect discrete samples. The samples were selected on the basis of maximum scattering of acoustic energy from the particles that are formed. They were then returned to the laboratory and analyzed.

The results are shown in the set of profiles or vertical samples from the upper 20 meters given in Figure 7. The main observation that can be made is that the concentration of iron being measured decreases significantly during the first 20 hours of measurement. Immediately after dumping, the samples show several thousand parts per billion or micrograms per kilogram of iron. After four hours, the concentrations are reduced to hundreds of micrograms per kilogram, and after 10 to 20 hours,

Figure 6 Looking down the wake of a tug and barge discharging acid-iron waste into surface waters at Deepwater Dumpsite 106. The discoloration of the water is due to the suspended hydrous iron oxide floc which precipitates upon mixing of the waste with seawater.

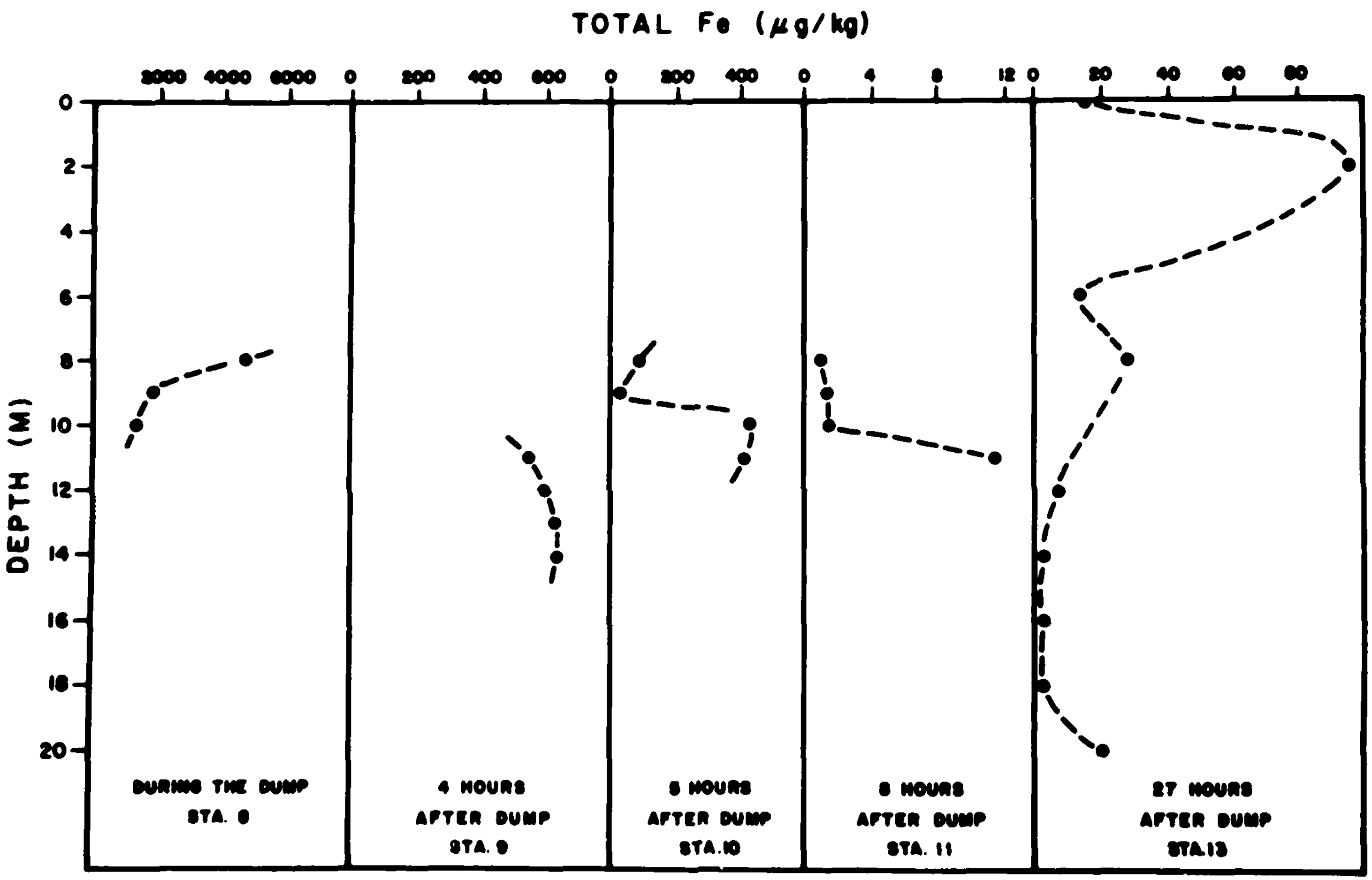

Figure 7 Iron concentrations in the upper 20 meters of a waste plume up to 27 hours after a dump of acid-iron waste. The samples from 0-8 hours after the dump were collected from 3 or 4 ports of a multiple-port pump system with 1 meter spacing built by M. Orr and C. Winget at Woods Hole Oceanographic Institution. The 27-hour samples were collected with a rosette sampler.

they are on the order of tens of micrograms per kilogram. Beyond the general observation, distributions cannot be determined from this type of sampling. We cannot tell how thick the layer of iron is, nor what the gradients are.

Perhaps the best way to look at these data is to plot the observed concentrations as a function of time, irrespective of depth. The resulting distribution suggests that two processes occur in this event. The first is rapid dilution of the material, largely attributable to the turbulence behind the barge, in the first several hours. After about four hours of mixing, one sees dispersion to a width of several hundred meters, with very distinct boundaries. Oceanic mixing further disperses the plume. The second process occurs very slowly: during our observations, the concentrations persisted up to 30 hours, and the concentration of iron was still two orders of magnitude above the background level (Kester, et al., 1980).

To define the actual distributions of these plumes with better resolution requires a pumping system to collect the samples, and an onboard analysis system to make continuous chemical measurements (Brown and Kester, 1980). During the past year, we have conducted two experiments using a pumping system developed by Orr and Winget at Woods Hole Oceanographic Institution (which is to be described more fully in the paper by Marshall Orr). The pumps are housed in a torpedo body and are towed behind the vessel. The system can sample at six different depths. Teflon tubing conducts the sample onto the ship. We used two ports to pump samples through instruments aboard the ship.

A second system was also used for continuous measurements (in September 1979). This system, developed by the National Oceanic and Atmospheric Administration, will be described in a subsequent paper.

The system is towed off the side of the ship, providing samples for continuous analysis. A laboratory was set up aboard ship to measure two properties: iron, by a colorimetric method using continuous flow analysis, and particle-size distributions, using an optical light blockage technique. The two instruments are shown in a chemical van in Figure 8. The continuous-flow analysis system brings the sample from the pump, combines it with reagents to produce a colored reaction, and subjects it to quantitative measurements. The particle counter allows a stream to flow through a light beam. As the light beam is interrupted by particles, the decrease in light intensity is scaled and counted, yielding a particle-size distribution over a range of about 1 to 100 micrometers.

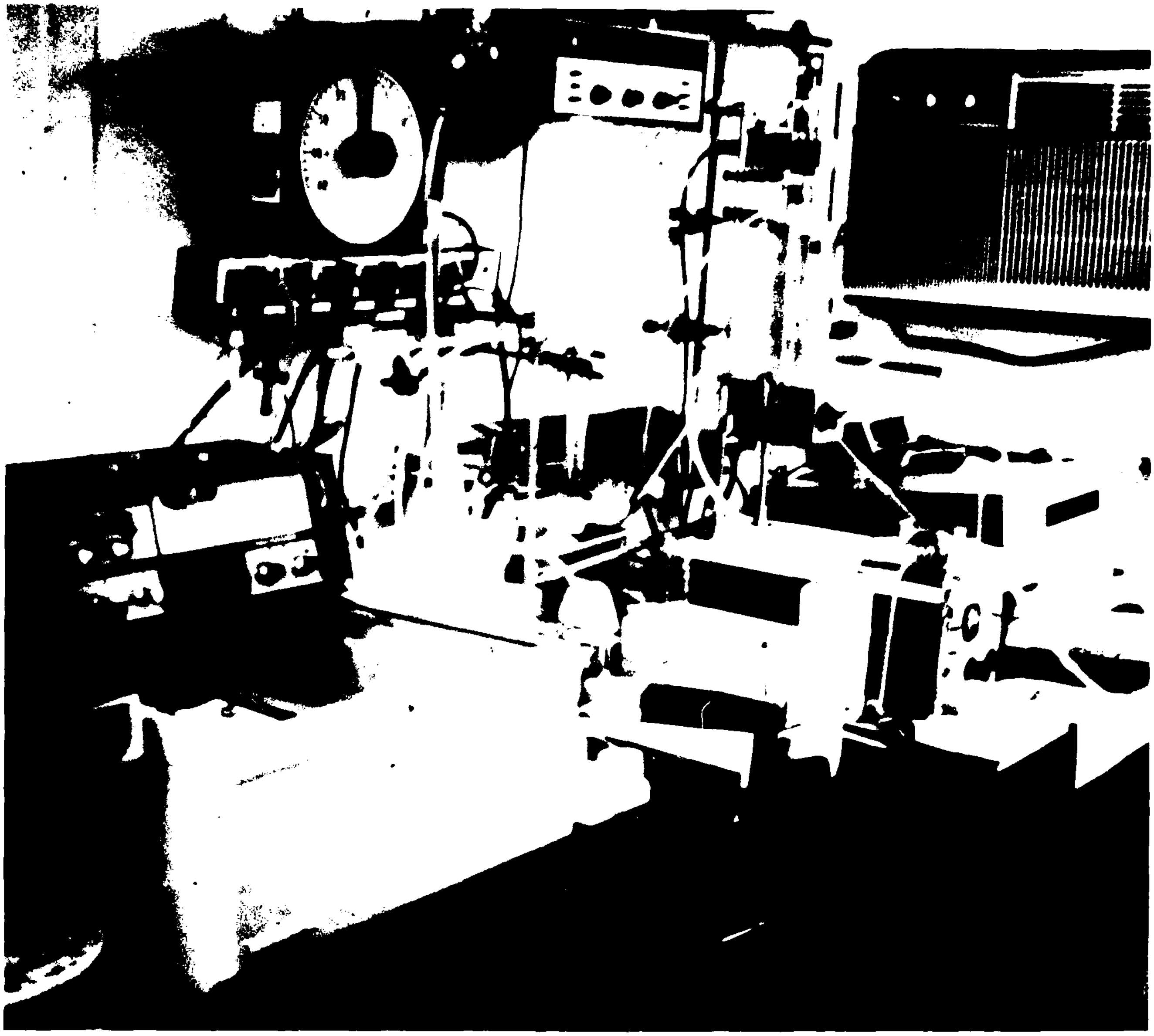

Figure 8 Chemical van aboard the NOAA ship MOUNT MITCHELL. Analyses were performed on-line with a pumping system to provide nearly real-time measurements of iron by continuous flow analysis (CFA) and particle-size distribution. From left to right on the lab bench are the CFA instrument for iron, the predigestion chamber, and the HIAC particle counter. A pH meter suspended from overhead monitored the effluent of the predigestion chamber.

The analytical system for the iron measurements requires that the iron particles be dissolved prior to reaction with the chemical reagents. This was accomplished prior to reaction by a predigestion chamber in which water was brought in, acidified to a pH of 1 to accelerate dissolution in an ultrasonic bath, and heated to about 80 degrees (Figure 9). The water is then drawn into the continuous-flow analyzer. The continuous-flow analysis consists of reagent addition, buffering to an optimum analysis pH, and passing the sample through a colorimeter where light absorption is measured.

The results obtained from the measurements are illustrated in Figure 10 for a series of crossings of two plumes which were laid down in the shape of a "U." The crossings occurred at the times indicated in Figure 10, between 0.5 to 4.25 hours after the dump.

Several observations can be made from the distribution illustrated. The first is that very good documentation can be obtained of the maximum chemical signal and the changes that occur with time. In this experiment, for example, the two plumes appear to converge with time. Crossings at a later time indicated that the maximum concentration persists, and is reduced only by about 25 percent in 10 hours.

In a second experiment (conducted with the NOAA pump system), we mapped iron concentrations from samples taken at various intervals of time (Figure 11). The plume is narrower, and the peak values are considerably higher. The values at a half hour were obtained as the ship steamed from east to west (represented from left to right in the diagram) and those for the 1.25 hour interval were obtained as the ship steamed in the opposite direction. These have been adjusted for the same orientation. A skewness is evident in the distribution, which appears to be an artifact of the sampling. At this point, we do not entirely understand it: a simple analysis would suggest that entrainment should erode the leading edge as well as extend the trailing edge.

After 11 hours, the plume has dispersed to the distribution seen in Figure 12, and in this case we think that the skewness is real, as the time scales are longer in width.

One application for data of this type, in addition to verifying the actual gradients that exist, and establishing a basis for sampling other chemical parameters, is for modeling the mixing processes by which the dispersion occurs. Csanady (1980), in an analysis of the mixing of plumes, has described the plumes in terms of one of two physical models. One of

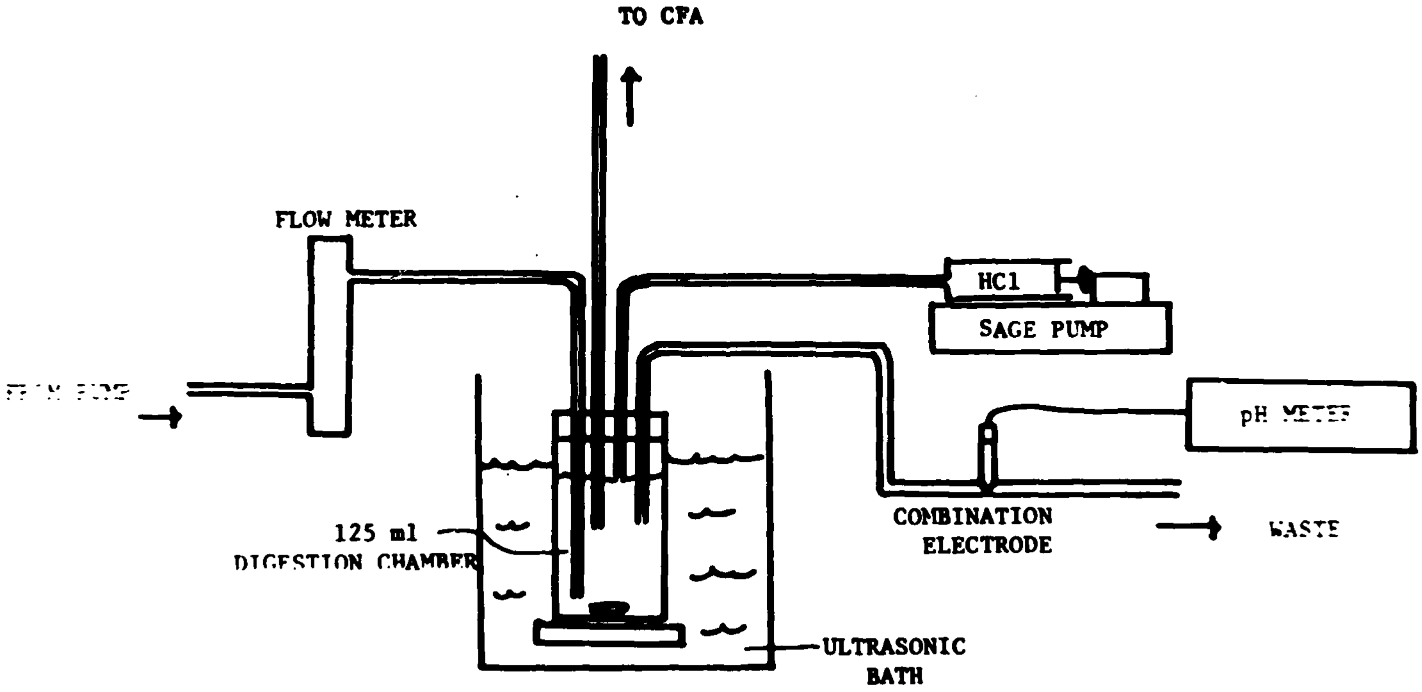

Figure 9 Schematic illustration of the predigestion system used prior to measurement by a continuous flow analysis (CFA) instrument.

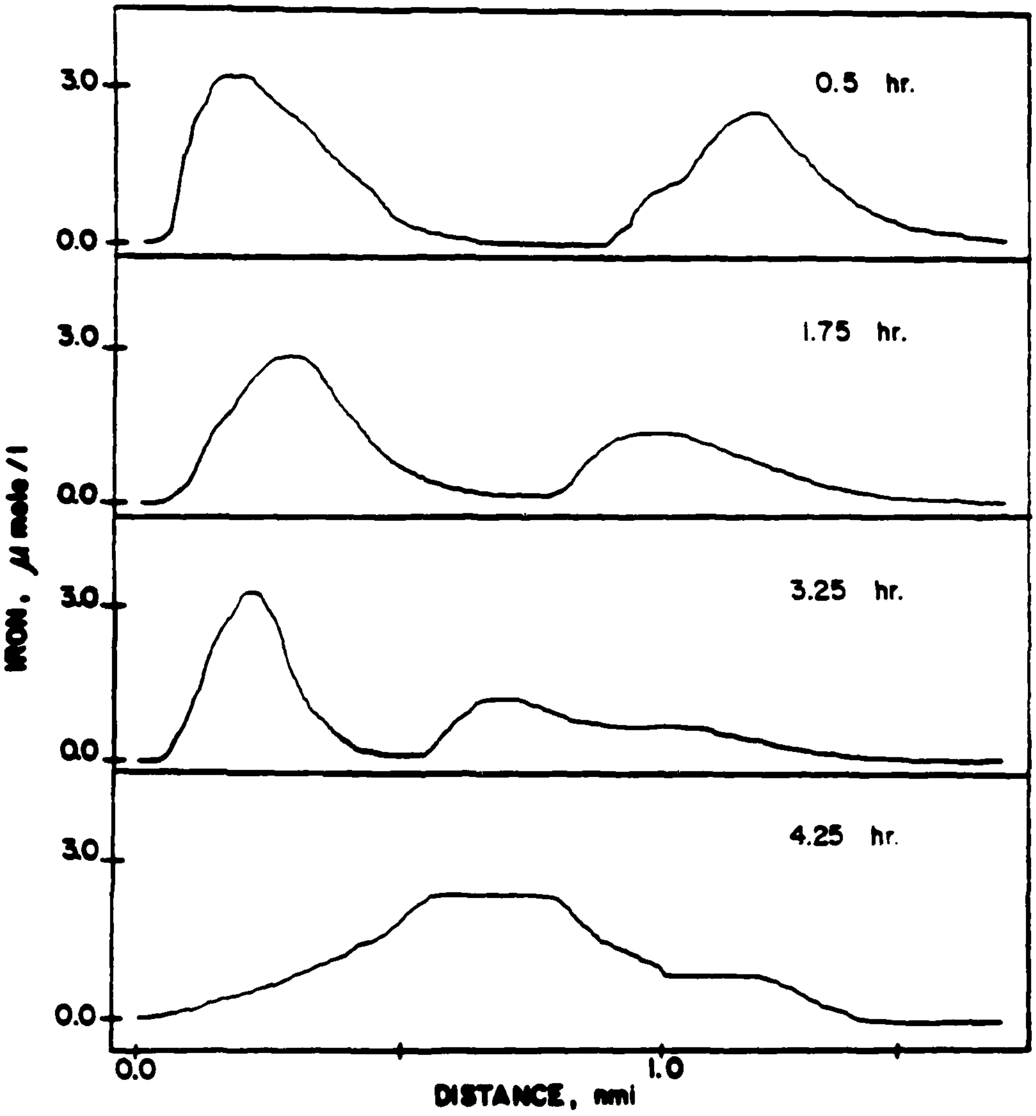

Figure 10 Continuous measurements of iron in seawater as a ship with a towed pumping system steamed across two legs of an acid-iron plume at four times after the waste was dumped in the surface waters. Depth of the pump was 3 meters.

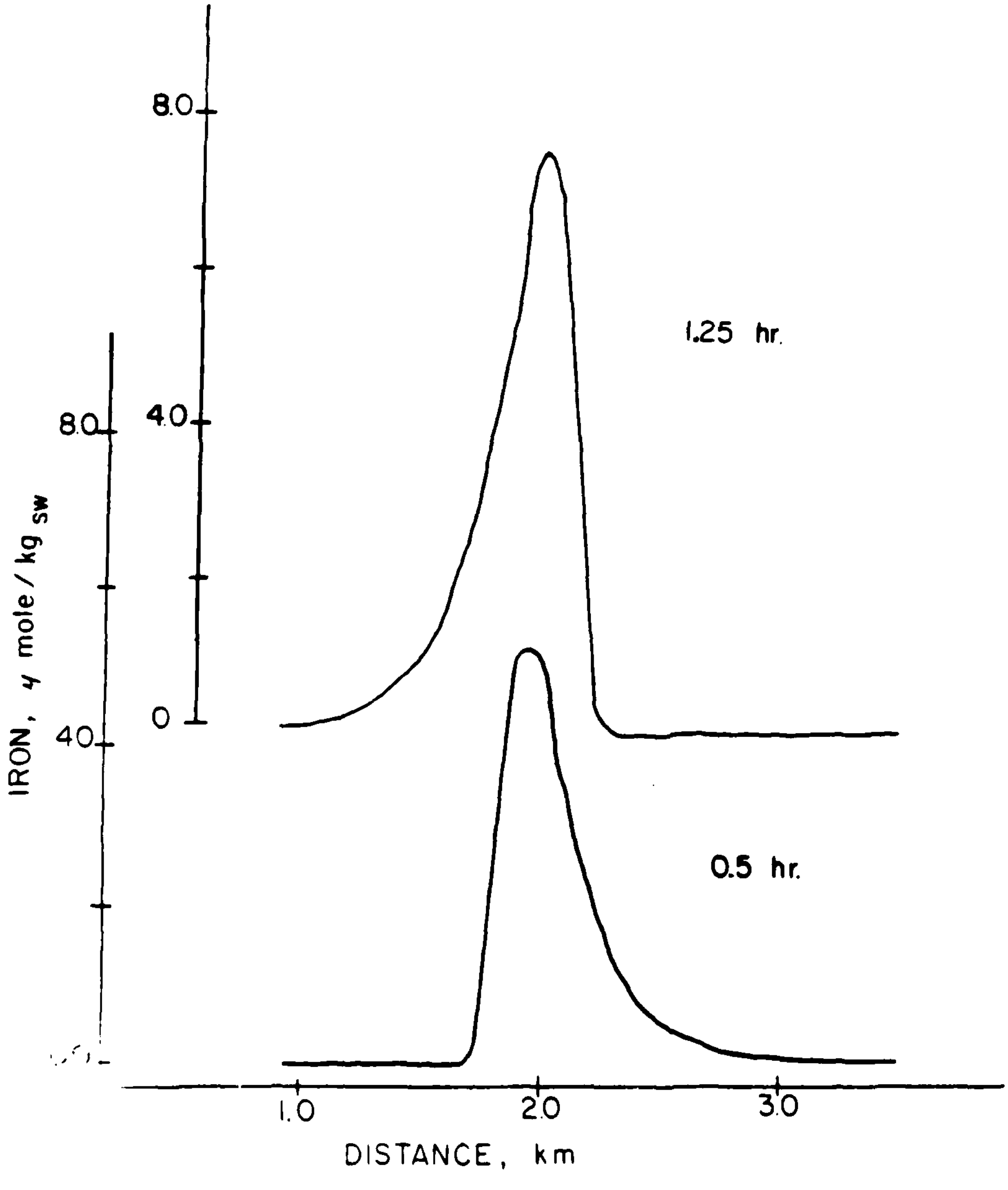

Figure 11 Two crossings of an acid-iron plume 0.5 and 1.25 hours after a dump. Sampling was from 3 meters using the NOAA underway towed pumping system and shipboard continuous flow analysis for iron.

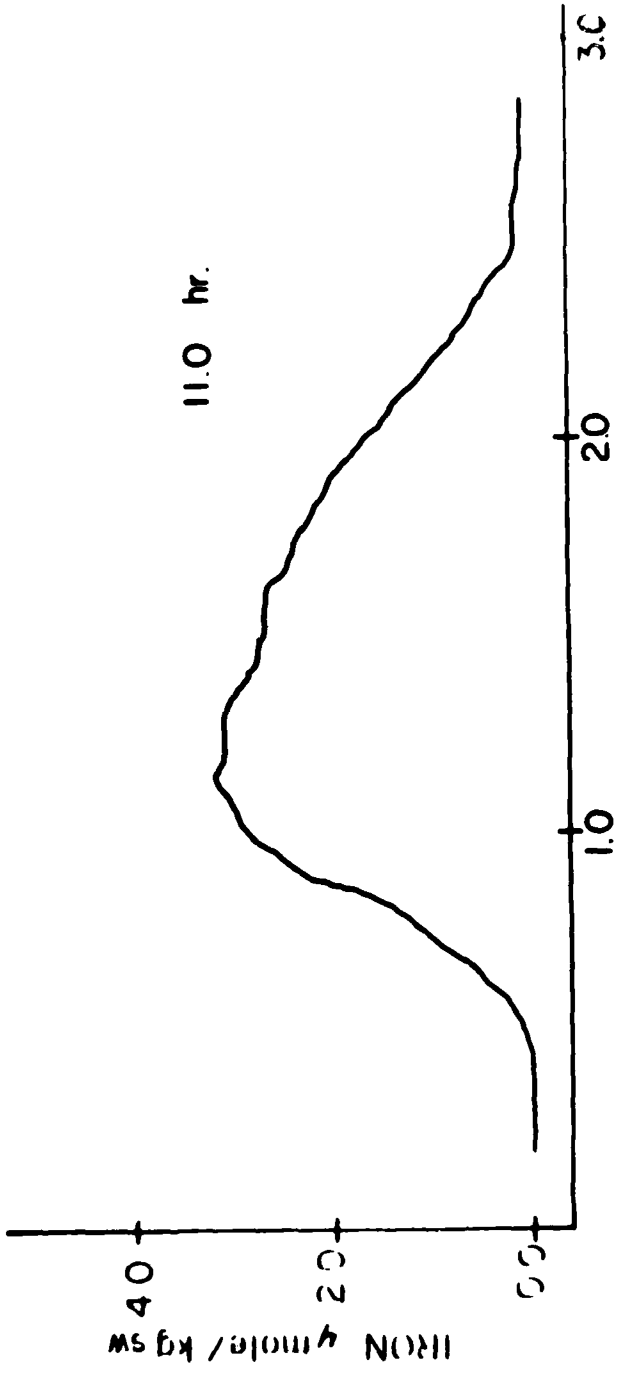

Figure 12 A crossing of the same plume in Figure 11 at 11 hours after the dump.

these models describes the variation in plume width in time in terms of a mixing coefficient. In this case, the plume width should vary as the square root of time. A plot of the three crossings by this model is shown in Figure 13. The results are curved, and we would conclude that the model does not provide a very good description of these data. The second model describes plumes in terms of a dispersion velocity. By this model, the plume width should vary linearly with time. The results (Figure 14) indicate that the dispersion-velocity model is a better description of plume dispersion than a mixing-coefficient model.

In addition to determining the horizontal distributions of these chemical plumes, information can be gained about the vertical distribution of iron and the factors that control it. Figure 15 illustrates the vertical variation in iron and temperature of the waters raised by a pump system positioned at fixed depths, and sampled for about 15 minutes at each interval. We see that the chemical plume is restricted to the waters above the thermocline. The use of the thermocline represents a floor to these distributions of iron.

A more detailed view of the iron distribution can be seen in the three profiles of Figure 16. The pump was allowed to fall through the plume, and the analysis was carried out continuously. The data, iron versus time and depth versus time, were replotted as iron versus depth. The profiles indicate that the plume is confined to the waters above the thermocline, as also indicated by the measurements plotted in Figure 15. There is significant variability among these three profiles. They were taken over a one-half-hour period in which the pump was lowered, brought back to the surface, lowered, brought back to the surface, and lowered again. They show considerable variability within the plume, and in the vertical distributions over these fairly short time scales and space scales.

Not only is this variation evident in the chemical measurements, but it can also be seen in the profiles of temperatures taken at the same time. In the second profile, we find that there is a change in the waters beneath about 20 meters. In this case, cold water overlay warm water, and a halocline stabilized the water column.

Desirable Characteristics of Pumped Sampling Systems

Based on these experiences, we can project the characteristics of a versatile pumping system. We would like to be able to sample from about half a meter to 200 meters to characterize the upper ocean. It would be useful to sample

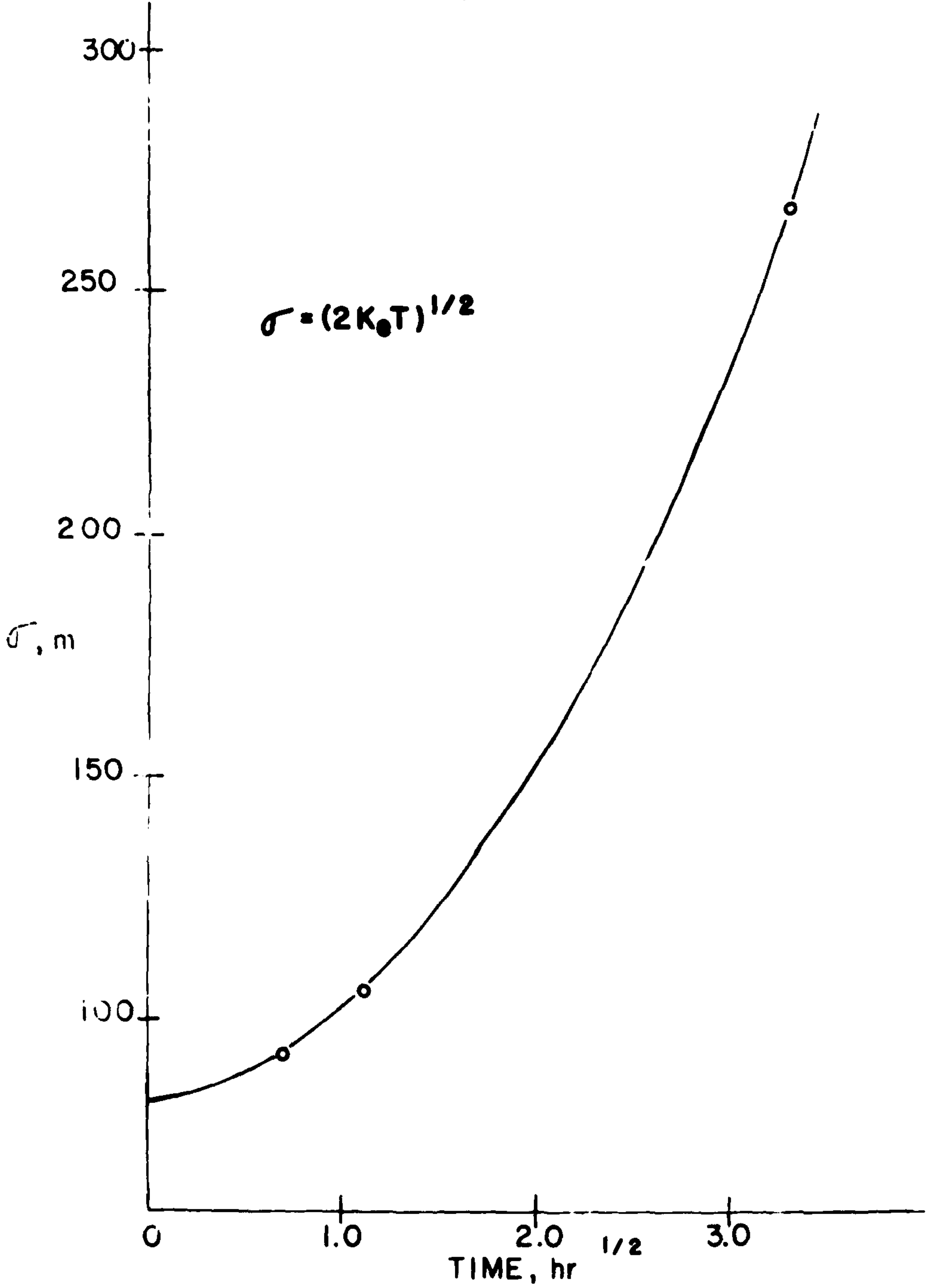

Figure 13 A plot of plume width, σ, versus $t^{1/2}$ for the plume crossings in Figures 11 and 12. The non-linearity of these values indicates that a dispersion model based on a constant K_e is a poor description of the plume mixing during the first 11 hours.

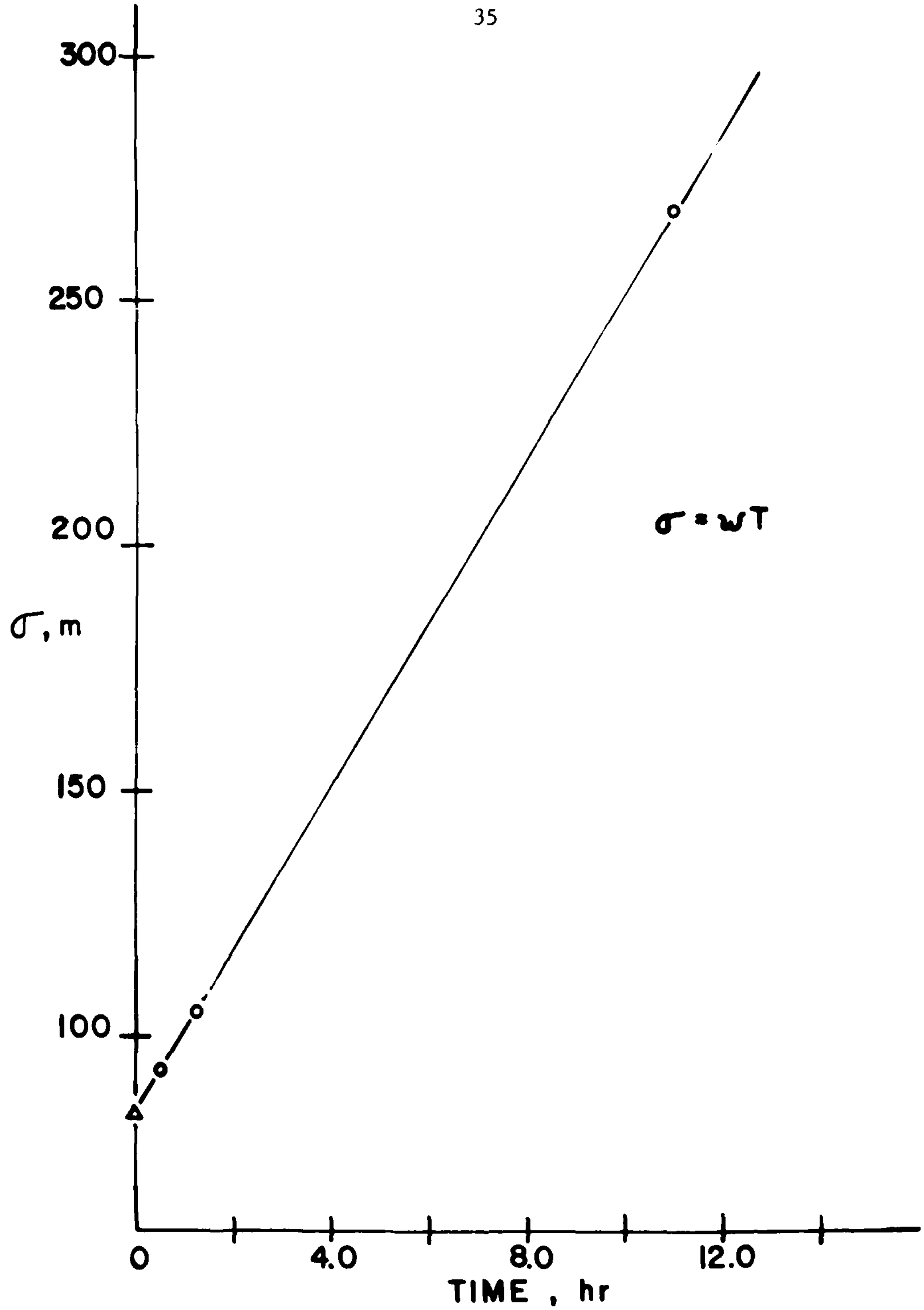

Figure 14 A plot of plume width, σ, versus time. A constant dispersion velocity, ω, provides a good fit to the observations in Figures 11 and 12.

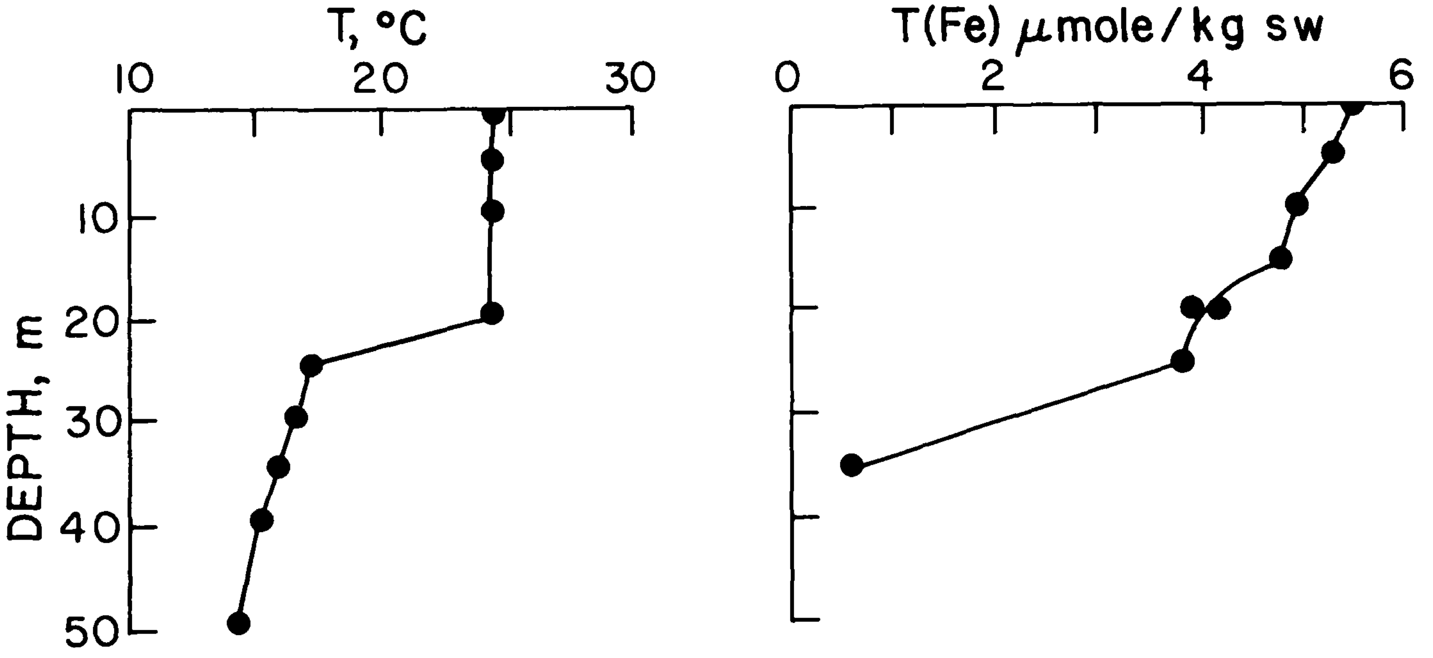

Figure 15 The vertical distribution of iron and temperature obtained with the NOAA pumping system by towing at each depth from 1 to 50 meters while steaming along the axis of an acid-iron plume.

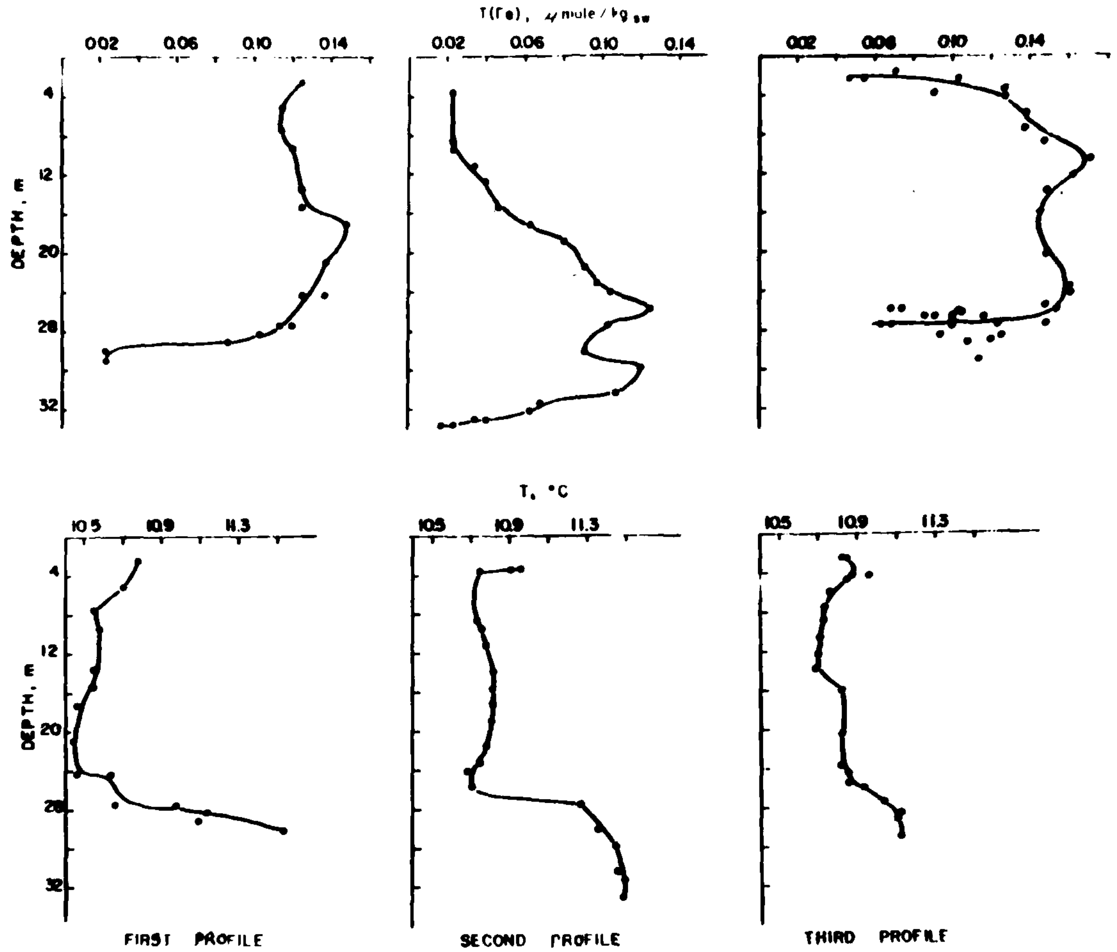

Figure 16 Three vertical profiles of iron and temperature in an acid-iron plume 53 hours after a dump. The WHOI pump was "yoyo-ed" from 3 to 30 meters by decreasing and increasing the ship speed in the plume.

deeper than this, but it is likely that there is a practical limit to the depths from which we can expect to pump and get good resolution.

For the space scales that we have seen, it would be useful to be able to tow the system at speeds between 0 and 5 knots. We would like to be able to do some work at a complete stop and tow at speeds up to about 5 knots.

For many chemical measurements, we need approximately two liters per minute of sample. A pressure head of about 25 psi at that delivery rate would be useful for most applications. This would allow a 30-foot head above the waterline and a 10 psi operating head to carry out filtration or passage through instruments.

Teflon is the best tubing material for sampling inorganic substances. In our evaluation of the Woods Hole pumping system, we found we could obtain cleaner samples for trace metals from the all-Teflon pumps and tubing than from conventional water sampling bottles (Kester, et al., 1980).

The system should be equipped with sensors at the intake for pressure, temperature, salinity, oxygen, and probably fluorescence for biological parameters.

Summary

Chemical variability exists in the upper ocean that can only be seen with continuous measurements. For some properties, these continuous measurements can be made by _in situ_ sensors. However, to extend the range of chemical measurements, continuous sampling and continuous shipboard analysis will be required.

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DISCUSSION

SIMPSON: I agree with you about the mixing-coefficient model, but I am surprised that Dr. Csanady did not look at the turbulence; that is, correlations of velocity with the signal--such as a horizontal component of velocity with the component of the iron signal--to get turbulent correlations for the velocity fields. You would make no assumptions about how the mixing takes place, but treat it statistically, and that might give you an unbiased model.

My other question: I have seen in the literature that for copper analysis you add a lot of acid. For general oceanic applications, I would think you would want to be able to differentiate between the amount of copper or iron that is free and that which is tied up organically. I am wondering if adding all this acid doesn't tend to mix these together. How do you, in fact, separate them afterwards, or if you have aggregate measurements only, how do you interpret them?

KESTER: With regard to your first suggestion, I agree that one should have more than just chemical data in these systems. If the chemical measurements can be coupled to corresponding physical measurements, much better analysis is possible of the resulting data. This has been done in some cases. In April 1979, Dr. Csanady's investigators measured vertical shear for coupling with these continuous traces. I have not seen the results of the analysis from the experiment.

In terms of the distinction between different chemical forms of the metals, I think this is a very important problem. We are attempting to measure the total content by these methods at the present time. In the future, we will probably want to distinguish different chemical states of the metals, as you have indicated. The first step is to determine the variation in the total chemical concentration, and as the state of the art progresses, to determine the variations in the individual metal species.

FARRINGTON: Could you comment on existing problems with electrodes, and what might be accomplished in the future with regard to *in situ* types of measurements? Electromechanical techniques are used quite extensively in the laboratory, but there are problems with seawater. They are among the techniques that would be amenable to some profile systems, if we could resolve the problems.

KESTER: Two basic electrode approaches can be used. One is potentiometric, in which an electrode is used for direct measurement of a particular constituent. The pH electrode is a good example of this type, and it can be used _in situ_. The performance exhibited by the fluoride electrode in seawater is also satisfactory for _in situ_ measurements.

Beyond these, I do not think any of the other electrodes perform sufficiently well in seawater to be usable. Work has been done with a copper electrode that exhibits two limitations. The amount of copper in seawater is below the limit for good performance with the electrode, and the chloride in seawater produces an interference. One can get an empirical measurement, but I am not certain how one interprets it.

The second approach with electrodes is to use polarographic techniques (anodic stripping voltimetry) and this also has potential future applications. There is uncertainty in how one interprets the measurements given by polarographic electrodes: only a portion of the metal is being sensed, and we are not really sure what portion that is. Artifacts also can occur at the surfaces of the electrodes.

Until the uncertainties are reduced, _in situ_ analysis based on these techniques is premature.

PELLENBARG: Can you comment on the turnaround time? You mentioned a response time in relation to measuring real time.

KESTER: Yes. In the continuous-flow analysis of iron and particle-size distributions, the time to bring the sample from the intake of the pump to the deck was about 3 minutes. The particle counts are essentially instantaneous. They occur within 10 seconds. The continuous-flow analysis of the iron has a delay of about 8 minutes after the sample arrives on deck. In the case of iron, the data were about 11 minutes behind the sampling.

In the case of iron, the predigestion chamber had a mixing time of about one minute, so that represents the limit of that system of spatial resolutions. In some of the early crossings of the plume, if you assume that the actual distribution in the ocean was a step function, the implied smearing time of the analysis is between one and two minutes, and most of that can be attributed to the predigestion chamber for that analysis, indicating very little smearing within the pumping system itself.

GREEN: At what typical depths were you pumping?

KESTER: I meant to mention the depth of those samplings. In most cases, they were between about 3 to 7 meters, except when we were trying to assess the vertical distributions, and then it was down to about 30 meters.

SCHINK: How long was the hose?

KESTER: The Woods Hole pump system had 150 meters of tubing and the NOAA pump had 80 meters.

A NEAR-SURFACE TOWED PUMPING SYSTEM FOR CHEMICAL OCEANOGRAPHY: DESIGN REQUIREMENTS RELATED TO TRACE-GAS ANALYSIS

Frank L. Herr

I would like to speak briefly about what we might be able to accomplish with a towed pumping system for trace-gas analysis. Next, I will describe some efforts at the Naval Research Laboratory (NRL) directed to the design of a towed pumping system, and some requirements for both discrete and continuous sampling for dissolved gases in the ocean. Finally, I will present some general design requirements for a towed pumping system, such as we might find we have at the end of tomorrow's workshops.

I would like to say briefly at the outset that I think the material requirements for gas analysis are not always as stringent as, for example, those for trace-metal analysis. On the other hand, I think that pumping is much more important for gas analysis than it is for analysis of many other trace components.

By way of introduction, I will list three significant sampling problems facing chemical oceanographers. First, we do not have, nor are we likely to have, in situ sensors for most of the advanced chemical analysis that we can contemplate doing in the open ocean in the next five to ten years, particularly laser fluorescence, gas chromatography-mass spectrometry, liquid chromatography-mass spectrometry, or immunoassay analysis, among others. It may be possible to tow Cadillacs behind ships, but in many of these cases, it is just not feasible to have in situ sensors without in situ analysts.

Second, we need a large number of samples for synoptic analysis of frontal systems, and the samples must be closely spaced if the concentration gradients in these areas are to be determined adequately.

Third, we have to use ship time in the most cost-effective manner. Now, there are a number of ways in which we can use ship time cost-effectively. One way is for oceanographers, using a towed pumping system, to take advantage of opportunities to sample during oceanographic expeditions in which chemists are not the primary scientists. Expeditions that do not involve a lot of stopped ship time, such as geophysical expeditions involved in bathymetric surveys, may provide excellent opportunities.

A second aspect of the use of ship time is that in areas prone to foul weather, a towed pumping system is quite capable of obtaining samples without the scientists' worrying whether they can deploy and retrieve the sampling system, CTD, and rosette under adverse weather conditions.

Figure 1 is a reproduction of a remarkable satellite photograph of the Arctic Polar Front between Iceland and the Faeroe Islands, a feature of substantial interest in the last few years. The dark area is the warmer water from the Atlantic mixing with colder surface water of the Norwegian Sea, and we see quite a number of eddies and meanders along the frontal region. This is the only clear shot of the Arctic Polar Front that I have been able to find from NOAA-3 satellite imagery. This particular photograph appeared in Deep-Sea Research.[1] We are particularly interested in this area north of the Faeroe Islands, and it is an area in which I have done some sampling. This front is well known to fishermen in the region for concentrating biological activity. In the last few years, we have seen that the surface water in frontal regions collects trace metals as well.

Figure 2 shows some of the surface-temperature data we have obtained in that region of the Faeroe Islands. It clearly indicates how strong the gradients can be in one of these eddies or meanders. The distance over ground measured by the loran-C is fairly accurate. In the steepest parts of these gradients, in which measurements have been taken continuously, digitized, and then examined in detail, we find temperature changes as great as a degree over a distance of only 50 meters. This gives evidence of very intense mixing and interleaving of water masses at these points.

These gradients are the sorts of features I would particularly like to look at chemically. What we would really like to know, as Dr. Kester said earlier, is to what extent biological activity is concentrating, producing, and consuming material along these gradients. To do this effectively, we have to cross the frontal region many times in a number of different areas. Use of a towed system is, I think, the only way in which we can do this effectively.

A system we started working with at the Naval Research Laboratory is shown in Figure 3. This is an early version of a commercial system by Fathom Oceanology. It works very well for what it was designed to do. The photograph shows almost all the sorts of items for a newly designed pumping system that I think will be discussed here today and tomorrow.

Figure 1 Infrared view of the polar front. VHRIR from NOAA-3 satellite. Date: 22 May 1975. By courtesy of H. Kaminski, Bochum.

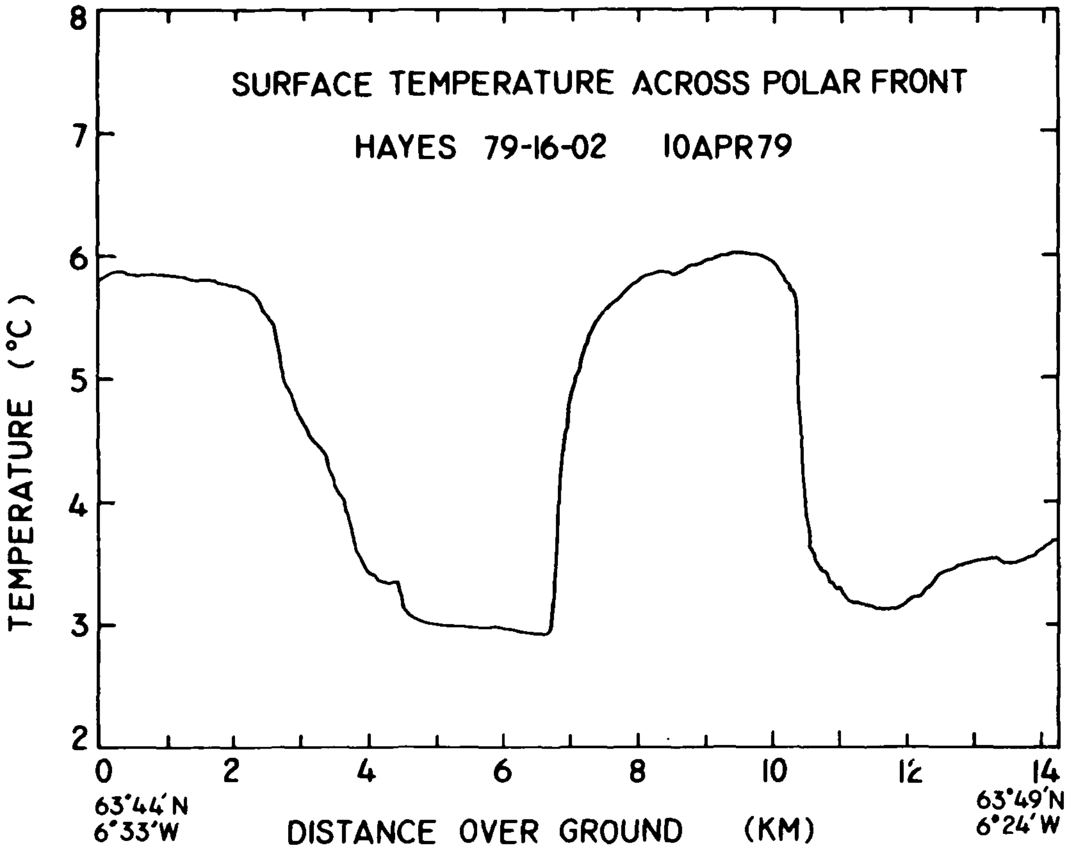

SURFACE TEMPERATURE ACROSS POLAR FRONT
HAYES 79-16-02 10APR79
TEMPERATURE (°C)
8
7
6
5
4
3
2
0
2
4
6
8
10
12
14
63°44′N
6°33′W
63°49′N
6°24′W
DISTANCE OVER GROUND (KM)

Figure 2

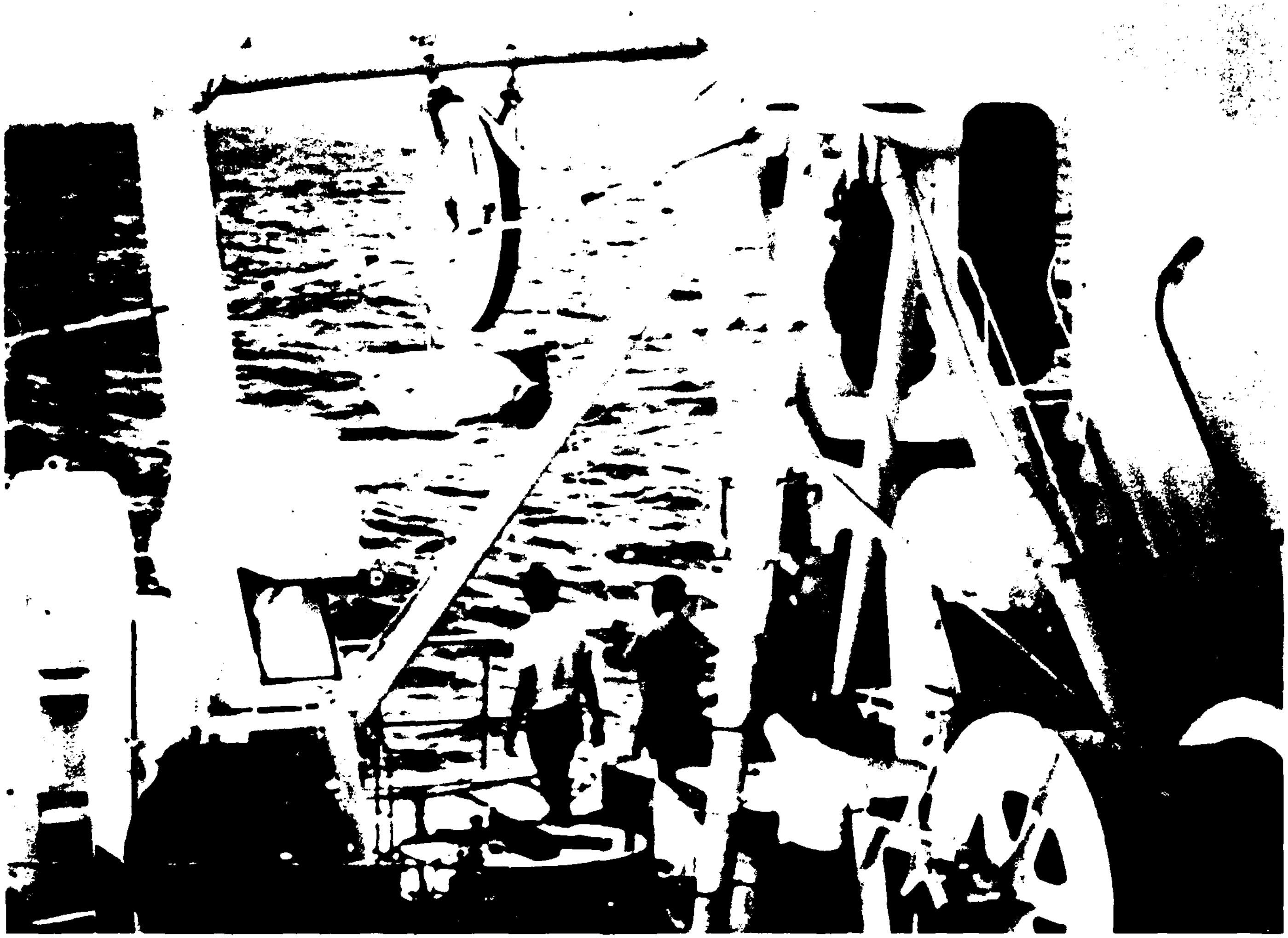


Figure 3 Towed pumping system.

One item we should not overlook is a slip-ring assembly for measurement of in situ electrical signals, so that the depth can be varied while sampling. Suspended from the faired cable is the fish, which is towed alongside our ship, with sensors and a pumping inlet in its nose.

We had some difficulties with this system that led us to think that in fact we needed something much different. One of the difficulties was that it did not pump fast enough. It came with a one-quarter-inch internal-diameter tube, and it delivered 1 liter of seawater per minute. After using this system extensively, we felt there was just too much smearing of the sample in the flow stream at these low flow rates, especially when the flow rate was combined with the one hundred meters of cable needed to achieve the desired depth capability.

The second difficulty we encountered was that the pump was a metal (steel), five-stage, deep-well pump. We found that the pump and its connections were contaminating the samples for some trace metals and for some of the trace gases that we were trying to measure. We attempted to use a metal-less centrifugal pump with only limited success.

The third difficulty was that the conductors in the cable were not sufficiently shielded. Conductors being used for power lines introduced noise spikes into the conductors used for the electrical sensors.

A final difficulty was that we needed to spend quite a bit of time tending to this system in order to keep it towing adequately. We had problems with stacking of fairings, which I hope we get into later on, which severely limited how fast we could tow this system before kiting angles became excessive.

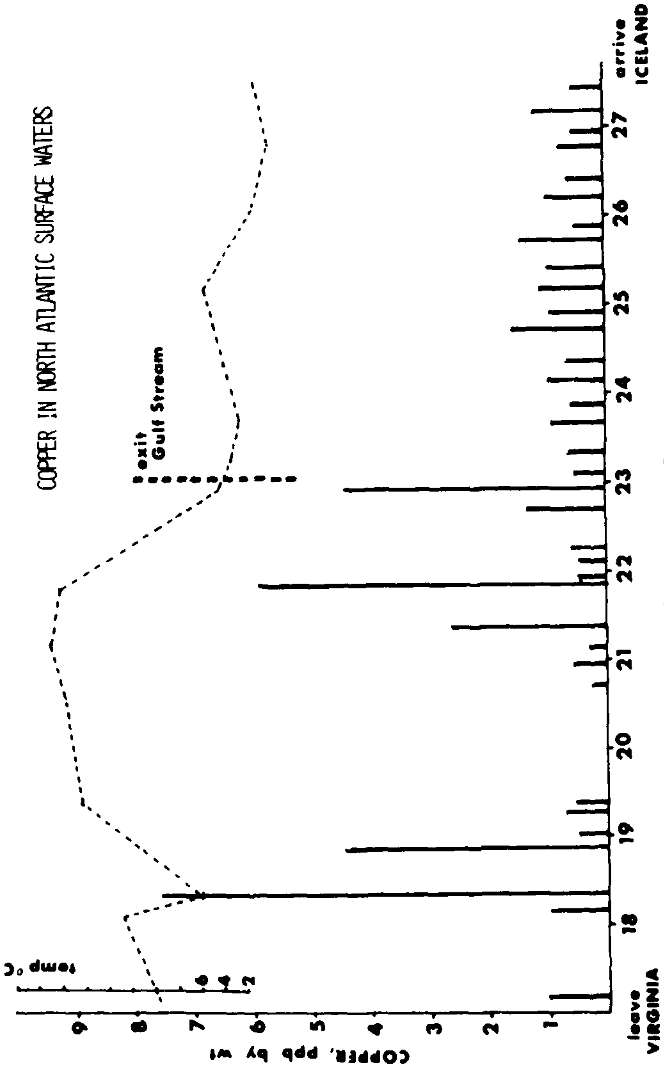
As a result, we stopped working with this system. We simply developed a bow penetration system to look at some surface water effects. This system works extremely well. The inlet is welded to the inboard side of the starboard hull of USNS HAYES, which is a catamaran, and the inlet is about a third of a meter below the hull at the foot of the bow. The inlet is continually exposed to water ahead of the ship, and water is brought aboard without any contamination from the ship. A centrifugal pump samples about seven meters with a suction head of two meters. Then seawater is pumped through a 5-meter head in a 45-meter line back to the laboratories. This system develops easily 22 liters a minute of flow through polyethylene tubing. It has been used for trace-metal analysis. The high rate of pumping, we feel, tends to flush the system well and keeps contaminants at negligible levels. We have also had no difficulty with cavitation in the system, and have therefore used it for trace-gas sampling.

The adequacy of this system can be shown with examples of data that we have taken. These data were taken last spring by my colleague, Robert Pellenbarg, across the Gulf Stream from Norfolk, Virginia, to Iceland. Figure 4 shows copper analyses along the cruise track.

We can see that while the system was only used sparingly every six to eight hours, the collected data show very dramatically how at the edges of some of the features described earlier the trace metals concentrate. Here we see that the copper can be increased by a factor of between seven and ten on the edges of the Gulf Stream, in gradients of temperature, whereas the open-ocean background measurements outside the Gulf Stream are significantly lower.

I think that it is clear that in some areas H_2 concentrations are higher and in some they are lower. Figure 5 pictures our samplings of dissolved hydrogen along the Iceland-Faeroe Islands Ridge. I am not certain whether the areas of higher hydrogen concentrations to the right of Figure 5 are connected with the Polar Front. Unfortunately, the sample spacing, shown as points, was limited by the rate at which two analysts could process the samples. We need to automate our systems to take advantage of more finely scaled sampling.

So much for surface sampling. We have defined some of the areas in which trace metals and gases can be profitably studied. At what depths would we like to see a towed pumping system sample? The study of trace dissolved gases involves air-sea interaction phenomena. Generally, those gases that occur in the atmosphere occur in the ocean as well, unless there is some mechanism causing chemical reactions or biological consumption to occur very quickly at the surface. The distribution of dissolved gases in water below the permanent density gradient in the oceans comes about in the following manner: Atmospheric gases come to equilibrium with surface waters in a couple of areas of the world--one is the Norwegian-Greenland Sea, and another is the Weddell Sea. The process of seasonal mixing and cooling causes dense surface water to be entrained, and carried down below the mixed layer, where the water masses circulate through the intermediate and deep waters of the Atlantic and the Pacific, and have no further contact with the surface and the atmosphere. To describe the behavior of trace gases adequately, we want to be able to measure dissolved gases in the mixed layer, and also to some depth below the mixed layer, thus allowing a description of the changes in concentration that occur between these two very distinct regions.



COPPER IN NORTH ATLANTIC SURFACE WATERS

Figure 4

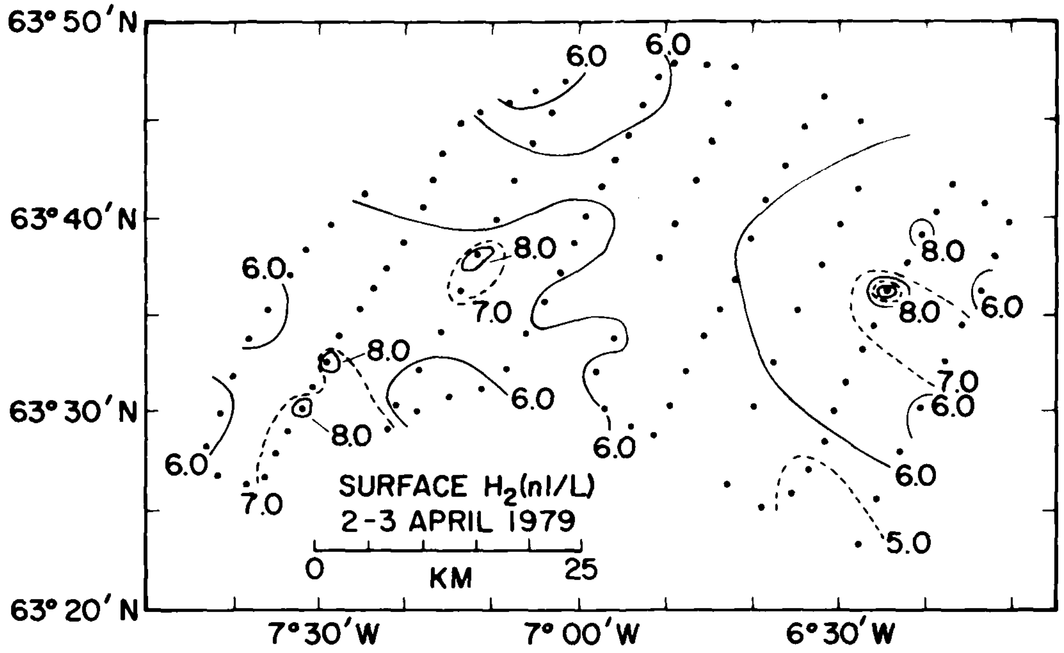


Figure 5 Dissolved hydrogen, Iceland-Faeroe Islands Ridge.

Figure 6 shows seasonal mixed-layer depths in the Sargasso Sea and in the north central Pacific. These curves represent averages for much of the tropical ocean and give us an idea of the depth capability we might need. As Dr. Kester mentioned earlier, 200 meters would appear to be sufficient for adequate description of dissolved trace gases in regions where we could expect to see the majority of interesting phenomena.

Table 1 shows a list of dissolved gases that have been identified and measured.[1] The table sets out the discrete sample size investigators have used, the ambient level in micromoles per liter, precision of the analysis at one standard deviation, and finally, some contamination problems. This is not an exhaustive table of dissolved trace gases.

We see that the order of concentration of the dissolved gases in the ocean starts with nitrogen, oxygen, argon, and carbonate (as total CO_2), at fairly high levels in micromoles per liter. Correspondingly, sample sizes are relatively small, and precision is quite good. There are not many contamination problems with these gases. For oxygen, there could be difficulties with leaks in the systems, and metal corrosion, which would tend to lower the oxygen content. But generally, if the sample concentration is close to equilibrium with the atmosphere around it, leaks would not be a major source of error.

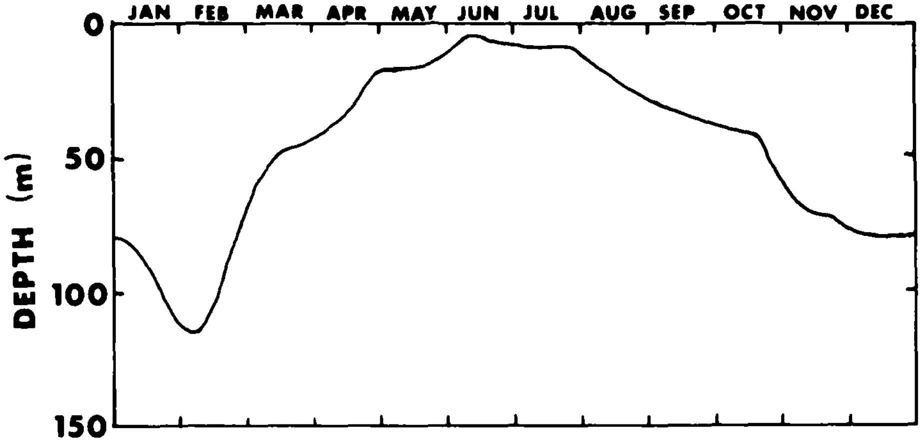
Leaks become more important for other trace gases. We find that as we drop down into the nanomolar region, species such as neon and helium, hydrogen, nitrous oxide, krypton, CO, and xenon would be susceptible to atmospheric exchange. I have found with hydrogen there can be significant corrosion problems. Metal systems can generate relatively large amounts of hydrogen at the nanomolar level, and for gases such as nitrous oxide and carbon monoxide, which are present in much higher levels in the dissolved state than their levels in the atmosphere, leaks can also be a problem.

Permanent atmospheric gases, such as oxygen, carbon monoxide, hydrogen, nitrous oxide, and carbon dioxide, which are all produced and consumed biologically, might be expected to show variations in frontal areas, which tend to congregate biological activity.

Among gaseous hydrocarbons, methane has been mapped extensively in areas such as the Gulf of Mexico by the oil companies. Ethane, ethylene, propane, propylene, and butane all have seen some surface and subsurface mapping. The only serious

SEASONAL MIXED LAYER DEPTHS

SARGASSO SEA



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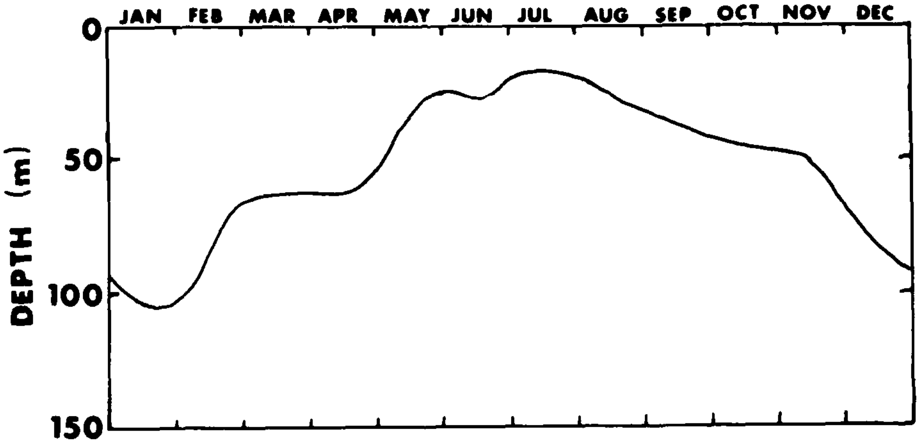


Figure 6

Table 1

DISSOLVED GASES

Gas	Sample Size (L)	Ambient Level (μmol/L)	Precision (% ± 1σ)	Contamination Problems
Permanent Atmospheric Gases				
N_2	0.01	350-620	1	
O_2	0.01	200-300	0.2	LEAKS, METAL CORROSION
Ar	0.01	9-17	1	
ΣCO_2	0.10	2200	0.5	
Ne	1.2	$6\text{-}8 \times 10^{-3}$	2	
^4He	1.2	$1.6\text{-}1.8 \times 10^{-3}$	1	
H_2	1.2	$0.1\text{-}1.3 \times 10^{-3}$	8	ACRYLIC, METAL CORROSION
N_2O	0.12	$5\text{-}10 \times 10^{-3}$	3	LEAKS
Kr	1.2	$2\text{-}3.6 \times 10^{-3}$		
CO	1.2	$0.9\text{-}6 \times 10^{-3}$	3	LEAKS
Xe	1.2	$0.25\text{-}0.5 \times 10^{-3}$		
Gaseous Hydrocarbons				
CH_4	1.2	$1.3\text{-}2 \times 10^{-3}$	2	
ETHANE	1.2	8.9×10^{-6}	5	
ETHYLENE	1.2	$90\text{-}270 \times 10^{-6}$		RUBBER
PROPANE	1.2	13×10^{-6}		
PROPYLENE	1.2	$20\text{-}160 \times 10^{-6}$		
BUTANES	1.2	4×10^{-6}		
Transient Gases				
^{222}Rn	20	$5\text{-}18 \times 10^{-16}$	7	
CCl_3F (F-11)	0.03	2.5×10^{-6}	20	LEAKS
CCl_2F_2 (F-12)	0.03	1.5×10^{-6}		
TRITIUM	1.2	$3\text{-}11 \times 10^{-10}$	4	

contamination problem that I know about with gaseous hydrocarbons is caused by the hydrocarbon-parting agents used in some rubbers, which can generate some contamination from gas-regulator diaphragms, septums, and "O" rings.

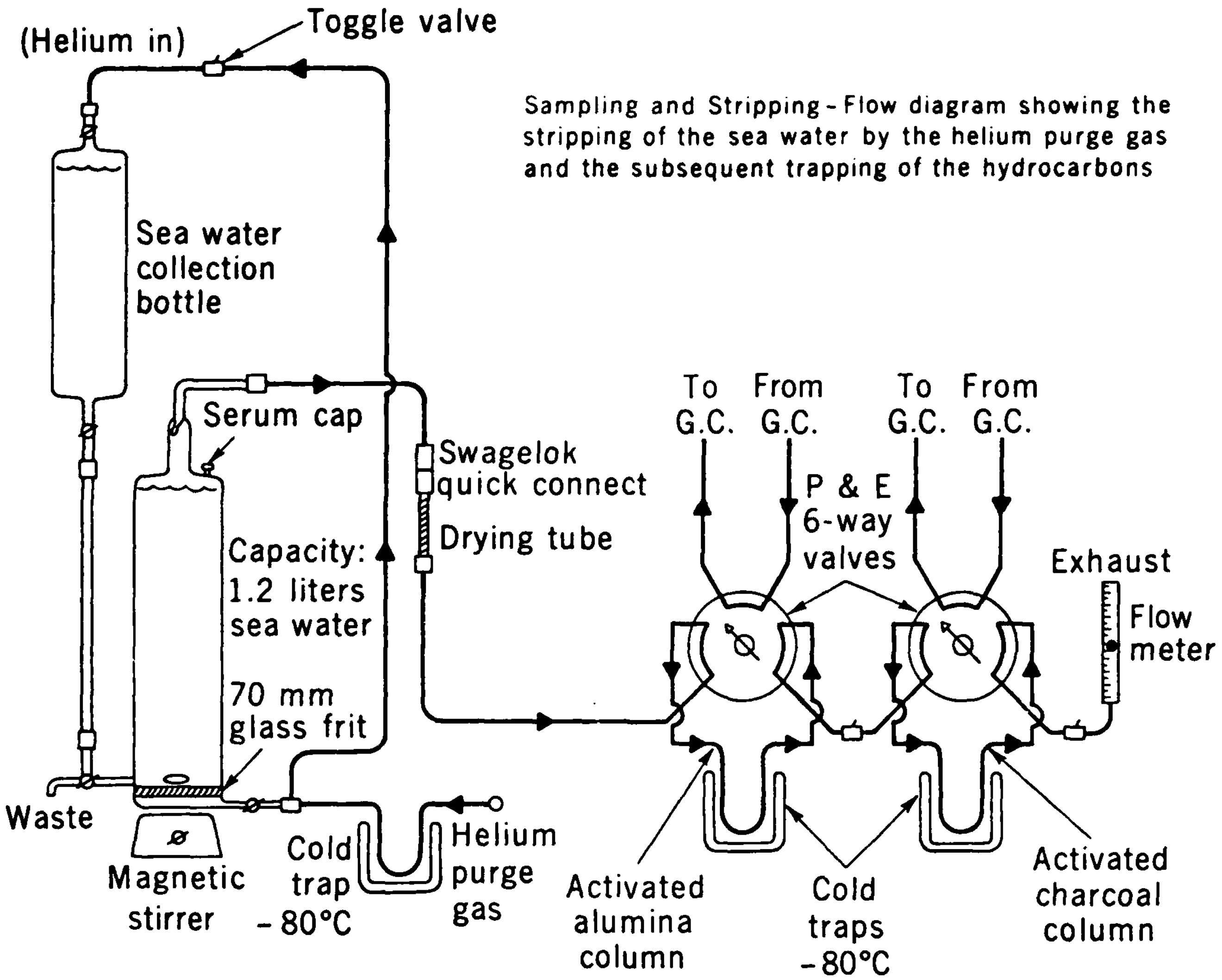
A transient gas that might be interesting to sample with towed pumping is radon-222, which, when compared to its parent radium-226, has been used to gain experimental evidence of rates of efflux of dissolved gases to the atmosphere. Also, Freons 11 and 12 and tritium in H_2O are transient gases introduced into the ocean from varying atmospheric sources. They have been used as ocean circulation tracers in recent years. Investigators studying pycnocline processes might also express some interest in a towed pumping system.

I would like to turn now to the general problem of getting these gases out of the seawater so that they can be measured. This problem is fundamental to the design and use of a trace-gas sampling system, because it bears on the sample volumes needed for analysis, and the basic method of sample collection--discrete or continuous processing. There are a couple of different methods. Figure 7 shows a scheme for stripping a one-liter gas sample with helium. The sample fills the stripping chamber, and then helium is introduced through a porous plate at the bottom. The helium creates a mobile second phase into which the dissolved gases migrate for collection on a molecular sieve trap.

This system can be modified for continuous sampling, in which case it is called countercurrent extraction. The seawater would enter continuously at the top and flow downward in the extraction tower. The helium stripping gas would percolate to the surface countercurrent to the seawater flow, and sample gases would be collected on a trap for a short period of time, and then injected into the gas chromatograph. Much of the work in trace gases has been done in this way, and the purge tower system is extremely well suited for gas chromatography.

Another method which William Barger and I have been experimenting with in our group at NRL allows a larger sample to be used, and, it is to be hoped, a faster turnaround time for some of the trace-gas analyses. In this system, which we have named a seawater headspace equilibrator (shown in Figure 8), we will allow water to flow into a manifold through a flow control valve, and then to distribute itself through a number of Venturi pumps, or simply laboratory aspirator pumps.

The Venturi pumps allow a very intimate mixing of a headspace gas with the water flowing constantly through them. The flow of seawater could be about four liters a minute (a gallon a minute)



Sampling and Stripping - Flow diagram showing the stripping of the sea water by the helium purge gas and the subsequent trapping of the hydrocarbons

Figure 7

SEAWATER HEADSPACE
EQUILIBRATOR

EACH VENTURI PUMP:
SEAWATER FLOW = 4.3 L/MIN
AIR FLOW (1 ATM) = 6.7 L/MIN

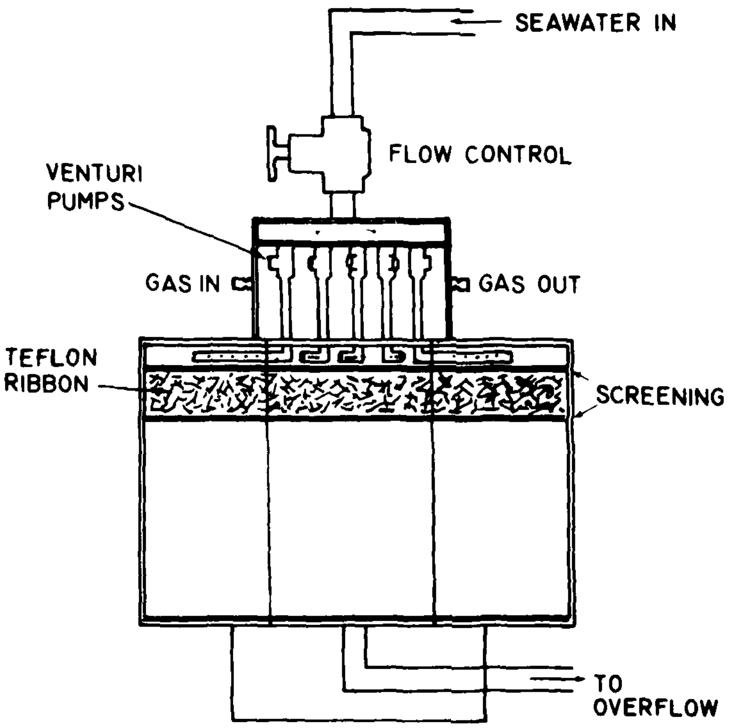


Figure 8

through each of these Venturi pumps. The air entrainment volume of a pump at one atmosphere is about six to seven liters a minute, so an enormous amount of mixing occurs, very intimate mixing, and the equilibration process, which is fast in itself, continually exchanges the gases which are dissolved for those which are in the headspace.

If the headspace volume is kept small, one can arrange for a complete turnover of the headspace in just a matter of seconds. We have found that Teflon ribbon causes bubbles to coalesce quite effectively. The water flows down the Teflon ribbon, and any bubbles associated with that water will selectively attach themselves to it. They grow as more gas is supplied to them. Finally, they are buoyant enough to rejoin the headspace.

We have used this system a couple of times. We find that it can be scaled from two or three Venturi pumps, with the same sorts of seawater flow rates (perhaps 12 liters a minute), up to 20 aspirators with seawater flow rates near 80 liters a minute.

Using this kind of system to do dissolved-gas analyses more quickly than might be accomplished with a countercurrent stripping technique moves us quite a bit away from the sorts of pumping system Dr. Kester alluded to with one- or two-liter-a-minute capacities. Here we are interested in high volume flows so that we can get a good measurement of a chemical gradient as we move a ship across it, and accomplish the analysis as quickly as possible.

I must mention that the headspace equilibrator method is compatible with different techniques of preparation for analytical instrumentation. The dissolved gases could be used as the carrier gas from the equilibrator to the instrument, for example. Infrared techniques such as are used for carbon dioxide analysis, P_{CO_2} measurements, can use air as a carrier. Or a selective make-up gas free of trace species could be introduced continuously into the headspace. In this case, a sampled output would contain, by Henry's Law, the equilibrated amount of the absent trace dissolved gas that was in the headspace.

Next, I would like to discuss a few design principles for dissolved-gas analysis. I think the most important design feature for dissolved-gas analysis is the prevention of sample loss by gas exchange with bubbles in the delivery system to the laboratory. Specifically, this means avoidance of both cavitation due to the pumps or restrictions in the line--anything causing a localized pressure drop that would allow separation of phases. Cavitation is harmful to all pumps, but some types of pumps can run with some cavitation occurring and others cannot. For dissolved-gas analyses, we should be extremely careful that in any design we settle on, cavitation is avoided under all operating conditions.

Along the same lines, dead spaces in valves and pulse dampeners (volumes not fully swept out by flow) can be particularly bothersome for trace-gas analysis. They allow generation of small headspaces as bubbles accumulate, or (in the absence of bubbles) small mixing volumes that can cause loss of sample or sample smearing as all these small, distinct phase operations themselves act as headspace equilibrators.

Second, the subsampling from the flow system has to be very quiescent; that is, we cannot allow bubbles to form there either, so sampling manifolds are needed at the delivery point on the ship.

The third design criterion is the exclusion of contaminating materials, such as metal valves and couplings, that can cause difficulties for analyses of hydrogen and oxygen. Hydrogen lubricants may also contaminate analyses for hydrocarbon gases and for other organics.

Last, we have to make certain that when a pumping system has been put together, it can be used more than once. Thus, the system design should allow some means of recirculation of fluids for cleaning at sea. Simple flushing with seawater may not be sufficient to remove all trace components below contaminating levels. In some cases, it may be necessary to circulate a cleaning fluid such as nitric acid through the system. I would also like to recommend sterile storage between expeditions.

REFERENCE

1. Hanson, B. and J. Meincke (1979), "Eddies and Meanders in the Iceland-Faeroe Ridge Area," Deep-Sea Research, 26A: 1067-1082.

DISCUSSION

GREEN: How do these measurements of trace-metal concentrations compare with accepted conventional modern measurements?

HERR: I think they are very close. The data that we took to spot-test these results with a rosette sampler along the cruise track compare nicely.

PELLENBARG: The results are for surface waters only. There is little evidence that studies of metals in surface waters over such large geographical areas have been done; in this regard, the data may be at variance with those collected over more restricted spatial and temporal regimes.

HERR: Other work that we have done with this pumping system concerns chemical surface mapping, which Dr. Mary Scranton and I did for dissolved hydrogen. Among the areas we mapped is the one shown in Figure 5 along the Iceland-Faeroe Islands Ridge, where the strong surface-temperature gradient shown previously was occurring.

We were working with another NRL group engaged in bathymetric operations. That is why I stressed that aspect of the use of ship time earlier. They were navigating along parallel grid lines with four-kilometer spacings and were not interested in stopping the ship to do a lot of profiling with a CTD and rosette sampler. On the other hand, they were towing magnetometers and hydrophone arrays, and to tow a pumping system would have posed no difficulty for them at all.

Hydrogen is biogenic, and we were interested in whether we could find patchiness in the surface concentration of this biologically produced and consumed trace gas in the ocean, and whether we could find mesoscale source areas due to microbiological sources, which would presumably mix with the surrounding ocean to form a surface distribution.

UNDERWAY MEASUREMENT OF ORGANIC MATTER IN SEAWATER: REVIEW AND PROGNOSIS

John W. Farrington*

Introduction

This presentation is intended to introduce marine organic chemistry to the conference participants, and more specifically, instrument engineers, by an overall review of the field and a few specific examples of research in the past several years. Then I will suggest some strategies for underway sampling and analyses of organic compounds. Please bear in mind that I approach this latter topic without a great deal of experience with underway analyses systems for chemicals, but with curiosity, and the belief that they will be of assistance to certain aspects of marine organic geochemical research.

Overview

Marine organic chemistry has been reviewed extensively within the past several years (Eglinton, 1975; Anderson, 1977; Gagosian, et al., 1978; Tissot and Welte, 1978 [sediments]; Hunt, 1978 [sediments]). We know that organic compounds in the environment can influence marine organisms by controlling their behavior; e.g., predator-prey relationships, reproductive processes, dominance, or succession of plankton species. This is in addition to their well-recognized role as a source of energy for marine life.

Marine organisms excrete organic matter to seawater as part of their life processes. It is not unreasonable to state that they leave their imprint in the form of organic chemicals in some volume of surrounding water for a period of time dependent on the chemical and biochemical stability of the compounds in question.

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* I thank Dr. Cindy Lee for many stimulating discussions and assistance in gathering the information on amino acids. Mr. Hein and Mr. DeBaar provided the conceptual drawings for Figure 1. Several colleagues in the Woods Hole Oceanographic Institution's Ocean Engineering Department, especially Mr. Cliff Winget and Mr. Fred Hess, have provided me with valuable insights for concepts elaborated on in this paper. Financial support from the Office of Naval Research, Contract N00014-79-C-0071 is gratefully acknowledged. This is Contribution Number 4619 from the Woods Hole Oceanographic Institution.

Organic compounds are part of marine particulate matter and can influence the chemistry of mineral, metal, or synthetic surfaces immersed in seawater. As a result, they can have a significant influence on sediment dynamics and solid/solution chemistry.

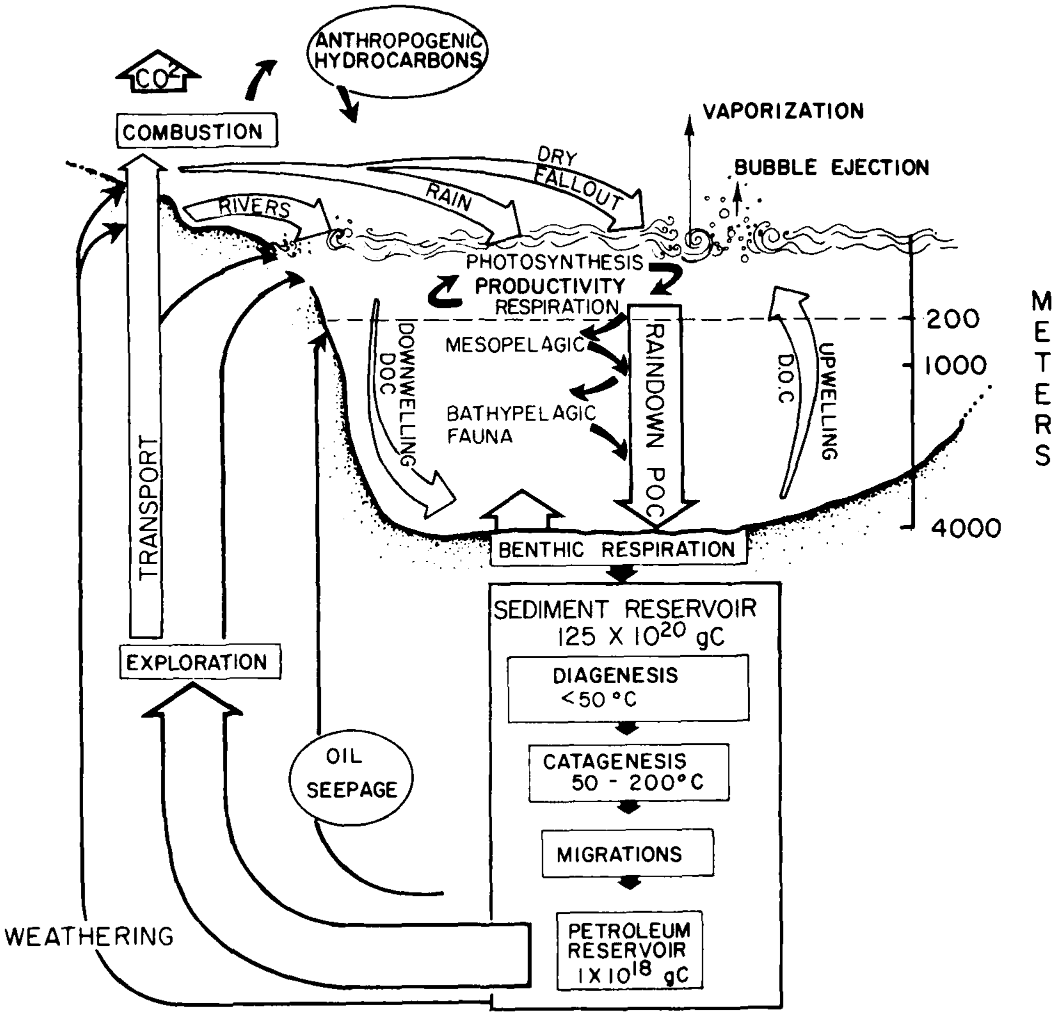
Many organic pollutants have been detected in the marine environment. Both long-term, low-level, widespread inputs of compounds such as DDT, PCBs, and specific point-source inputs such as kepone have been recorded. Even VX (nerve gas) was reported last year in European river-estuarine systems (Verweije, et al., 1979). DDT and PCBs have been detected in Antarctic and in benthic ecosystems at 5000 m on the Nares abyssal plain (Harvey and Steinhauer, 1976). This indicates that some parts of the global, geochemical cycles of organic compounds act on a few decades' time scale to penetrate the deep sea.

Organic compounds can interact with trace metals. Organic compounds can be significant in the global cycle of elements other than carbon. There are some indications that organic sulfur compounds play an important role in the sulfur cycle and are not merely short-lived trace transients (Schwarzenbach, et al., 1978).

Some organic compounds have also been proposed as tracers of air-sea exchange processes, and water-mass movements. Among these are volatile, soluble, man-made halogenated hydrocarbons.

A schematic of the global organic carbon cycle is given in Figure 1. Much more detail could be added, but this will suffice for our consideration. The major active processes are indicated. One feature of the cycle, which is not shown but can be described, is the relative time scales of the dynamics of the system. The sediment reservoir turnover time is very long--on the order of 100,000 to 10^6 years. Deepwater dissolved organic carbon (DOC) has an average age of about 500 to 3600 years, indicating average turnover times in that range. Particulate organic carbon (POC) has a much shorter turnover time; for example, fecal pellets have a sinking time on the order of 20 to 100 days; large carcasses, 2-5 days, and clay-size particles perhaps 50 years. Resuspension and redeposition make these very rough estimates.

There have been significant advances in the last several years in understanding the organic carbon cycle in the contemporary marine environment. Benthic respirometer chambers have given a better estimate of the utilization of organic matter at the sediment-water interface (Smith, 1978; Hinga, et al., 1979). There has been a re-examination of marine particulate matter via particle-interceptor trap or sediment trap studies and in situ pumps, as well as by free diver, DSRV Alvin, and other submersible observations of "marine snow" (Honjo, 1980; Gardner, 1977; Staresinic, 1978; Silver, et al.,



GLOBAL ORGANIC CARBON CYCLES

DOC = Dissolved Organic Carbon
POC = Particulate Organic Carbon

Figure 1

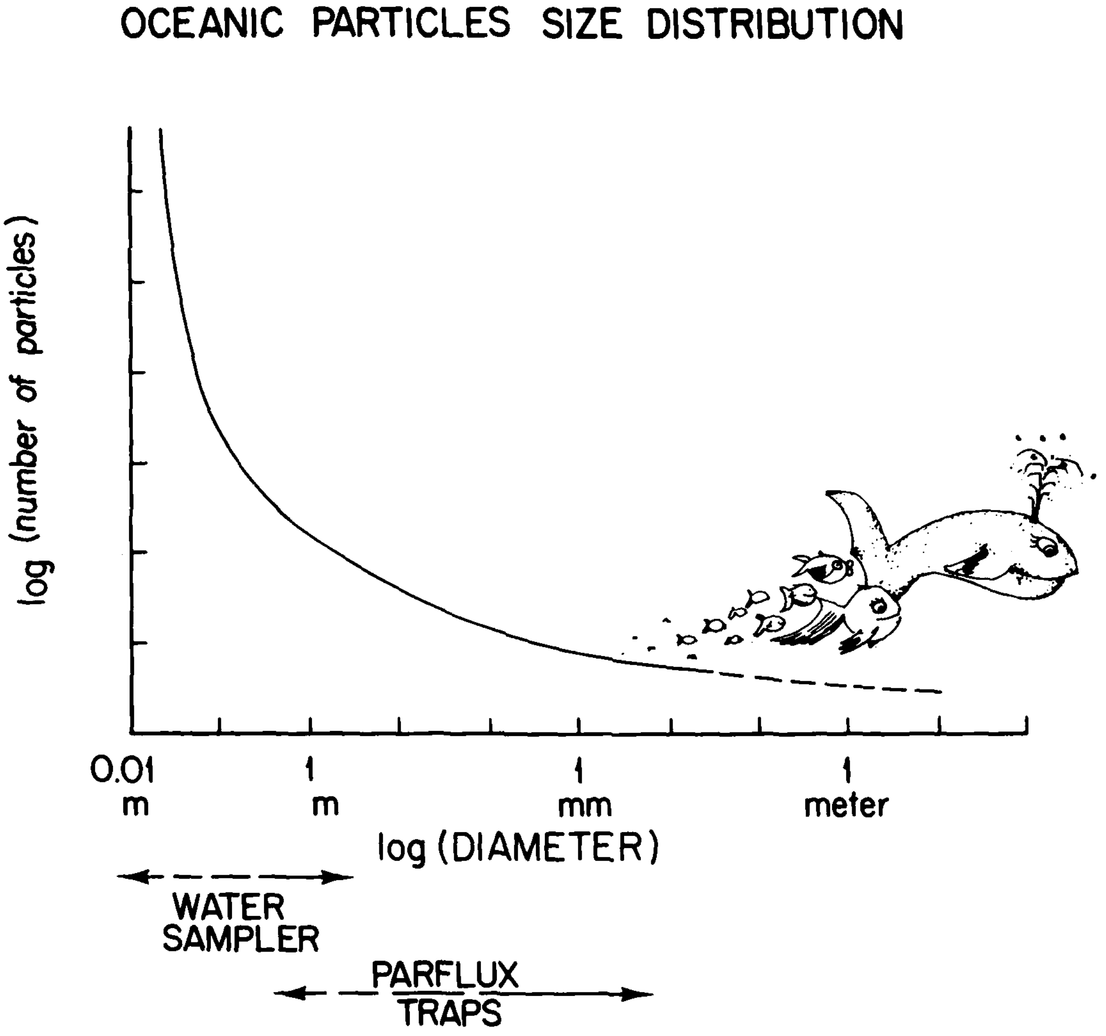
1978, and reference therein). Finally, there is a growing realization of the magnitude of fragile organisms not caught in nets, but present and very active in all depth regions of the sea. An important question for marine chemists, and indeed, marine scientists as a whole, is, "What fraction of the world's ocean passes through a marine organism each day as marine life pumps seawater to extract food and oxygen?"

Measurements of organic compounds in the sea are obviously an integral part of research in the processes controlling organic compound distributions. These organic compound distributions reflect biological, chemical, geological, and physical processes. The present state of knowledge (as I will describe below) is somewhat akin to the early stages of unravelling a massive fishing-line snarl. As marine organic chemists, we think we have the important loops in our grasp, but we are pulling slowly to make certain that we have not missed an important loop, or even worse, that we are misleading ourselves and are making matters worse. We could waste significant effort and funds if we do not carefully define why we wish to collect vast data via underway sampling and measurement.

POC and DOC

The distinction between DOC and POC has been set as a rather arbitrary division for filtering systems. The problem can be visualized by considering a particle-size distribution cartoon (Figure 2). Where do we draw the line when sampling? For some, in fact, most questions concerning organic compounds, we need to know about the entire size range, and the distribution and composition. The problems with DOC are similar. In the operationally defined DOC fraction, we have several physical chemical states: true solution, emulsifications, and colloids. Here we come to a problem which this workshop should consider. How do we sample with towed underway systems, and minimize (or at least define) what happens to the integrity of the continuum from true solution to large particles?

Unfortunately, no methods are yet available for DOC or POC amenable to rapid analytical schemes at the DOC and POC levels (0.5-1.0 mg/liter and 10-50 mmg/liter, respectively) found in typical open-ocean samples. Even with careful laboratory techniques on land or onboard ship, there are still several controversial issues, such as whether measurement of all the DOC has been accomplished (Sharp, 1973; Gordon and Sutcliffe, 1973). Development of a sufficiently rapid analytical measurement is the stumbling block today, rather than the pumping and sampling system. Researchers and engineers have neglected these problems in favor of other important topics in marine organic geochemistry. There are conceptual solutions that seem quite reasonable. For example, coupling of rapid and efficient oxidation techniques for organic-matter conversion to CO_2, and



FREELY ADAPTED AFTER (Mc CAVE, 1975)
(SHELDON, 1972)

Figure 2 Particle size distribution (adapted from I. N. McCave (1975), Deep-Sea Research, 22: 491: 491-502, and R. W. Sheldon, et. al. (1972), Limnology and Oceanography, 17: 327-340).

subsequent direct measurement of CO_2 or of excess oxidant in a nutrient autoanalyzer would be amenable to processing sequential samples from a towed underway system pumping water on deck. An alternative would be a direct high-energy UV photo-oxidation pulse, again converting organic matter to CO_2, and subsequent measurement of CO_2, with all events in a processing line.

A cautionary note is in order at this point. There have been several attempts to measure "gelbstoff" or fluorescing material by UV-fluorescence systems and to equate the signal to dissolved organic matter (DOM). This may have an application in a qualitative mapping of river plumes near coastal areas, but has to be reviewed with caution. Careful measurements showing the direct conversion between UV-fluorescence measurement and that of total DOM are lacking. In fact, current data indicate that this would be extremely unlikely except in isolated cases.

The fact that little effort has gone into this suggests to me that challenging problems exist elsewhere in marine organic geochemistry research. Indeed, with few exceptions, profiles of DOC in the marine environment show only minor fluctuations below the euphotic zone. Nevertheless, the focus on the deep-water DOC question may have diverted attention away from the euphotic-zone DOC measurements, which do exhibit significant horizontal and vertical fluctuations (Sharp, 1973; Williams, 1975). Underway sampling analyses for DOC may provide some interesting and valuable measurements, and yield insight into the cycle of organic matter in the euphotic zone.

Classes of Compounds and Individual Compounds

What are the constituents of DOC and POC? It has become customary to note in most discussions of DOC and POC that there have been very few samples for which more than a few classes of compounds were measured, and only the major constituents of each class were measured for these. Thus, our knowledge of the composition of DOC and POC is a collage of data from several different samples taken from different geographical areas. Hundreds of individual compounds have been measured, yet the collective opinion and reviews of the data by many marine organic chemists suggest that by assembling the data of these sources, we can account for 20-30 percent of the DOC, POC, or both.

The approach to analysis of organic compounds in seawater is to sample with water samplers--1-liter to 60- to 90-liter samplers. The compounds in question are removed from the seawater by solvent extraction, adsorption or ion-exchange techniques, or gas stripping. The compounds are then isolated or separated by liquid chromatographic techniques with appropriate detection, or by combinations of liquid chromatography on various solid supports, coupled with gas chromatographic analyses and gas chromatographic/mass spectrometric analyses.

By these means, we are gaining insight into the composition of DOC and POC, and the biogeochemistry of specific processes in the ocean. The time scales of these analyses range from hours to days.

Marine organic geochemistry is a new and merging effort compared to inorganic geochemistry. Knowledge of major ions, dissolved major gases, nutrients, and the geochemical system dynamics of trace metals is far more advanced in the quantity of data collected on appropriate spatial and temporal scales, and their interpretation. Marine organic geochemistry has much to offer in gaining better understanding of the geochemical and biological processes of the ocean. A wealth of information about these processes is stored in organic matter, and in the specific structures of organic compounds. This has been thoroughly discussed in the reviews cited above.

I will use one example to illustrate the types of information that can be obtained. Figure 3 shows dissolved combined amino acid (DCAA) profiles for two stations in the Pacific from Lee and Bada (1977). The depth profiles below 600 meters are fairly constant and are interpreted as indicating utilization of dissolved free amino acid (DFAA) maintaining this low uniform concentration. Above 600 m, there are some fluctuations in the profiles, interpreted as combinations of phytoplankton and zooplankton production of amino acids and consumption by bacteria and zooplankton, all coupled with the influence of the Cromwell Current on the dynamics of the system at the 200-600 m depth range. Station 1 lies in the northern edge of the current and Station 2 is east of the Galapagos Islands, which successfully block the Cromwell from that area. These data illustrate several important facts about marine organic geochemical research pertinent to the considerations of this workshop:

1. The data points are usually quite sparse compared to many inorganic geochemical studies. The 12 data points in Figure 3 would have taken about one week to obtain in 1977 (Dr. Cindy Lee, personal communication). The samples were discrete samples taken from Niskin bottles. Amino acids were isolated from subsamples onboard ship and analyzed back in the laboratory.

2. Biological processes are extremely important considerations in interpreting most organic geochemical data in the contemporary marine environment. This may seem so obvious that it need not be explicitly stated. Nevertheless, when considering designs of underway sampling systems for organic geochemical studies in the ocean, the importance of obtaining concomitant biological data wherever possible cannot be overemphasized.

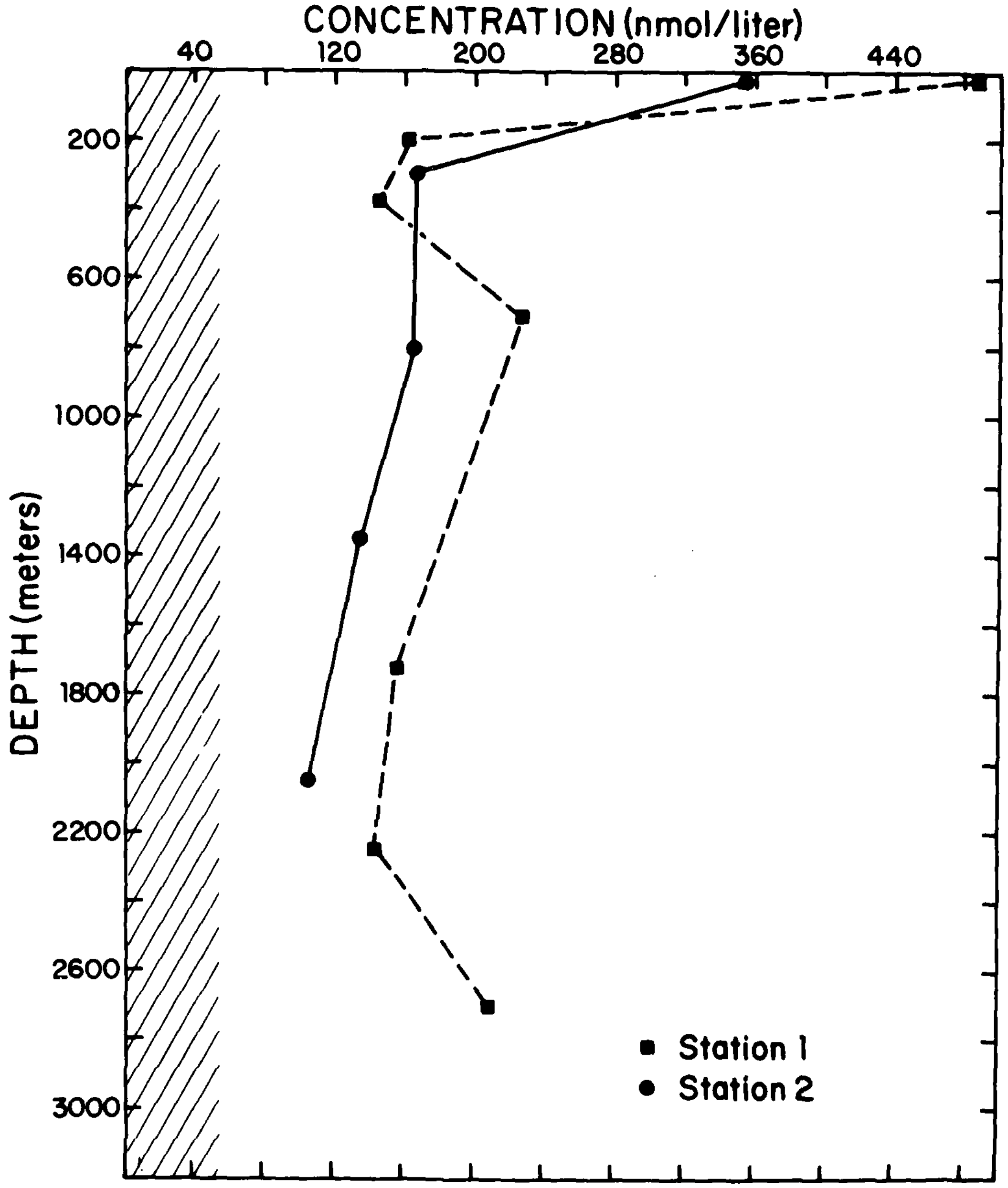


Figure 3 Depth profile of combined amino acids in the equatorial Pacific Ocean (from C. Lee and J. L. Bada (1977), Limnology and Oceanography, 22: 502-510).

3. The need to consider physical processes is illustrated by the direct or indirect influence of the Cromwell Current on the amino acid profiles.

4. The fluctuations in the profiles occur in the upper ocean, mainly above 1000 m. For other organic compounds (see reviews cited previously), the fluctuations are quite marked in the euphotic zone. The processes governing the biogeochemistry of organic compounds in the euphotic zone are thought to be quite rapid. For example, Lee and Bada (1977) calculate a turnover time of less than one to two days for dissolved free amino acids.

Given this rapid turnover time and the spatial heterogeneity of biological systems (as discussed in the next section), more frequent sampling points in time and space should allow us a better understanding of the coupling of the biogeochemistry of organic compounds in the upper ocean and biological and physical processes.

Amino acids are only a small percent of the organic compounds being investigated. The examples given above are based on consideration of dissolved amino acids as a class of compounds that is actually relatively simple. The dissolved amino acids are composed of at least 10 to 12 major individual amino acids. In comparision, the analysis of all other classes of organic compounds involves hundreds to thousands of individual constituents. For some research questions this may not be necessary: a few key compounds may give us the answer. For other questions, we may need to tackle these complex analytical tasks.

Examples of Underway Measurements

There are already a number of reasons why we wish to measure organic compounds using towed underway systems. A few examples are given here.

Biological Productivity. One of the more advanced towed organic chemical measurement systems depends on UV-excitation and fluorescent emission to measure chlorophyll in seawater. By appropriate measurements of the relationship between chlorophyll and photosynthesis rates, and application to the chlorophyll fluorescence "map" of an area we can estimate the standing stock of phytoplankton and its productivity. The use of towed systems provides better data to determine how given marine ecosystems function (Herman, this volume).

Several commercial instruments on the market are capable of working at depths of 500 m. Two approaches are used for taking these measurements. One is to pump the water through a UV-fluorescence instrument onboard (manufactured by Interocean Systems); the other is to tow the UV-fluorescence sensor in the ocean, and transmit the signal via cable to the ship. Incorporation of laser-induced fluorescence has provided sensitive instruments, and commercial systems with laser-fluorescence measurement for chlorophyll a have been used on several occasions (see Alex Herman, this volume, and Frungel and Koch, 1976), instruments manufactured by Endeco, Impulse Physics, and others. (For descriptions of these sampling experiments, see "Concepts in Marine Organic Chemistry," reference 1.)

Organic Pollutants. Organic pollutants, such as aromatic hydrocarbons from oil spills, or certain petrochemicals with aromatic rings, also fluoresce. The same approach used for chlorophyll could be applied to measurements of these compounds in seawater (NOAA/EPA, 1978). Sensitivities can be at the mm/kg or ppb range. However, the precision and accuracy of such measurements depend on the extent of interference from other molecules in the sample. Careful calibration, and finely adjusted optics and filters are needed.

The importance of such measurements is the ability they offer to estimate the extent of advection of the pollutant in question away from the source; e.g., that of soluble aromatic hydrocarbons from an oil slick dissolving in water, and advecting away from beneath the slick. In addition to providing such estimates, the underway measurements provide guidance for the optimum deployment of larger-volume water samplers to obtain samples for more detailed and sophisticated analyses.

Non-Fluorescing Compounds. Many naturally occurring and pollutant organics have spectral characteristics that do not make them amenable to such sensitive measurements as fluorescence spectrometry. However, some organic reactions will proceed in seawater if appropriate reagents are added. These reagents are chosen to impart a desired spectral character to the molecules to be measured; e.g., fluorescence, thereby allowing sensitive detection. Recent advances in the methodology for analysis of amino acids in seawater exemplify this approach. Figure 4 provides an example of the types of reactions that can be used to prepare a fluorescent derivative of amino acids. A preliminary example of the application of the o-phthaldialdehyde derivative method to the analysis of amino acids in a seawater sample has been given by Lindroth and Mopper (1979). The derivative amino acids were separated by high-performance liquid chromatography (HPLC) using reverse phase columns. The detection limit was in the range of 100 x 10^{-12} molar (picomolar). The sample size needed was on the order of 100 x 10^{-6} liters (microliter) of seawater. The analysis time for the HPLC phase was 25 minutes; this allowed measurement of at least 20 amino acids.

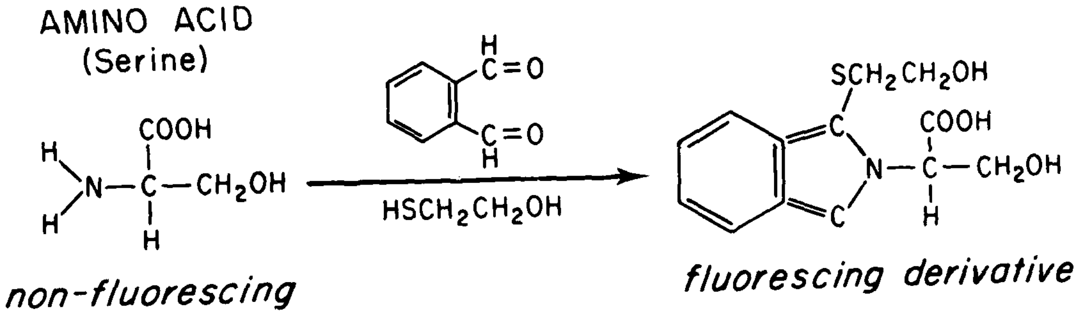


Figure 4 Conversion of amino acid derivative to a fluorescing compound: an example.

A conceptual approach combining an underway pumping system with an amino acid analysis scheme is given in Figure 5. While it is true that there can be as much as an hour's delay between taking the sample and its analysis (owing to the time needed for HPLC analysis), this approach represents considerable advance over discrete sampling using hydrocast samples onboard ship and analyses back in the laboratory. Discrete sampling was the state of the art in 1975, only five years ago (see Lee and Bada, 1977).

Given the innovations analytical chemists and engineers have introduced in the rapid development of HPLC over the past decade, there is no reason to doubt that the time needed for HPLC analysis can be reduced in the next several years. There may be some sacrifices of resolution; i.e., in the number of compounds analyzed. For some research and monitoring programs, the reduction might be acceptable. It is also reasonable to expect that fluorescing derivatives will be developed for HPLC analyses of many other organic compounds in seawater.

As discussed by Lee and Bada (1977), biological processes have a large influence on amino acid distributions in the water column. It should be feasible to investigate further the relationships between biological processes in seawater and free amino acid distributions using the scheme illustrated in Figure 5, and those of other compounds as well, including organic pollutants.

Some Practical Considerations

The construction materials that are best for avoiding the contamination of samples for organic analyses are glass, stainless steel, and Teflon. It must be recognized that there will be adsorption of some organic compounds of these types of materials (Neilhoff and Leob, 1974). This could be important in altering the measured concentration from the actual concentration in situ by removing compounds during passage of water through the system, and their bleeding back into the water at a later time.

Fouling is an important consideration. The system must be designed for ease of disassembly, cleaning, and reassembly to avoid the growth of fouling communities. This design consideration is also important if a system is used in an area of high concentrations of organic compounds, as these compounds might bleed back into water at a later time.

The influence of a pumping or measuring system on the physical state of the organic compounds to be measured (e.g., dissolved particulate or colloidal material) needs to be known for correct interpretation of the data.

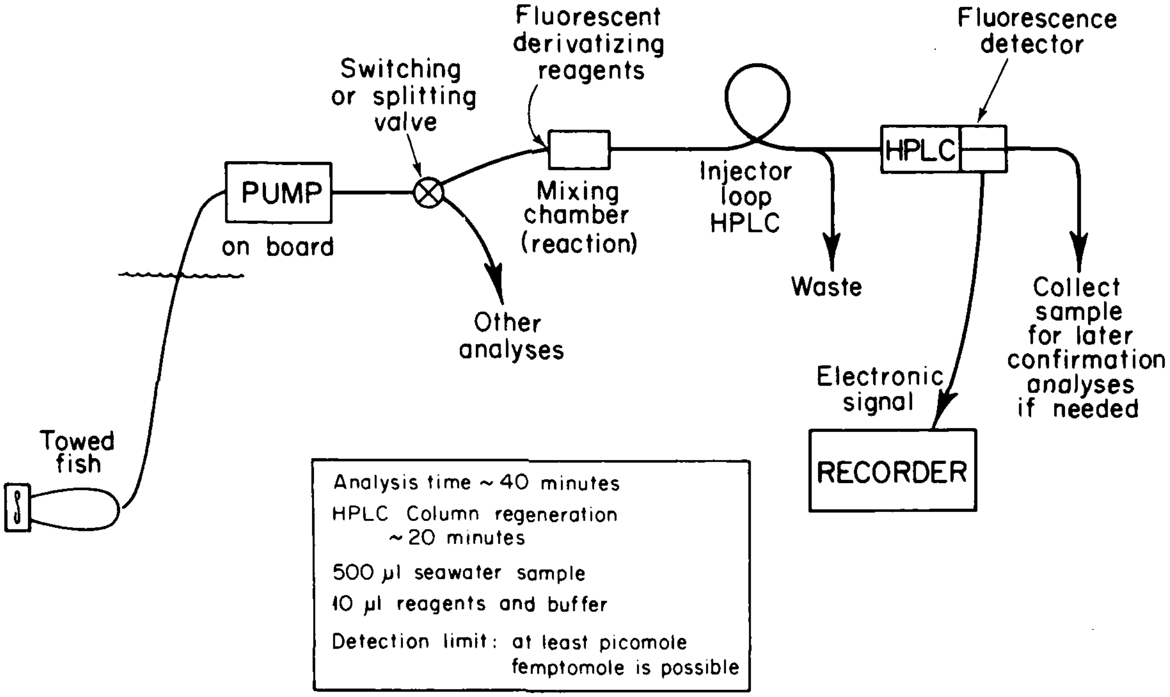


Figure 5 Schematic outline of proposed towed-fish pumping system for amino acid analyses.

Calibration of the system, including detectors, is a problem that needs to be carefully considered: How? How often? If different systems are used, how can the data be interrelated? A related problem is how the data obtained can be referenced to real time and space coordinates in the marine environment. In some cases, relative, rather than absolute coordinates may suffice. This problem becomes critical in consideration of the relationship between pumping or _in situ_ systems and remote sensing, as discussed in the next section.

Data recording, storage, and manipulation should be given a good deal of attention early in the system design. This seems obvious, but in my opinion, has too great a chance of being neglected in the excitement of meeting the challenges presented by pumping and detector systems.

Remote Sensing

Satellite and airborne remote sensing has become a fast-growing area of research. There is neither time nor space here to provide an adequate review of this area of research. However, there are some first-order aspects that are pertinent to this conference. Measurement of pollutant oil concentrations and chlorophyll _a_ concentrations in surface seawater from aircraft have been proposed (Computer Genetics Corporation, 1980, among others). If the laser spectrometry systems proposed are compatible with aircraft mounting, they could also be mounted on research vessels or other ships. In addition, some of the proposed systems will have range-gating features that allow penetration into the top 10 meters or so, and integration of concentration _vs._ depth signals. As described earlier, a specific type of laser spectrometry, laser fluorescence spectrometry, is already being used in an _in situ_ towed system to measure chlorophyll _a_. Thus, it seems reasonable to propose that other applications of laser spectrometry, such as those being contemplated for airborne systems, could also be adapted to towed _in situ_ systems.

The principle is to bring the measurement device to the water parcel in question, rather than the water parcel to the measurement device, as is the case for underway pumping systems.

The specific research needs, and the application of the results to the solution of many problems have been accepted, and remote sensing from aircraft and satellites is now funded for many millions of dollars over the next decade. A very important part of the use of such systems is in providing sea- or ground-truth calibration for remote sensors. Towed underway pumping or _in situ_ systems provide the most reasonable means of obtaining sea-truth data on time and spatial scales that allow calibration of remote sensors from aircraft and satellites.

Conclusion

The air-sea interface is only one of the many "boundaries" or interfaces in the ocean where spatial or temporal considerations (or both) indicate needs for data that can be obtained by pumping or *in situ* systems. The recent discoveries of the vents and unique biological systems of the East Pacific Rise and Galapagos oceanic ridge are just examples (Corliss, et al., 1979). The need to learn more about near-bottom processes in mid-ocean plate areas in preparation for possible implacement and disposal of nuclear wastes (*Oceanus*, 1977, reference 21) is another example. For those, analyses *in situ* may prove more efficient and practical than pumping water onboard from thousands of meters.

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DISCUSSION

SIMPSON: You raised a very good point about the effects of the pumping system on the sample itself. We have to define what we mean by a signal, and what we mean by noise. Relevant space, time, and mass scales are associated with that signal. If our system contaminates the sampling in a region that is outside the relevant space, time, and mass scales, it is really not a problem in the context of the current measurement. If it contaminates the sampling within that region where the signal is defined, it is a serious problem.

We must have a clear picture of what we want to do, and a basic definition of the space, time, and mass scales from which everything is derived to assess the contamination problem and the sampling problem.

KESTER: I would like to comment on the point you raised about the effect of sampling on what you are measuring, specifically with particle size. In our work with the NOAA pump last fall, we conducted what should have been a simple experiment. We did discrete sampling to depths of 30 meters or 40 meters, and pumped from each of those depths, then compared the size distribution of particles by these two sampling methods.

The results indicate that for samples collected between 10 and 30 meters, in the mixed layer, the particle-size distribution was indistinguishable whether the material was collected by pump or by discrete samplers. However, the pump gave higher concentrations.

For the 40-meter samples, the particle-size distribution collected by the pump shifted from particles that were initially about 30-40 microns to 10 or 15 microns.

These interpretations are based on the assumption that the particle-size distribution was not variable during the time of sampling. I think the previous speaker noted that the separation of time and space scales in these samplings is a very difficult problem.

But at least in this attempt to compare the two methods, the indication was that some particles in the ocean are affected by pumping, and others are not. It is something that has to be looked at very closely as one proceeds with this type of work.

PHYSICS AND PRACTICAL ASPECTS OF TOWING, WITH EMPHASIS ON UNDERWAY WATER SAMPLING

Shelton M. Gay, Jr.,* and Reece Folb

Introduction

Towing is an art that appears deceptively simple. Its primary elements consist of tying something to be towed to a propelling body, a tug, by means of a slender flexible member, the towline, and simply pulling the towed object or towed body along behind the tug. And it is, in fact, no more complicated than that so long as the product of the towing depth and the square of the towing speed is not large.

In general, the towing objectives of this conference (800 meters at 8 knots) are not considered difficult to meet.[1] The problems arise from other limitations that effectively constrain what can be done with the towed system itself. This report was prepared to review briefly the fundamentals of towing, and to show how other consideration impinge on the design of towed gear. The examples given are specific to underway water sampling, but the material is applicable to a wide class of towing problems, and thus may be of interest to anyone contemplating the use or design of a towed system.

Theory

The towline is a structural member so slender that it may be considered completely flexible except where it interfaces with the tug and towed device. Structural stiffness must also be considered when dealing with faired towlines, as it affects the tendency of the streamlined cross-section to twist relative to the direction of motion.

Two-Dimensional Theory. The most general exposition of the mathematical theory of the hydromechanics of cables in two dimensions has been given by Pode.[2] His nomenclature is based on the equilibrium configuration of a cable segment, as illustrated in Figure 1. The cable is assumed to lie in the plane defined by the direction of motion and gravity, and to be immersed in a fluid having uniform properties. This development will not be reviewed in detail, as the results are readily available.

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* Presenter

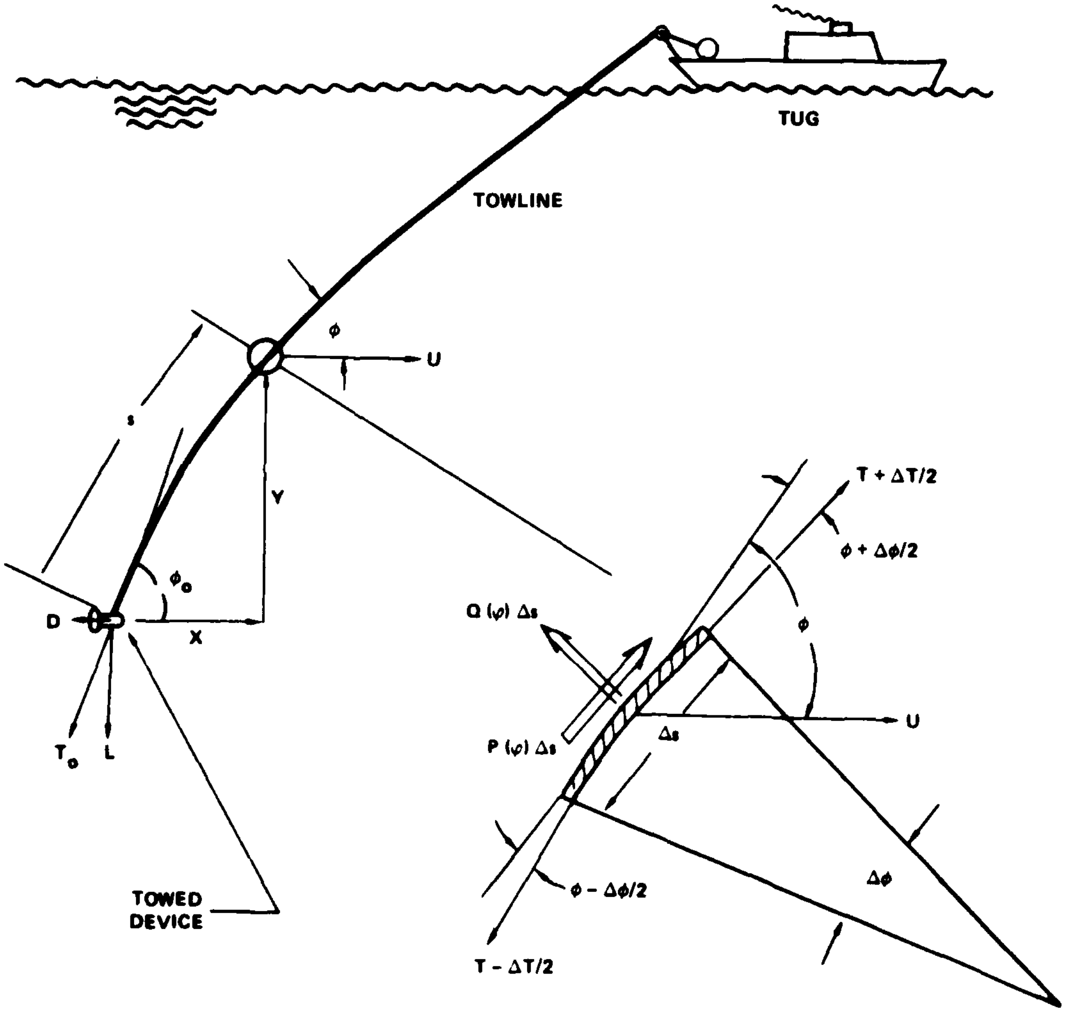

Figure 1 Definition sketch for towing configuration.

Pode's work was developed in terms of generalized hydrodynamic loading functions. As illustrated on Figure 1, there are two such functions representing, respectively, the loads per unit length normal and tangential to the towline. The normal load is represented by the function

$$Q(\phi) = R[f_n - w\cos\phi] \qquad (1)$$

and the tangential load by the function

$$P(\phi) = - R\ [f_t - w\sin\phi] \qquad (2)$$

where f_n and f_t are the normal and tangential hydrodynamic loading functions, R is the hydrodynamic resistance per unit length of towline and w stands for the ratio W/R, W being the weight per unit length.

The configuration of the towline may be determined by specifying R, W, f_n and f_t; and a set of initial conditions, T_o and ϕ_o. For example, for a round towline

$$f_n = \sin^2\phi\ , \text{ and}$$

$$f_t = \text{constant}\ .$$

In general R, f_n and f_t are determined experimentally. Tabulations for bare towlines are given by Pode and for faired towlines by Folb.[2,3] Computer programs have been developed that permit input of f_n and f_t in very general form.[4,5] A number of excellent programs are also available in the private sector.

Referring again to Figure 1, the physical situation is relatively simple:

1. The initial conditions that establish the tension and angle at the nether end of the towline are established by the tow device, i.e.

$$T_o = \sqrt{L^2 + D^2}\ , \quad \text{and} \quad \phi_o = \tan^{-1}L/D\ .$$

2. The towline curvature at any point along its length is determined by the ratio

$$\frac{d\phi}{ds} = \frac{R}{T}\ [f_n\ (\phi) - w\cos\phi]\ ,$$

and the tension by the quantity

$$T = T_o - R \int_o^s [f_t\ (\phi) - w\sin\phi]\ ds,$$

where ϕ is a function of towline length s.

The only limits that apply pertain to T in that the tension may not exceed the breaking strength of the towline. Note that $f_t\ (\phi)$ is negative by definition. Since the towline curves, it must ultimately assume an angle for which the curvature is zero. That angle is found from the normal loading function

$$f_n\ (\phi) - w\cos\phi = 0,$$

and is called the critical angle, ϕ_c. For a round towline

$$f_n\ (\phi) = \sin^2\phi;$$

and thus for a heavy cable,

$$\cos\phi_c = -\frac{w}{2} + \sqrt{\left(\frac{w}{2}\right)^2 + 1}. \qquad (3)$$

If $\phi_c = \phi_c$, the configuration of the towline will, of course, be a straight line inclined to the horizontal at the angle ϕ_c. For example, a typical one-inch diameter, double-armored cable will have a resistance R of about 25 lb/ft at 8 knots towing speed, and will weigh about 1.5 lb/ft in water. The value of ϕ_c is thus about 14 degrees. The length of cable needed to reach a depth y is thus 4.13 y, and 3306 meters of cable would be needed to reach a depth of 800 meters. The tension at the tug would be about 12,000 lb.

If the value of R is decreased; for example, by streamlining (i.e., fairing) the cable, the value of ϕ_c can be increased substantially. It is not at all difficult to achieve a resistance coefficient C_R on the order of 0.3 to 0.5. Suppose we were to fair the one-inch cable such that $C_R = 0.5$ and W remained the same. In this case, $f_n\ (\phi)$ will have a different form. If the faired cable has a reasonably high fineness ratio, studies have shown that

$$f_n\ (\phi) \simeq 0.7 \sin^2\phi + 0.3 \sin\phi$$

provides a reasonably accurate representation of the normal loading function for a wide class of faired towlines. Assuming that for this case, W is unchanged, then ϕ_c is found to be 20^o and the length S needed to reach 800 meters is 2339 meters, or 70.8 percent the length of unfaired cable. The volumes of the faired and unfaired towlines, respectively, are approximately 266 cu-ft and 75 cu-ft. The gain achieved by fairing the cable is highly questionable.

R may be put in the form

$$R = C_R q t,$$

where t is the towline thickness and $q = \frac{1}{2}\rho U^2$, ρ being the fluid density, and U is speed of tow. The maximum value of T may be put in the form

$$T_m = \Omega k_1 A$$

where Ω is the maximum allowable stress, A is the area of cross-section of the towline and k_1 is the proportion of A that is load bearing ("k_1" is in this discussion a "packing" factor).

"A" also may be related to t for a particular geometry of the cross-section by the expression

$$A = k_A t^2 \ .$$

Thus, we may put the limiting value of R/T in the form

$$R/T = C_R q / k\Omega t \ , \qquad (4)$$

where $k = k_1 . k_A$.

The utility of the loading-function concept resides in the fact that the dimensionless ratios (refer to Figure 1 for definitions of y, x, s, etc.):

$$\frac{\eta}{\tau} = \frac{Ry}{T} \ ,$$

$$\frac{\sigma}{\tau} = \frac{Rs}{T} \ ,$$

$$\xi = \frac{Rx}{T} \ ,$$

$$\tau = T/T_{\pi/2} \ ,$$

can be computed once the loading functions $f_n(\phi)$ and $f_t(\phi)$ are defined. $T_{\pi/2}$ is the value of T at the reference angle $\pi/2$. There exists an angle $\bar{\Phi}$ for which $\bar{\eta}/\tau$ has a maximum. That such a maximum exists is intuitively plausible, as the depth gain per unit scope is a monotonically decreasing function of scope, whereas the tension is a monotonically increasing function of scope. The maximum value of η/τ is designated by a bar, $\bar{\eta}/\tau$ Unpublished values for $\bar{\eta}/\tau$, $\bar{\sigma}/\tau$, $\bar{\xi}/\tau$, and τ_1/τ_0 have been developed at DTNSRDC for those faired towlines whose loading functions have been reported by Folb.[3]

The expression for the product of the square of the speed and depth may thus be put in the form

$$yq = \frac{k\Omega t}{C_R} (\bar{\eta}/\tau) \quad . \qquad (5)$$

This simply shows that the strength of the towline increases with size more rapidly than its resistance, so that in theory, one may tow as deep and as fast as one may please, provided that a tug exists sufficiently large and powerful to stream and tow the gear.

Note that the value of $\bar{\eta}/\tau$ is a function of ϕ_o and ϕ_c, and that the maxima of $\bar{\eta}/\tau$ do not tend to be very sharp; thus, they are only mildly constraining as design considerations.

These functions provide a convenient means to ascertain feasibility without resorting to a computer. Nevertheless, towing systems are not usually designed to satisfy optimum towing conditions. There are other constraints. Parametric studies using a computer are generally necessary to find the towing configuration that recognizes all (or most) system constraints.

The value of C_R is established primarily by the shape of the towline, and is only mildly influenced by the Reynolds number. Typical values range from 1.6 to 2.0 for round, stranded towlines to 0.1 to 0.5 for faired towlines. The high values of C_R for round, stranded towlines, and apparent insensitivity to Reynolds number, as compared to circular cylinders, are results of cable strum. Faired towlines are also relatively insensitive to Reynolds number. This can probably be attributed to the roughness produced by their construction and in-service handling.

The value of C_R for round towlines may be decreased to about 1.2 or 1.4 by attaching strum-suppression devices. A large variety of these is available, commonly referred to as "ribbon fairings," "hairy fairings," or "elephant ears." Their primary function is to destroy the coherence of the shed vortex street to prevent development of synchronism between the transverse vibrational periods of the towline and the vortex-shedding period. An evaluation of several techniques for strum reduction is given by Rispin.[6]

The reduction in C_R achieved by strum-reduction devices and fairings is not a free gift, however, as the frictional resistance is typically much higher than for round towlines. This is especially so for the ribboned and haired towlines, and results in a significant reduction in the values of $\bar{\eta}/\tau$, merely indicating that the limiting tension is reached with a shorter length of cable.

How does all this apply to the problem at hand? Recall that

$$yq \sim \frac{k\Omega t}{C_R}.$$

The value of Ω is fairly well fixed. Unless exotic materials are used, about the best that can be achieved inexpensively would result from the use of galvanized, improved plow steel wire for the tensile member. Average values of Ω for this material are about 320,000 psi and the average packing factor is about 0.31. That is, the maximum strength in a typical stranded cable (including electrical conductors) is about 100,000 lb x t^2, where t represents the diameter of a round cable.

The form factor k_A will be small for the application at hand, owing to the large voids needed to transport water to the surface.

For the same reason, the weight in water W, and consequently W/R, will be small.

To illustrate these points, values of k_1, k_A, and W are compared in Table 1 for a typical, round, galvanized plow steel electromechanical cable, and a cable designed to contain three, 3/8-inch ID sampling tubes for collecting water at a depth of 150 meters.[7]

TABLE 1 COMPARISON OF SAMPLER CABLE AND TYPICAL ELECTROMECHANICAL CABLE

Characteristic	k_1	k_A	k	W
Electromechanical	0.40	1	0.40	$1.5\ t^2$
Sampler	0.40	0.27	0.11	$0.82\ t^2$

The implications of these data may be seen by comparing the thickness required to attain a depth of 800 meters at 8 knots. Since the yq product is the same for both cables (and likewise the value of $\overline{\eta}/\tau$), we may write:

$$\frac{k_s\Omega t_s}{k_E\Omega t_E} \cdot \frac{C_{R_E}}{C_{R_s}} = 1,$$

where subscript s stands for the sampler cable and E for the electromechanical cable. Since Ω and C_R are equal (or nearly so) for both cables,

$$t_s/t_E = k_E/k_s;$$

and thus, using the values of k from Table 1,

$$t_S/t_E = 0.40/0.11 = 3.64 .$$

It must be recognized that this is an "all other things being equal" example. The important message is that a round sampler towline will necessarily be rather large as a result of the voids. Of course, if no restrictions are placed on size, weight, costs, and so on, a towline can be designed that will satisfy the requirements.

Three-Dimensional Theory. In the most general case, the cable and gravity are not co-planar. The analogous three-dimensional equations have been written [8, 9, 10] with provision for introducing a side force, which necessitates a third loading function. By definition, a side force is one with line of action normal to the tangential and normal components of force.* Three-dimensional and two-dimensional equations may be reduced to nondimensional form in the same manner. Tabulations of the general solutions of the nondimensional equations are difficult for the three-dimensional case, since three infinite sets of solutions are required, rather than two infinite sets for the two-dimensional case. In any event, the general availability of high-speed computers has largely negated the value of tabulations such as those produced by Pode[2] and Eames.[11]

The side-force loading function has not been explored in detail. A model for the side force on stranded cables was suggested by Gay,[9] and the case of the faired towline was explored by Rayle[10] for a prescribed distribution of the angle of attack along the towline.

Fairing

The diameters of the previously discussed towlines lead us naturally to consider other arrangements. One such technique is to build the towline in a faired shape (thereby reducing C_R) and to arrange the sampler hoses in a row within the faired shape aft of the strength member. This arrangement has been suggested by other investigators, and some are in operation. One such arrangement is suggested by Figure 2 which shows a DTMB No. 7 fairing[12] developed for a torpedo countermeasures project during the 1950's.

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* In the two-dimensional case, the normal and tangential forces are co-planar with the gravitational and velocity vectors. In the three-dimensional case, these forces are co-planar with the cable and velocity vectors. Thus, if the unit velocity vector is $\overline{v}$ and the unit cable tangent vector is s, the direction of the side force is given by $\overline{n} = \overline{s} \times \overline{v}$, where the sign depends on the order.

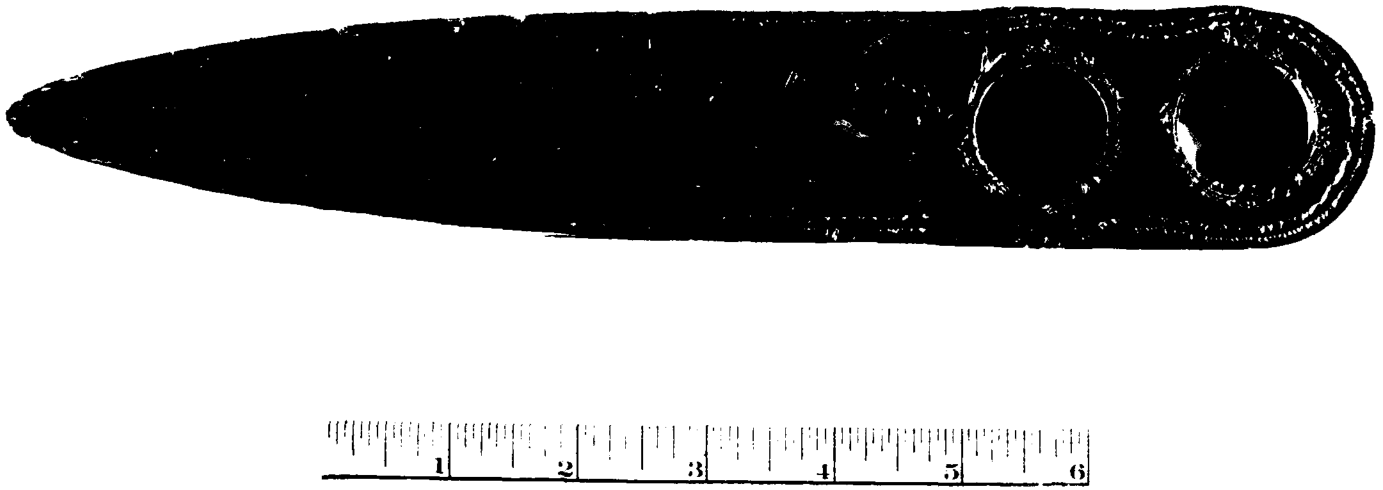

Figure 2 DTMN No. 7 two-hole fairing.

The hole nearest the nose carried a 7/8-inch diameter wire rope. The aft hole, of the same size, carried a 5/8-inch diameter wire rope under fairly high tension. The configuration was stable, and was once towed for about 7,000 miles.

The faired towline configurations obviously do not suffer in static (i.e., constant speed) performance since the factors k_1 and k_A are the same with or without the voids, assuming that the fairing is sufficiently thick to accommodate the tubing needed to match flow rates and pumping power limitations.

A number of fairing types are available for consideration. These include fully enclosing (DTMB No. 7), sectional (SQA-13, FATHOM FLEXNOSE, etc.) and trailing (TMB). Several of these are illustrated in Figure 3. Loading function data exist[3] for most.

The major technical problems to be addressed in the use of faired towlines are associated with:

- o Stability against kiting;
- o Tangential load buildup, and
- o Storage and handling.

Figure 4 illustrates the loads acting on a faired towline. Since the towline is curved relative to the axis of maximum structural stiffness, it tends to twist relative to the flow. The twisting moment is opposed by the hydrodynamic moment, and the fairing will assume the desired orientation relative to the flow only if the hydrodynamic stabilizing moments are greater than the structurally induced twisting (or buckling) moments. Hegemeir[13] and Cox[14] discuss the theory in some detail.

In general, stranded cables develop a twist when loaded.[15] It is common practice to allow the fairing to swivel freely about the strength member. The fairing is then constructed with a relatively low modulus afterbody to minimize the structural moments induced by the curvature, or in short, rigid articulated sections. The latter must be torsionally constrained by linking the sections to prevent development of a rotational wave that travels up and down the towline.

The flexible rubber fairing is subject to tangential hydrodynamic loads, and unless supported by periodic attachment to the strength member, will elongate and bunch, thereby destroying its utility. The tangential load accumulates in the intervals between stops, however, and since the line of action is aft of strength member, contributes to the destabilizing moments acting on a curved towline. Thus, in considering the stability of an elastomer-type fairing it is necessary to account for the tensile forces developed in the fairing member, and of any tubes, wires, cables, and so on, that it may enclose.

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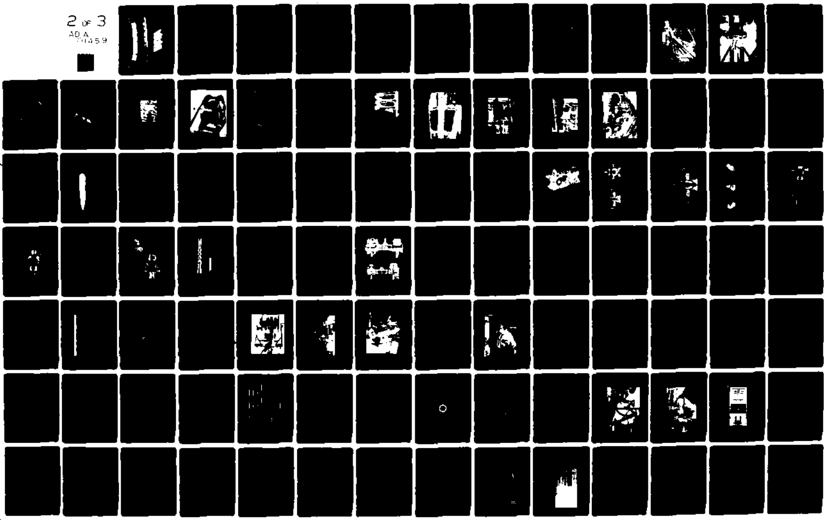


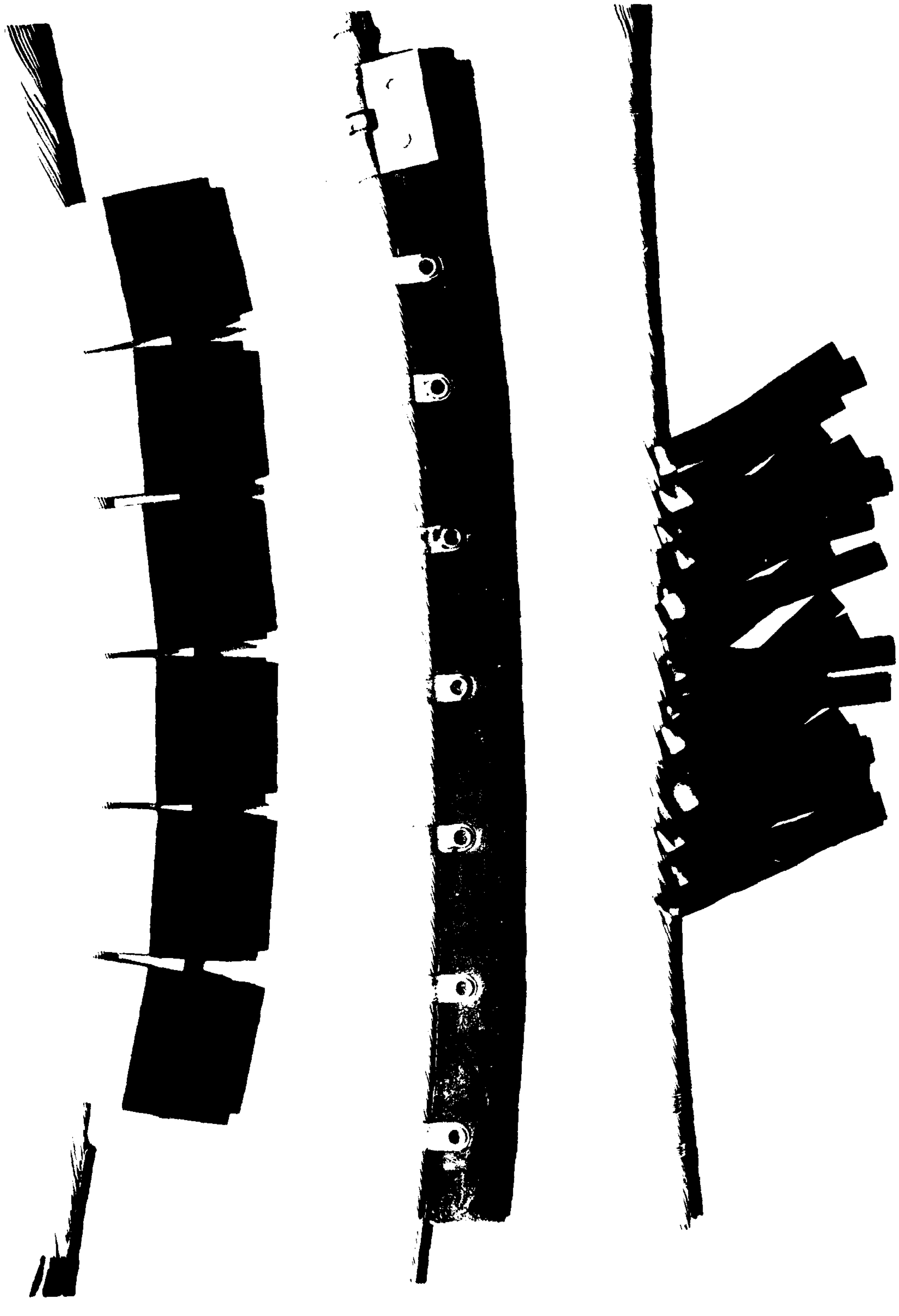


Figure 3 Sectional, trailing, and strum-suppressed towlines.

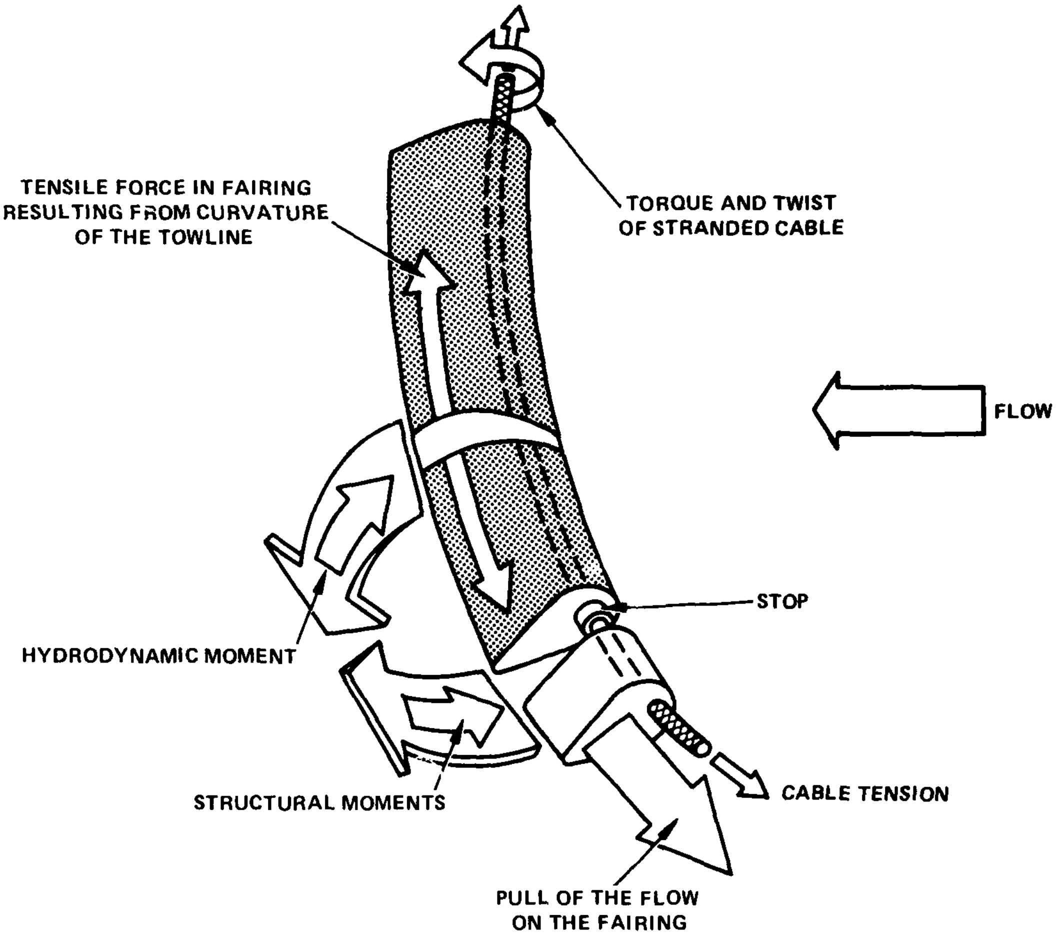


Figure 4 Loads acting on faired towline.

Sectional fairing must also be supported at intervals by the strength member. If the sections are column-loaded; that is, those sections nearest the tug are supported by those further down the towline, misalignment will occur and the towline will kite. If suspended by the linking members, the situation is analogous to that of the flexible fairing. In both cases, the loads developed in enclosed tubes, wires, cables, etc. must be considered if structural twist is to be avoided.

Kiting

The configuration of a kited towline is shown in Figure 5. On the left is shown the concave downward configuration of the towline that results if kiting is caused by a side force on the fairing. On the right, the configuration is concave upward as a result of kiting caused by a side force on the towed body. Our concern is with the former.

In general, kiting results from any phenomenon that introduces a side force on the towline. We thus preclude ocean currents as a cause of kiting, as a properly designed fairing will orient with the relative flow so that only a drag force is produced. Kiting may result from structural or hydrodynamic instability of the fairing, or asymmetry in its cross-sectional shape. Structural and hydrodynamic instability is a consequence of the shape of the cross-section and the arrangement of the materials from which the fairing is fabricated. Asymmetries, on the other hand, are functions of the manufacturing process, materials used, and deformation under load.

With the exception of certain cases in which the location of the towed body relative to the tow ship needs to be known with some accuracy, kiting constitutes a problem only with respect to the degree to which it occurs. However, any amount of kiting beyond a few degrees will create problems with handling, as the towline will not be aligned with the on-board sheave unless the sheave is specifically designed to accommodate the kite angle. Overboarding will usually create no problem as the run of the inboard towline is fixed and the rolling of the sheave wheel under the towline does not tend to carry it over the lip of the wheel.

It should be noted that round stranded towlines are also subject to kiting as a result of circulation induced by the stranding. This is particularly noticeable with three-strand wire rope. This is used to advantage in minesweep wires to prevent excessive sag of the sweep wires.

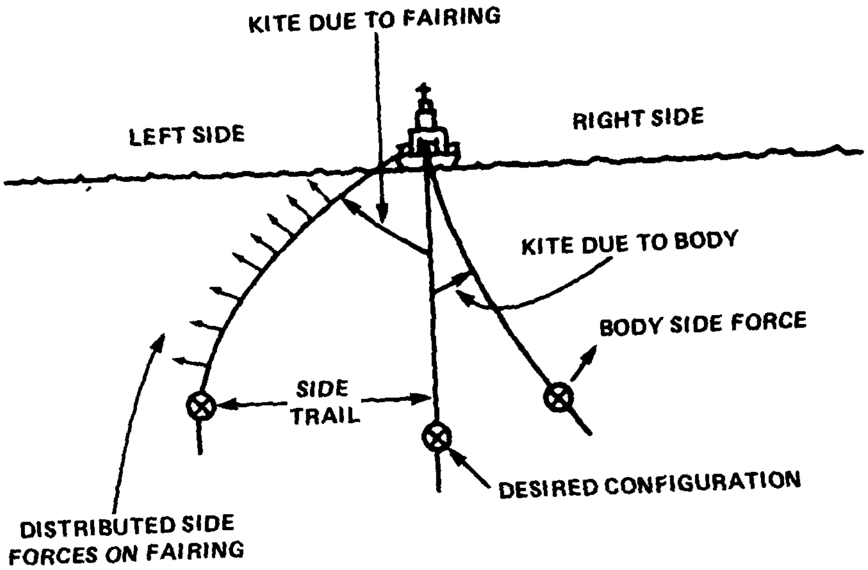


Figure 5 Illustration of kiting due to towline and kiting due to towed body.

Role Of The Towed Body

The towed body develops the downforce needed to provide the desired towline configuration. If the downforce is L and the drag D, as shown in Figure 1, the end-conditions are as previously stated, viz.

$$\phi_o = \tan^{-1} L/D,$$

$$\text{and} \quad T_o = \sqrt{L^2 + D^2}.$$

The downforce may be developed by weight alone, dynamic lift alone, or both.

The principles of towed-body design and stability are well developed, and will not be reviewed here. It is well to note, however, that the static or arrow stability of the body is appropriately referenced to the point of attachment of the towline. Also, for a body intended to be towed below the tug, stability against kiting is promoted by placing the center-of-weight in water ahead of the tow-point so that the body hangs somewhat tail-up when not under way. The desired pitch trim can be obtained by adjustment of the pitch stabilizers. The stabilizing effect of the above is enhanced by minimizing the static yaw stiffness.

The body should be free to pitch about the point of attachment to the towline, but it is usually best to constrain the towline in rotation. This prevents a stranded cable from unlaying as tension is applied. The torque developed as a result of applied tension is usually quite small and is effectively resisted by the static yaw stability of the body.

Although the principles of towed-body design are well developed, it may be necessary to use model test facilities, such as towing tanks or wind tunnels, in the evolution of a new design to measure the various hydrodynamic coefficients. This is particularly true for bluff bodies (say, fineness ratios less than 4) and configurations radically different from those previously tested.

Role Of The Tug

To state the obvious, the tug must carry, deploy, tow, and recover the towed gear. Unless the handling and storage mechanisms are configured for independent powering (i.e., with a self-contained prime mover) the tug also must furnish the power for the winch drive, the equipment within the towed body (e.g., pumps, sensors), and instrumentation and other ancillary items. The tug provides the thrust to pull the towed gear through the water, and when operating in the sea, imparts transient disturbances to it.

The electrical systems of ships typically exhibit significant fluctuations in voltage and frequency. This occurs as a result of pumps, and other loads coming on or off line in a system that typically has small excess capacity, and negligible inertia. Isolating sensitive electronic and electrical equipment is prudent. Ground loops are also an ever-present hazard.

The power required to tow at moderate speeds is usually small compared to an oceangoing ship's total propulsive power. The ship's speed control, particularly its minimum speed, is important to overboarding and recovering the towed gear. Overboarding and recovery should always be accomplished under way, as this assures proper orientation of the towed system and permits selection of the most comfortable course for those operations. In particular, if the towed body is hoisted into and out of the water from a ship with high freeboard, attempts to launch and recover while laying to can result in excessive pendulation of the towed body, and consequent danger of damage to equipment, injury to personnel, or both. Most ships will come broadside to sea and wind when laying to, and roll rather heavily, even in moderate seas. If faired towlines are used, underway launching and recovery is virtually mandatory.

The most important interaction between the tug and towed system occurs at the overboarding station. Close coordination between the winch control station and the bridge is absolutely necessary if overboarding is to proceed smoothly and safely.

The selection of the location for streaming the towed gear must be made with due consideration of the characteristics of the towed gear. The least risky place from the standpoint of entangling the tow in the ship's screws is the ship's fantail. If the towpoint must be located along the ship's side, arrangements should be made to avoid having the ship's stern slide across the towline. Remember that when under way the towline angle at the surface will typically be near the horizontal, and that a significant length will be necessary to reach the water on a ship with a high freeboard.

Handling and Storage

The term "handling" includes all equipment and actions involved in overboarding, streaming, and recovery of the towed gear. In most cases, the storage unit is an integral part of the handling equipment.

It is occasionally beneficial to separate the two functions, however, and this provides a convenient division for the purposes of this discussion.

A typical handling system includes a means for placing the towed body in the water, streaming the towline, recovering the towline, and retrieving the towed body. This requires an ability to apply tractive forces to the towline to control the rate of deployment and retrieval, a braking mechanism, and a prime mover, together with a transmission. This discussion will be limited to the interaction of the towed system and handling gear.

Handling systems tend to be highly specialized, as they function as the interface between the tug and the towed system. The geometric arrangements of components is heavily influenced by the tug's deck arrangements, and the configuration of individual components depends on the characteristics of the towed system.

From a system viewpoint, it is highly desirable that the so-called fleet angle be minimized. This is the angle subtended by the long axis of the towline and the plane defined by the sheave or grooves of a traction drum or winch. Winches handling round cable will spool properly for fleet angles up to about 1-½ degrees for smooth drums, and about 2 degrees for grooved drums. If larger fleet angles are necessary, level wind devices are required; for example, the Lebus type or the diamond thread reversing screw type.

The fleet-angle problem is aggravated significantly if a sectionally faired towline is used, as the rigid sections must be bent in a direction transverse to the plane of symmetry to accomplish fleeting. Methods for avoiding this problem will be discussed later.

Most towed systems use a towing sheave with a fixed axis. If the towline kites (as when the tug is in a turn) the towline will assume an angle relative to the plane of the towing sheave. This angle is not predictable, as kiting may arise from any of several causes. It is therefore prudent to guard the sheave to assure that the towline does not jump out of the sheave groove.

A preferred approach consists of allowing the sheave to rotate about an axis co-linear with the inboard standing line. If a conventional powered drum is used and fleeting is required, the streaming sheave should be free to rotate about a vertical axis, as illustrated by Figure 6.

There are three reasons for this concern with towline entry attitude into sheaves, or onto grooved drums:

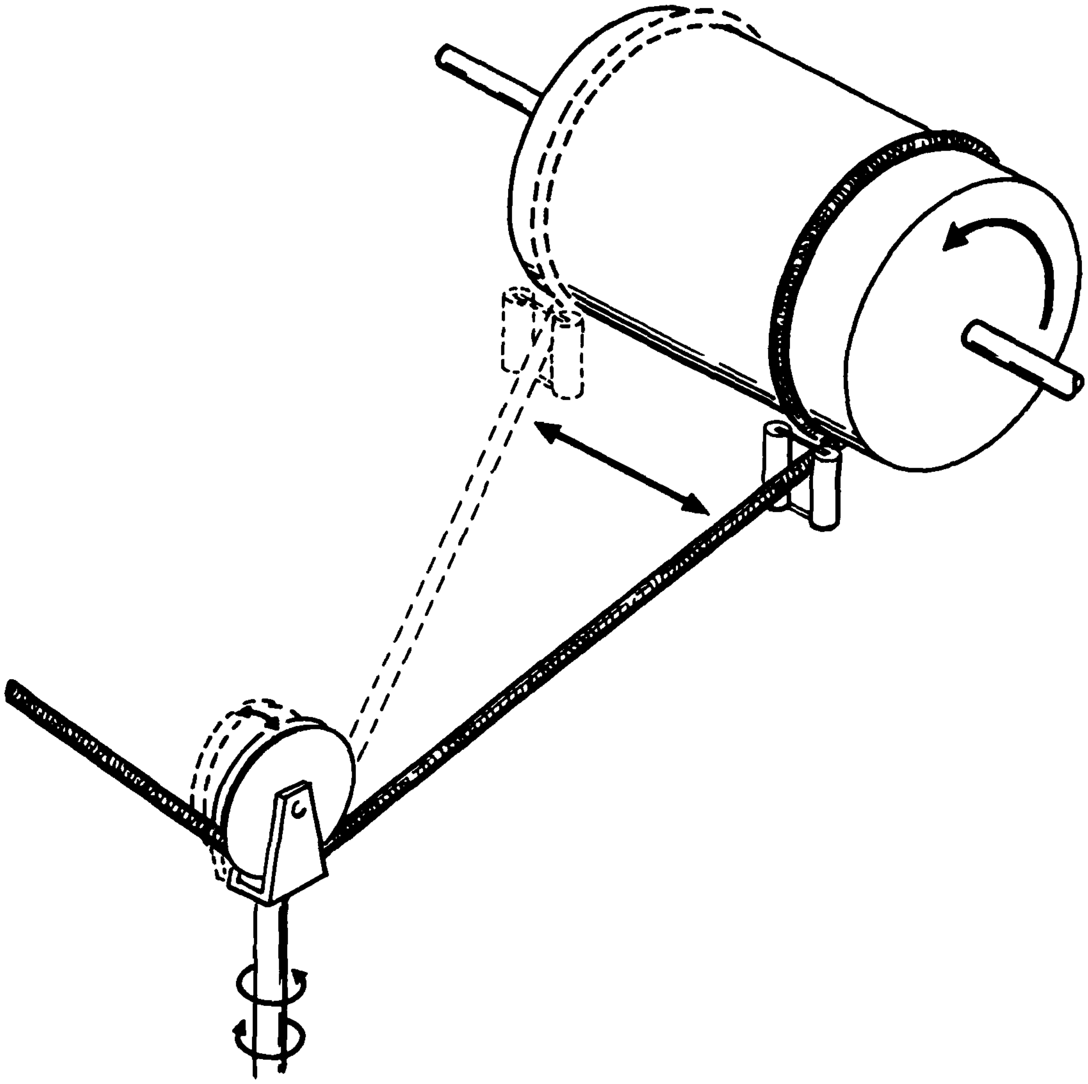


Figure 6 Conventional stowage configuration.

1. The towline may climb over the lip of the sheave or groove and pop out when the towline is inhauled.

2. Significant abrasion of both towline and sheave may result.

3. If the towline is faired, the friction forces may rotate the fairing into an improper position. With a round towline, rotations may accumulate to the extent that under certain conditions the towline may become "wild" when tension is relieved.

The concern is illustrated by tests conducted with a normal fleeting-type winch, a vertically pivoted streaming sheave, and a towline faired with trailing-type fairing as shown in Figure 7. Kiting was simulated by lateral displacement of the towline outboard of the streaming sheave. The resulting configuration of the towline relative to the streaming sheave is shown in Figure 8. Significant abrasive damage resulted when the towline was inhauled.

If the towline is faired, these considerations become very important. Sectional fairings, for example, with their rigid articulated members, can sustain only moderate bending athwart the plane of symmetry without damage. If a change in direction of the towline run is required, it is desirable that the sections be rotated into the plane of the turning sheave. Some concepts developed in 1969 for solving these problems are illustrated in Figures 9, 10, and 11.

If a flexible fairing is used, the fairing may be bent athwart the plane of symmetry. This is illustrated in Figure 12, in which a towline with trailing fairing is wrapped about an inter-digitated, canted drum winch.

The storage volume required for faired towlines is quite large in comparison to that required by equal lengths of round towline. Typical fairings do not have sufficient structural strength to permit winding in multiple layers like wire rope. Sectional fairings are typically wound on a drum with the trailing sections normal to the drum face. Several strategems have been developed to increase the storage density. The slotted-drum concept, for example, has been promoted by Fathom Oceanology, Ltd., and is illustrated in Figure 13. Another concept, the SCAT (Submerged Concentric Axially Traversing) winch was developed for the U.S. Navy. The principle of operation is shown in Figure 14. A prototype of this winch was developed and successfully tested in the early 1970's.

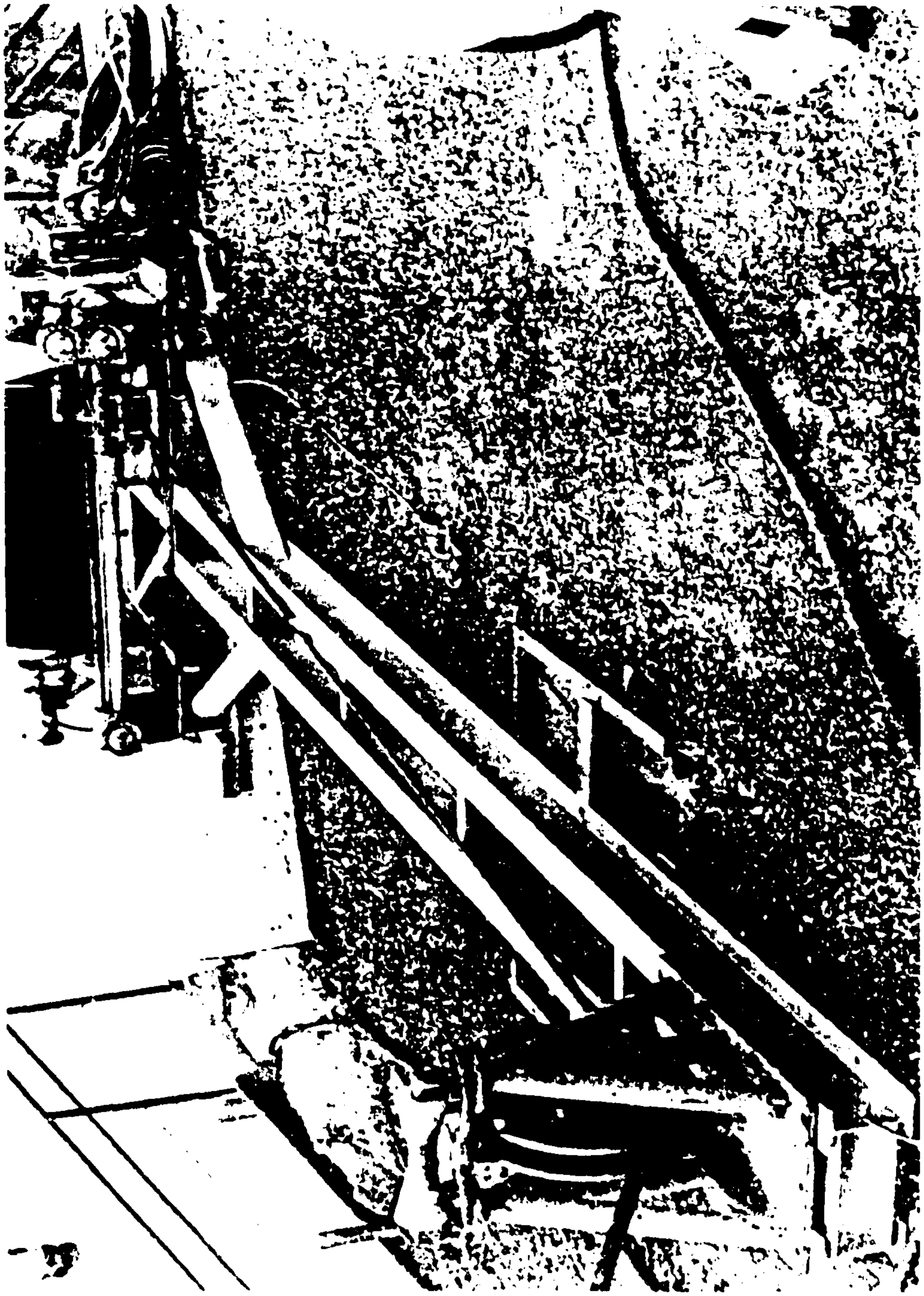


Figure 7 Winching and streaming sheave mounted on test bed.

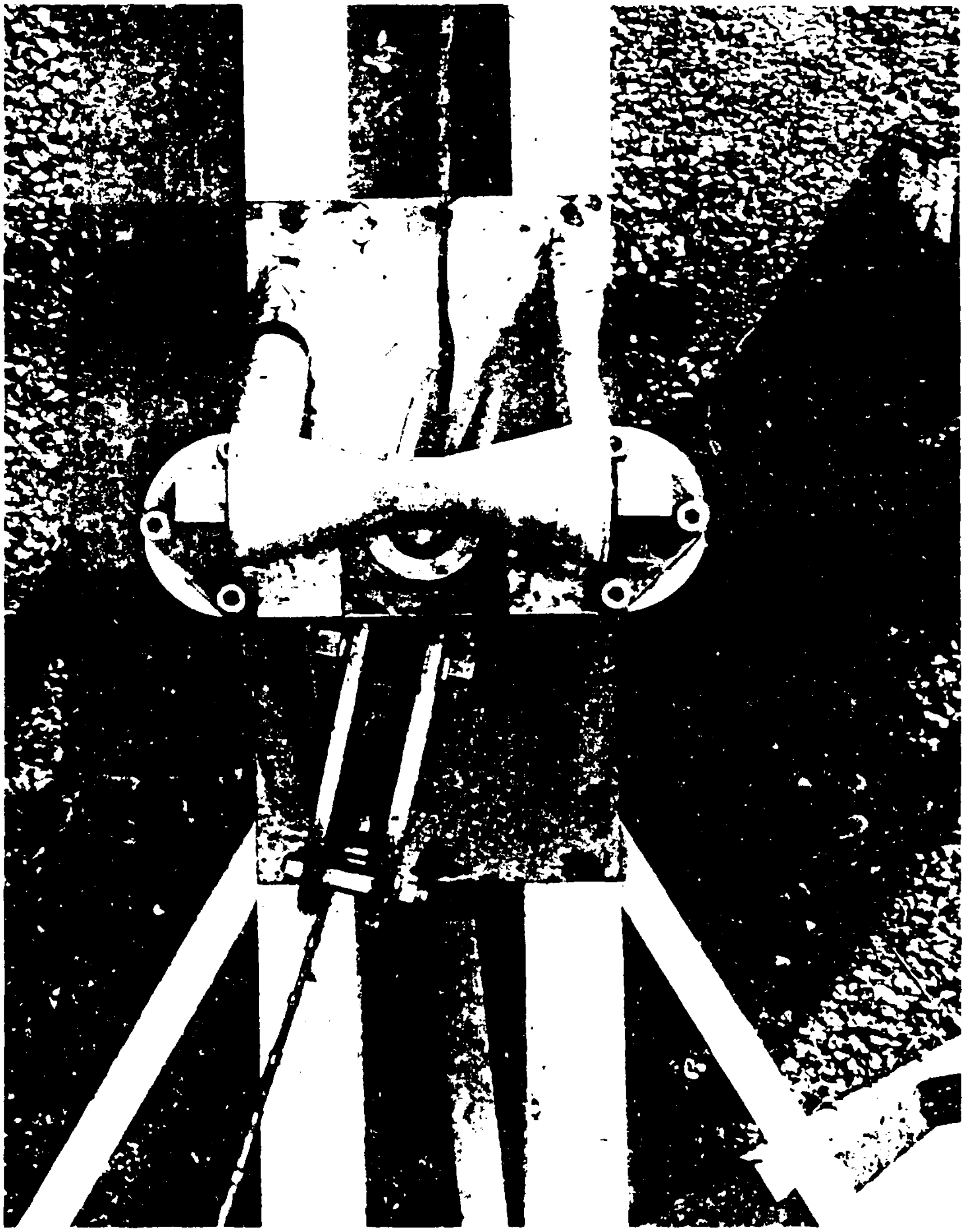


Figure 8 Streaming sheave, illustrating the effect on non-vertical orientation of the towline.

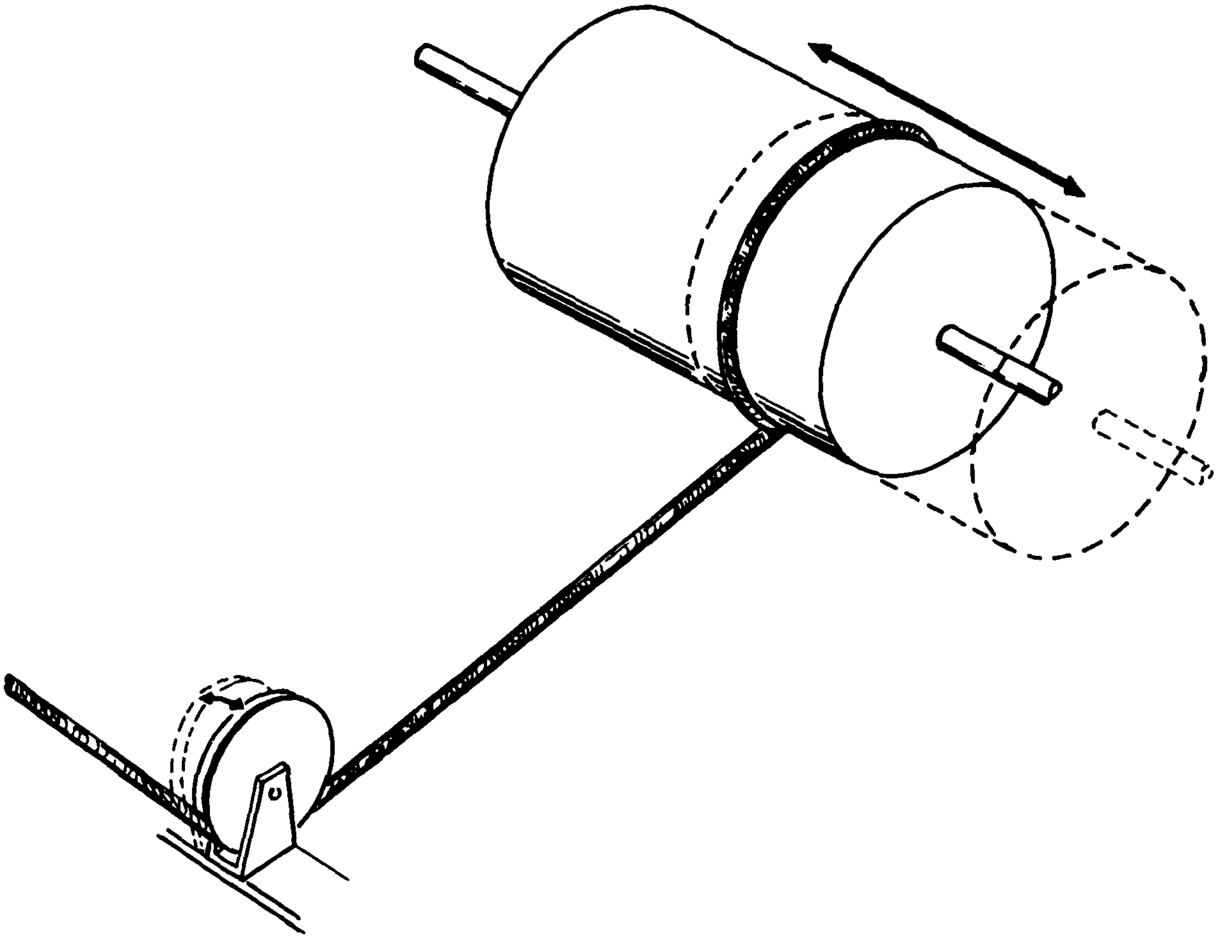


Figure 9 Traversing storage drum configuration.

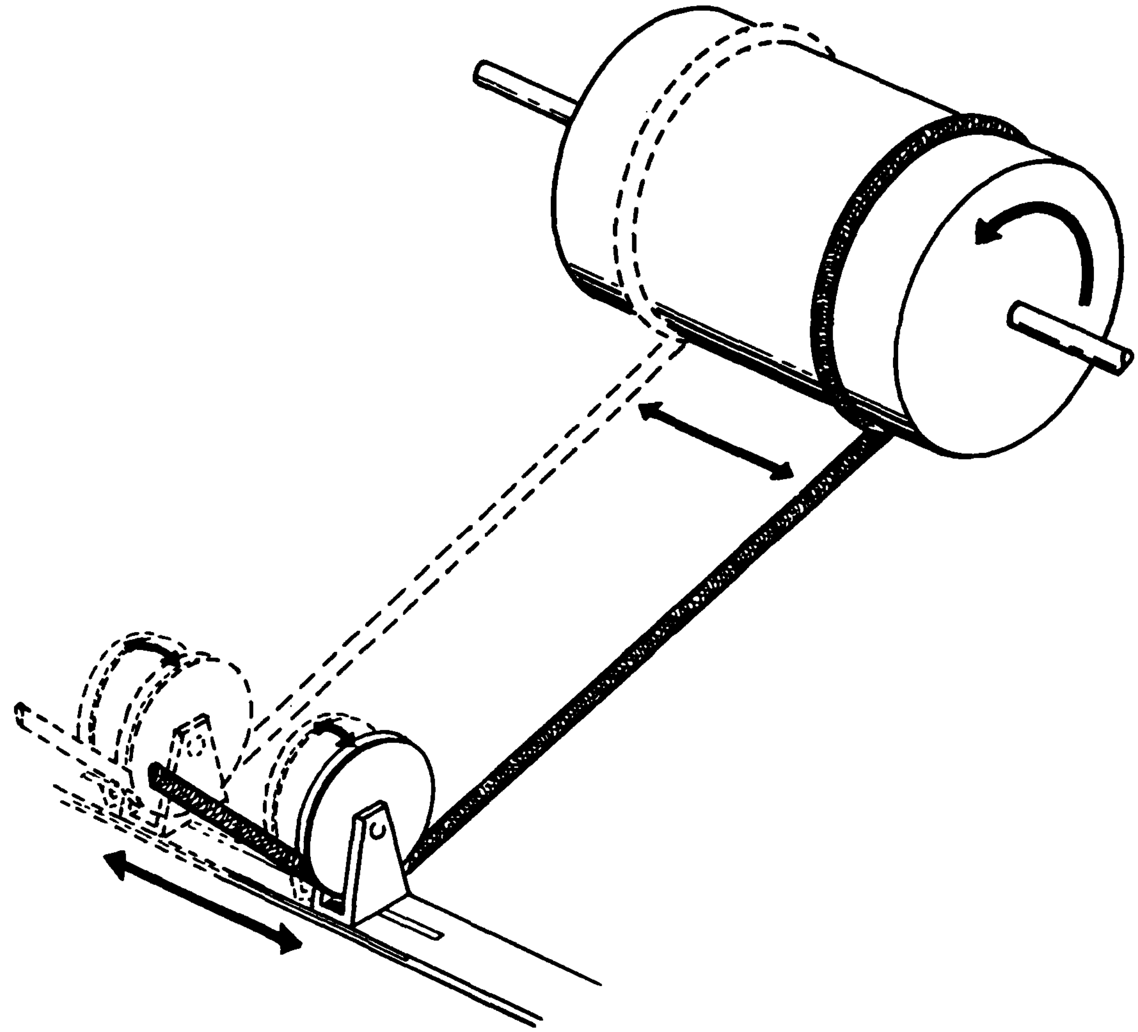


Figure 10 Fleeting-streaming sheave configuration.

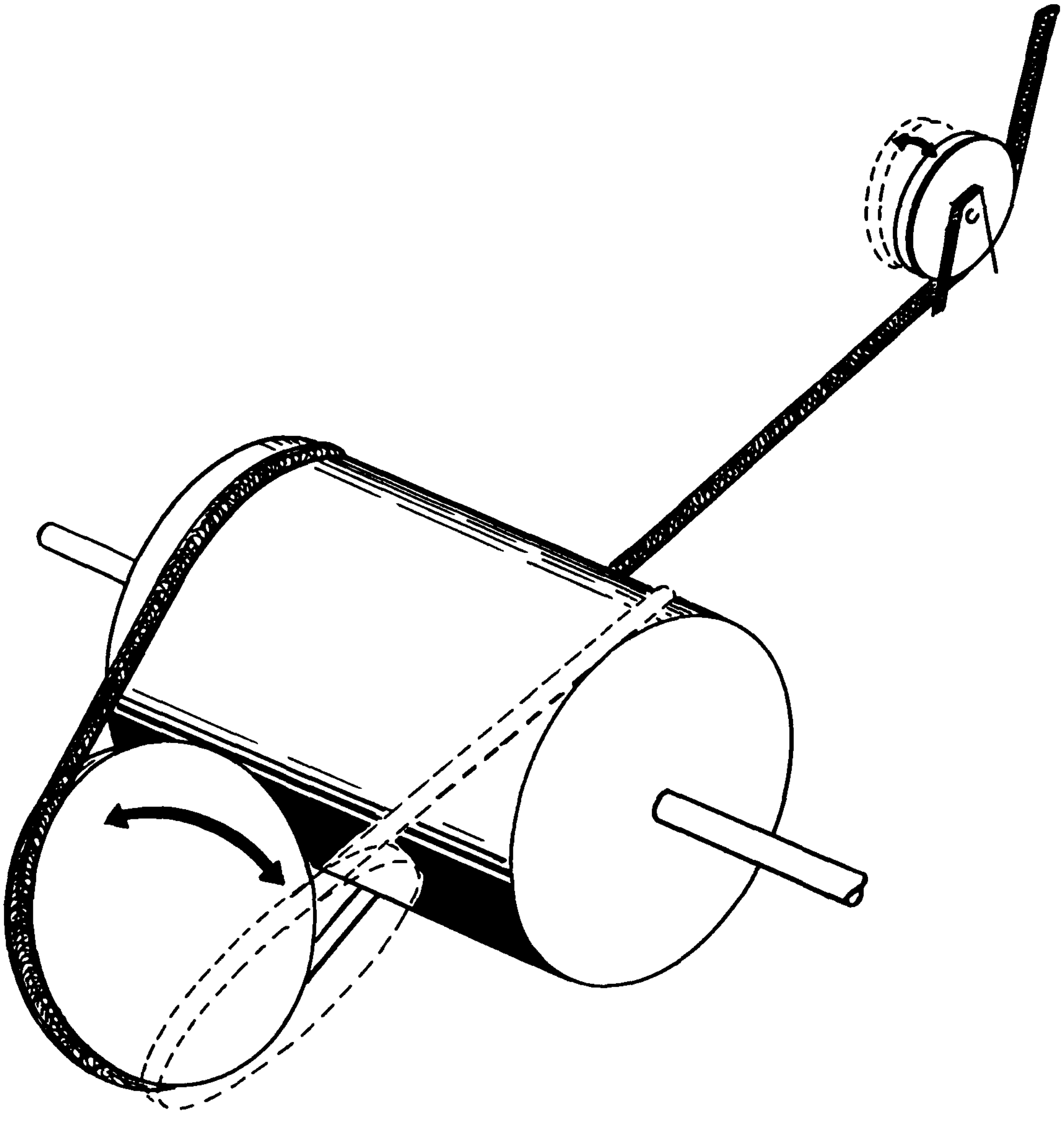


Figure 11   Pivoting sheave configuration.

Figure 12 Interdigitated traction winch with DTMB trailing fairing.

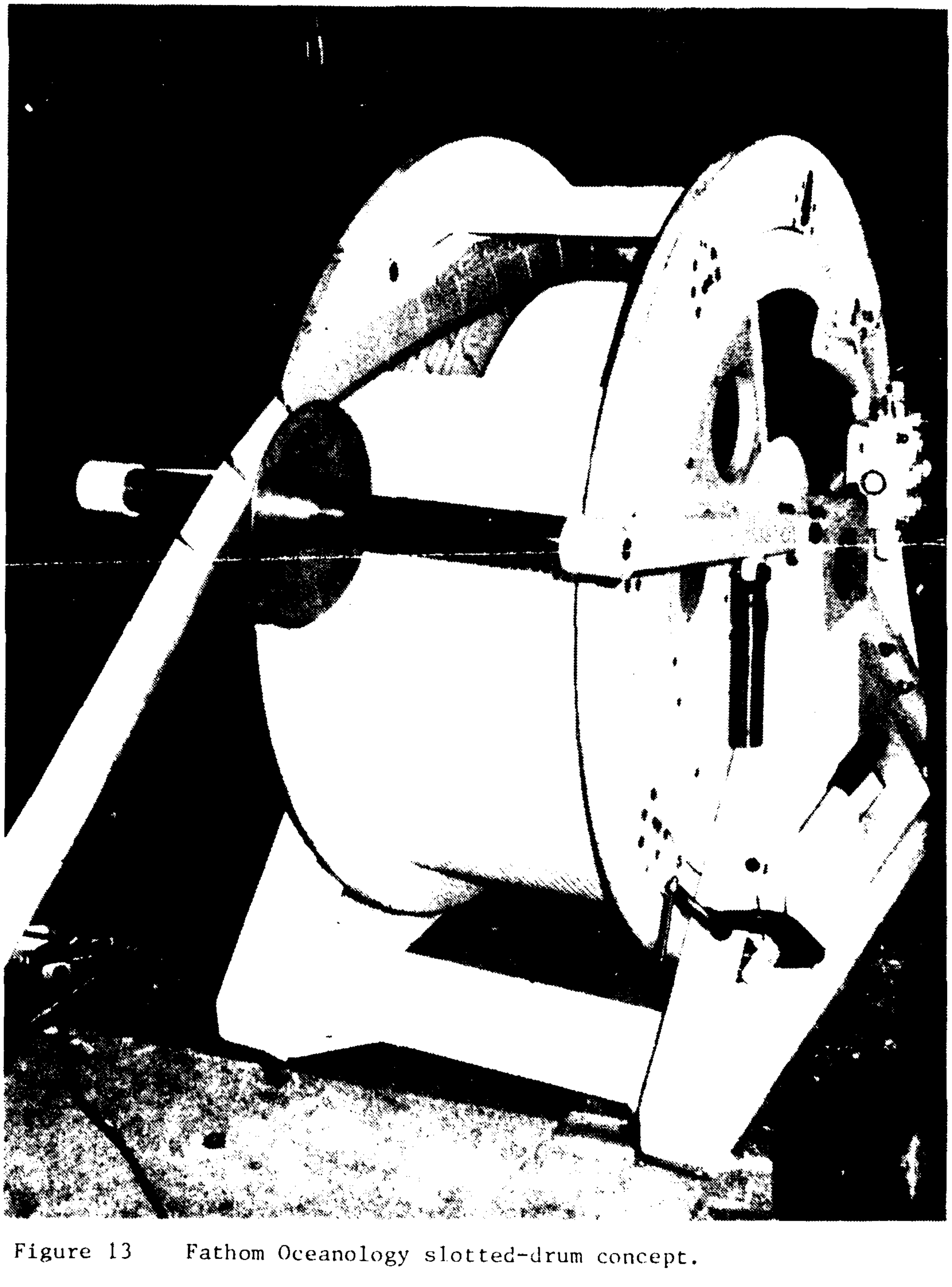


Figure 13   Fathom Oceanology slotted-drum concept.

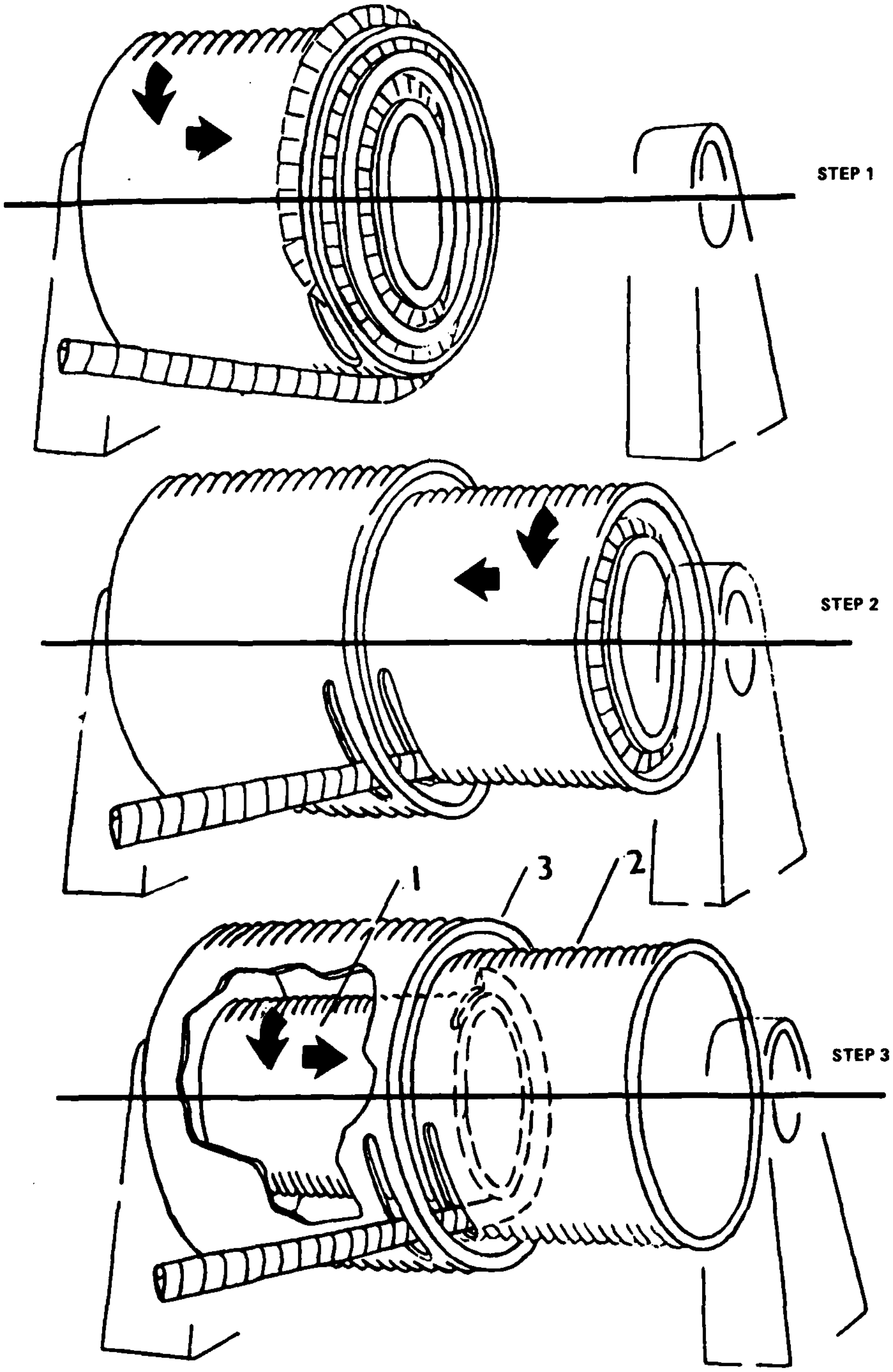


Figure 14 Axially traversing multiple-drum winch for faired towlines.

Towlines with flexible fairings are also stored tail up. It is obvious that the slotted drum and SCAT concepts also could be used with flexible fairings. Two other methods, particularly useful for the trailing-type fairings (in which the strength member is exposed), have been used. These involve the use of traction devices to sustain the tensile load with separate multiple-layer storage.

Tests[16,17] on linear-traction machines produced by Entwistle and Western Gear were conducted in the early 1960's with positive results. Figure 15 shows the Entwistle line-puller and Figure 16 shows the Western Gear cable hauler. The latter incorporated features that allowed the machine to pass "lumps" in the towline, such as the instrument module shown.

A second method, shown in Figures 17 and 18, involves the use of dual drums (or capstans) arranged such that the axes of rotations are inclined (canted) in a way that transports the towline laterally each half-revolution. The towline is moved along the pair of drums without sliding or rolling. A compact configuration in which the two drums are interdigitated has been described by the Naval Research Laboratory.[18]

Towlines faired with fully enclosing continuous fairing cannot be handled by these mechanisms unless the fairing is sufficiently deformable to transmit the shearing loads into the tension member.

Strum-suppressed towlines typically use a very tough elastomer for the strum-suppression appendages. The towline may thus be handled like bare armored cable. A certain number of the strum-suppression appendages (e.g., ribbons) may be cut or torn in the process of reeving, but this is not serious, as a significant number can be lost without loss of anti-strum properties.

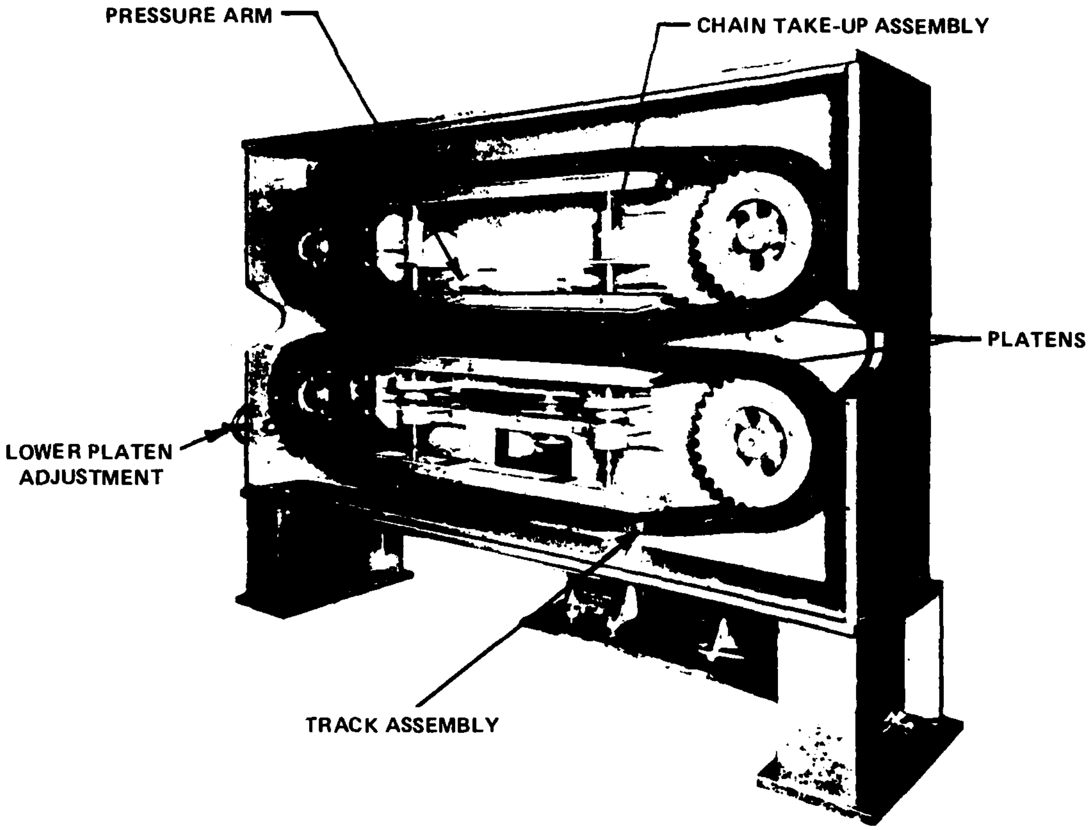
Porpoising And Depth-Controlled Systems

The depth of the towed-body end of the towline can be varied by changing scope, by varying the value of T_o and ϕ_o, or by a combination of both methods. The method selected depends entirely on the users' requirements.

Winch-Controlled Systems. The change of depth per unit of change in scope is given by

$$\Delta y = \sin\phi_l \ \Delta s$$

At large scope-to-depth ratios, $\phi_l \rightarrow \phi_c$.



CLASS D
TYPE D-VA-72
CATERPULLER

TRACK DESIGN: FLOATING AND BOTH DRIVEN
TRACK ARRANGEMENT: VERTICAL
LOADING: SINGLE TRACK – MULTIPLE PNEUMATIC
EFFECTIVE TRACK LENGTH: 45 INCHES
MAXIMUM PULL: 4000 LBS. AT 100FPM
MAXIMUM POWER INPUT: 20 HP
TREAD DESIGN: FLAT (Material – Black Neoprene Jacket Compound, 60 ±5 Durometer)

Figure 15 Entwistle Manufacturing Company linear cable engine.

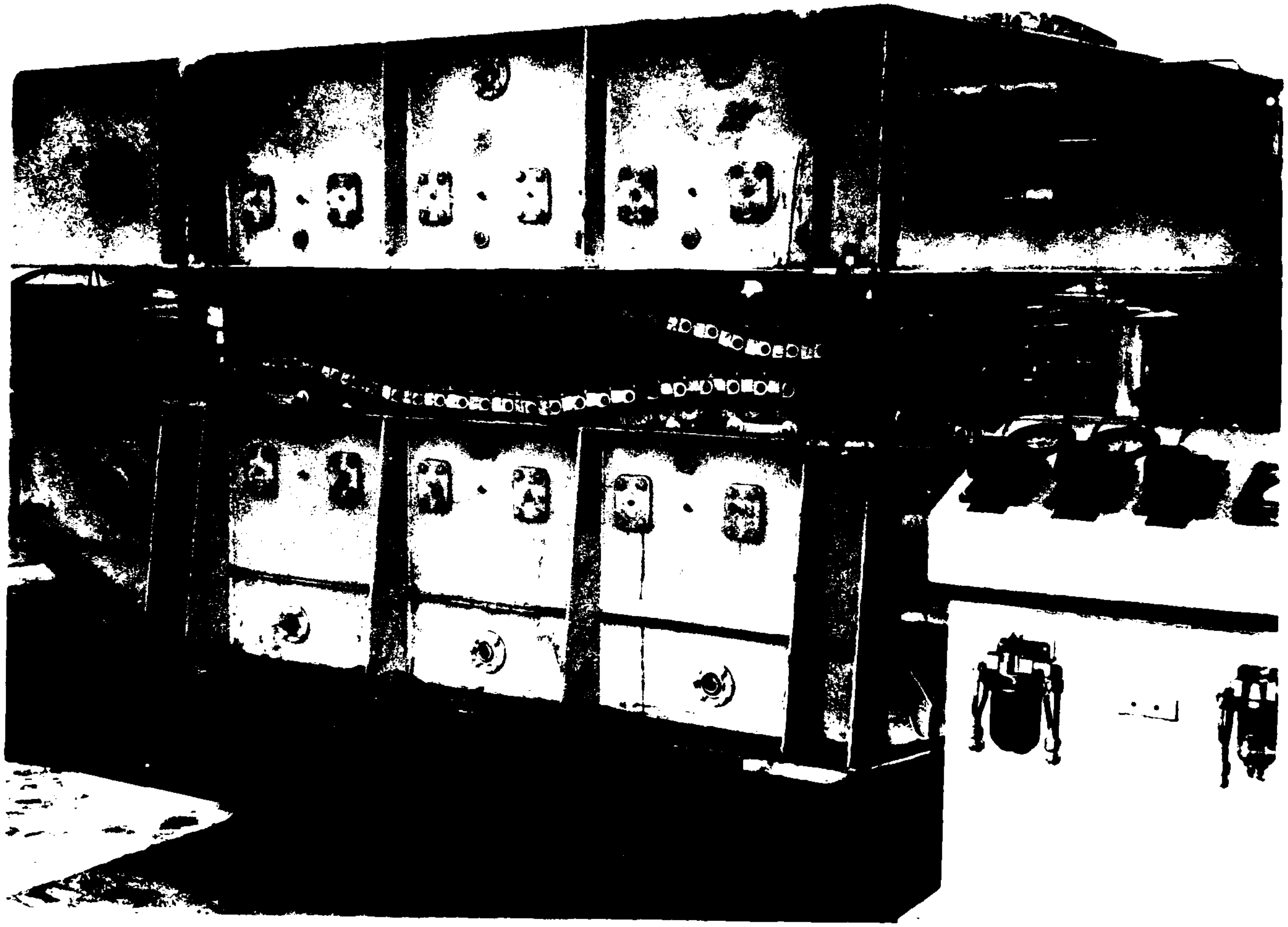
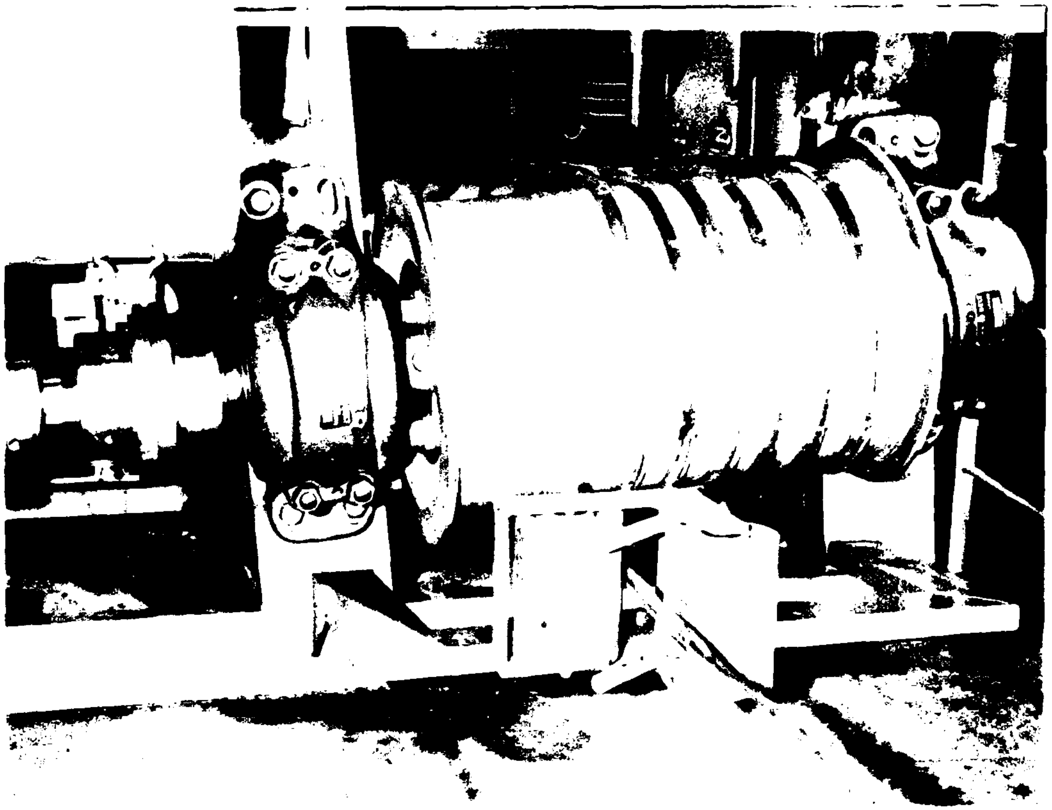
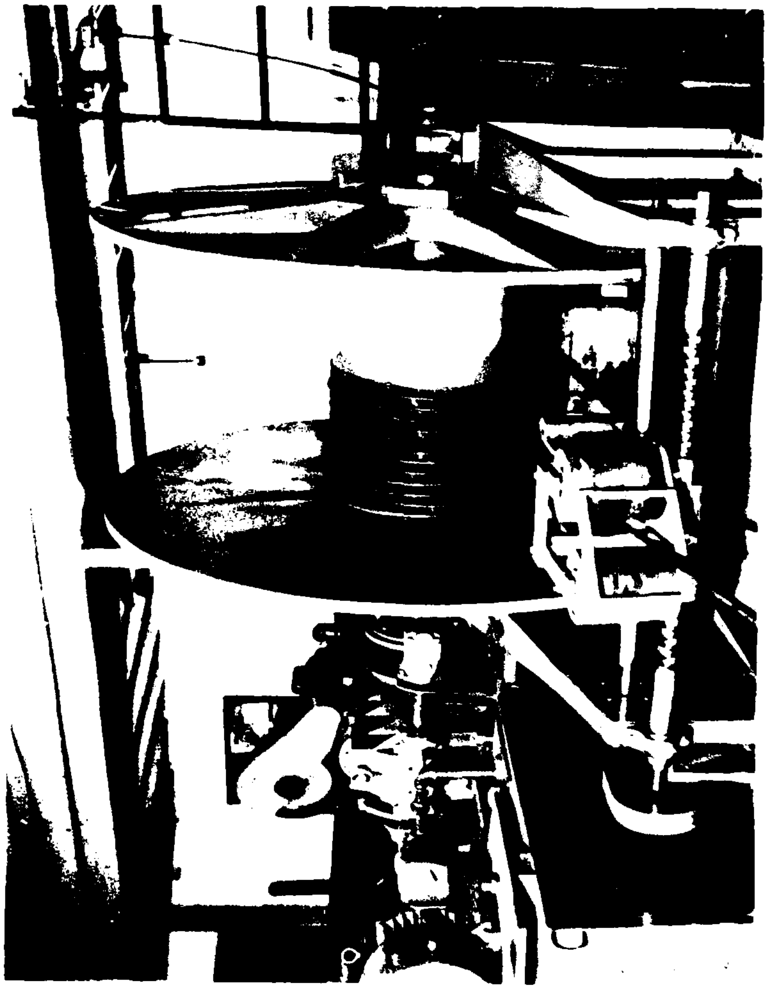


Figure 16 Western gear cable hauler showing passage of a large module.



A. Traction Drums

Figure 17 Canted drum capstan reeved with DTMB trailing fairing.



B. Storage drum.

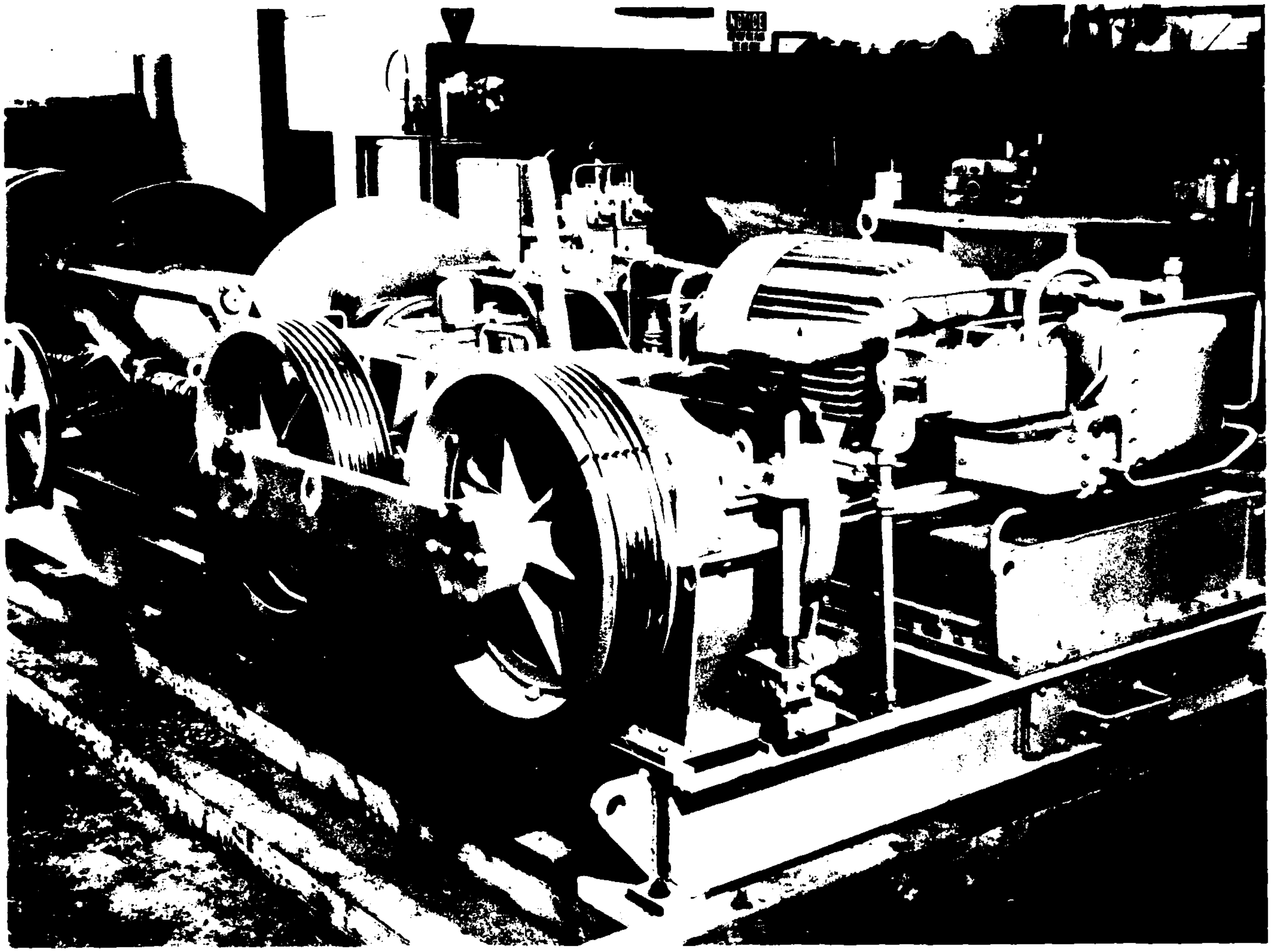


Figure 18 Canted dual drum capstans for round towlines.

The technique is especially applicable to systems with low towing speeds for which ϕ_1 *may* be large. The value of ϕ_1 is usually small for systems used at high towing speeds, so winching will be unsatisfactory unless a very slow rate of change of depth is acceptable.

From a winching standpoint, the technique is most satisfactorily used with round towlines, as the techniques for handling these are well understood. If a faired towline is used, great care must be taken to assure that the fairing is not damaged.

Under appropriate circumstances, the winch can be automatically controlled by feedback sensors. One such system is in use in the Navy.

The major disadvantage of the winching approach, other than the inherent response limitations, is that the winch must be powered to inhaul at the maximum tensions developed by the towed system instead of at the lower tensions perhaps available at a lower speed of tow.

Body-Controlled Systems. If T_o and ϕ_o can be controlled, the depth of the towed-body end of the towline can be changed. The limits are established by the range of T_o and ϕ_o available and the characteristics of the towline catenary.

For round towlines, the system may be designed to rise above the depth established by the critical angle by exerting an upward force on the end of the towline. In this case, the towline will approach the towed body from below and the body must be towed from the nose or by a bail that can pass across the nose. Special consideration must be given to body stability in this case, as the towed system is generally not in stable equilibrium in this configuration, and may roll over.

The depth region above that established by the critical angle is not available to systems using faired towlines, as for angles less than critical, the fairing must buckle. This would of course lead to extremely erratic towing, and is thus unsatisfactory.

The usual method for controlling T_o and ϕ_o is by controlling a hydrodynamic lift device (a wing) attached to the body. Control can be effected by changing the wing attitude relative to the body or by changing the attitude of the body (with a fixed wing) by means of an elevator-type control in precisely the same manner that a pilot controls the attitude of a fixed-wing aircraft. In either case, a particular configuration will result in a map of T_o and ϕ_o as a function of the angle of attack.

The limits on response time are established by the range of T_o and ϕ_o available, the maximum value of T_o (relative to the strength of the towline) and the frequency response of the towline. In general, to obtain the full range of depth variation established by steady-state parameters, the response rate must be limited to that for which the towline is in near-static equilibrium during the depth transients. Also, the velocity of the towed body will exceed the steady-state velocity when depth is increasing. Since the hydrodynamic forces are proportional to the square of the relative velocity, the maximum response rate must not be so high as to exceed the tensile capacity of the towline. Relative velocities on the order of 2 to 3 times steady state may be developed.

When decreasing depth, using a faired towline, the relative velocity may not be so high as to reverse the flow over the towline, as this will have the same effect as towing at depths less than those established by the critical angle.

The hydrodynamic control can of course be programmed to vary periodically, thus producing porpoising, or to respond to some environmental sensors such as depth, height above bottom, or thermal gradient.

Anticipating some later results, it is very doubtful if a system can be made to change depth in response to water parameters measured on deck due to the large lags required for sample transport.

Combined Systems. The range of depth variation available is a function of towline scope. Therefore, a scope for each depth range must be established within which the towed body can maneuver properly. It is, of course, feasible to automate this process, but it may not be worthwhile owing to the overall technical complication of the system.

Applications

Some of the undesirable effects of incorporating sample delivery tubes in a round towline were discussed earlier. The EG&G design[7] was used as an example to show these undesirable effects and well illustrates the effect of system constraints on the design process. It is obvious that a design of this type will never achieve the objectives of 800 meters at 8 knots with equipment of acceptable size. Therefore, it is evident that a faired towline will be required.

In either case, the first thing we need to know is how large to make the sample tubes. Examination of the optimum values of $\bar{\sigma}/\tau$ and $\bar{\eta}/\tau$ (recalling the meaning of $\bar{\eta}/\tau$) shows that the optimum scope-to-depth ratio is about two. Thus, for a depth of 800 m, the wetted length of towline will be about 1,600 m (5,248 ft), say 5,500 ft for convenience.

The pumping power per unit length of smooth tubing can be written in the form

$$\frac{550P}{QL} = \frac{\rho\lambda}{2D}\left[\frac{4Q}{\pi D^2}\right]^2 .$$

The value of λ is given by the Blasius equation[19]

$$\lambda = 0.3164\ R^{-\frac{1}{4}}$$

which is valid for $R = \frac{\overline{U}D}{\nu} \leq 100{,}000$.

In the above:

P = horsepower
Q = volume rate of flow
L = total pipe length
$\overline{U}$ = average velocity = $Q/(\pi D^2/4)$
D = tube I.D.
and ν = kinematic viscosity.

Taking the minimum flow requirement, 20 liters per minute[1], the quantities shown in Table 2 were calculated.

It thus appears that a 5/8 in. ID tube would suffice. For three tubes we require 5.25 HP delivered to the fluid. Accounting for inefficiencies, say 6 HP. We have now arrived at a point where a decision must be made. What type of power will be available to drive the pump? For the moment, it is assumed that the necessary power and control information can be transmitted.

If we select 5/8 in. as the ID of the tubing, we can project a fairing 1 in. to 1-1/8 in. thick. For purposes of this preliminary study, let us select a DTMB No. 7 fairing with four holes as illustrated by Figure 19. A fairing thickness of 1-1/8 in. would provide a wall thickness of 1/4 in., which should be sufficient. Assume the fairing to be neutrally buoyant.

We find, assuming $C_R = 0.14$ (a conservative value)

R = 2.4 lb/ft
W = (1.5) lb/in^2 $(0.625\ \text{in})^2$
= 0.59 lb/ft
W/R = 0.2445

and therefore $\phi_c \simeq 20^\circ$.

TABLE 2 - Effect of tube size sampler requirements for flow of 20 liters/min.

D (in.)	1/4	1/2	5/8	3/4	1
P/L (HP/ft)	2.5×10^{-2}	9.2×10^{-4}	3.2×10^{-4}	1.34×10^{-4}	3.42×10^{-5}
P (HP) (L = 5500 ft)	136	5.1	1.75	0.74	0.19
R	60,000	30,000	24,000	20,000	15,000
Δp (psi) (L = 5500 ft)	44,200	1,600	568	240	61
$\overline{U}$ (ft/sec)	34	8.6	5.5	3.8	2.2
T (minutes)	2.7	10.6	16.6	23.9	42.5

Figure 19 Suggested four-hole arrangement for DTMB No. 7 fairing.

A 5/8 in. diameter, double-armored cable is assumed for the strength member. As the fairing is assumed to be neutrally buoyant, the weight in water is entirely due to the strength member.

Assuming $\phi_o = 70^o$, the value of $\bar{\eta}/\tau$ for $\phi_c = 20^o$ is 0.769. Thus,

$$T_1 = \frac{RY}{(\bar{\eta}/\tau)} = \frac{(2.4)\ (2624)}{0.769} = 8189 \text{ lb}$$

Also, $\tau_1/\tau_o = 5.88$ (from the unpublished tabulations); therefore,

$$T_o = 8189/5.88 = 1392 \text{ lb.}$$

and

$$S = (\bar{\sigma}/\tau)\ \frac{T}{R} = \frac{(1.6366)\ (8189)}{2.4} = 5584 \text{ ft} = 1700 \text{ m.}$$

Experienced towed-body designers will recognize that selection of $\phi_o = 70^o$ is highly conservative. This value corresponds to an L/D of less than 3 and is easily achievable with very crude designs.

These parameters are now compared with those for a round cable containing the 5/8 in. diameter tubes. For this purpose, assume a scaled-up version of the cable design developed by EG&G.[7] That cable weighed 2.1 lb/ft in water and had a 1.6 in. diameter. A scaled-up version incorporating 5/8 in. ID tubes would have a diameter of 2.7 in., and would weigh 5.98 lb/ft. The value of R ($C_R = 1.6$) is 65.7 lb/ft. Therefore,

$$W/R = 0.091$$

and

$$\phi_c = 17^o.$$

It can be shown that for critical angles greater than about 6 degrees, the minimum tension is obtained if the cable is towed at the critical angle. Thus, the cable scope is

$$S = 2624/\sin 17^o = 8975 \text{ ft}$$

$$T = SR\ [f_t + w\sin\phi]$$

$$= 27{,}500 \text{ lb}$$

where a value typical of armored cables, $f_t^* = 0.02$, has been assumed. Applying a downforce to this cable will decrease the scope but increase the tension.

---

* The mathematical conventions established by Pode[2] require that $f_t < 0$. It is common practice to quote it as a positive number, however.

The results are compared in Table 3.

TABLE 3 - Comparison of faired and round cables containing three 5/8 in. ID tubes

	Speed (kts)	Depth (m)	T_1 (lb)	T_o (lb)	Scope (ft)	Size
Faired	8	800	8,200	1,400	5,600	1-1/8" x 6-3/4"
Round	8	800	27,500	0	9,000	2.7" O.D.

The handling gear required for the round cable would be so massive that it is likely only a limited number of ships could accommodate it. On the other hand, the faired cable also presents problems. If a flexible fairing is used, a simple scheme comes to mind.

Suppose the fairing were separated in discrete lengths with a linking means. For example, let us use 1,000 ft lengths. Six 1,000 ft lengths could be spooled like tape on six spools mounted side by side on a single axle. If the hub were 3 ft in diameter, 45 wraps would be required, for a total spool diameter of about 12 ft. Reducing the lengths to 500 ft results in an 8.5 ft diameter spool. The widths of the individual spools would be about 7 in.* Allowing for the side walls, say 10 inches. The minimum total width of the six, 12 ft spools would be 5 ft, and the minimum width of 12 spools, 10 ft. The fairing and cable in air would weigh about 12 tons. Adding 5 to 10 tons of structure, motor, gear box, etc. we see that a handling storage unit weight of 17 to 22 tons is involved.

The towed body for the faired cable could be relatively small if dynamic lift is used to produce the downforce of 1,400 lb. In fact, without any allowance for body weight, a wing area of 15 square feet with an aspect ratio of 3, operating at an angle of attack of 10 degrees would meet the requirement.

Pumping

It will not be possible to pump from the deck, unless extremely low flow rates are acceptable, as the pressure drop across the tubing will result in cavitation. On the other hand, the pump will not necessarily have to be located at the lower end of the towline.

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* A DTMB No. 7 fairing was assumed. This fairing has a fineness ratio of 6.

It could be positioned at any level for which ambient pressure equals the pressure drop across the line on the suction side of the pump. This is readily calculated, and might be of interest for decreasing the voltage drop to the pump motor.

It is technically feasible at 8 knots to use propellers to meet the power requirement for the 5/8 in. tube shown in Table 2. Variable pitch would be required to permit pumping at lower speeds if the sample delivery rate is held constant. There will, of course, be some towing speed below which performance will significantly decline, even with variable pitch propellers, and of course, no samples could be taken if not under way.

Concluding Remarks

This paper has attempted to provide a basic knowledge of the factors underlying the physics and art of towing. Emphasis has been placed on the effect of system constraints on the towed sub-system and the feedback effects on the power/handling/storage interface with the tug.

These considerations were applied to the stated goals for a round and faired towline, and it is readily apparent that sample flow/power requirements drive the towline to a rather large size that in turn, drives the handling/storage interface to a size and bulk that significantly affects other goals--system portability, installation on a variety of ship classes, etc.

Thus, a very careful trade-off of the parameters is required to establish the field of options available. Also, making the prejudgment that a system meeting the towing performance and sample volume objectives will be extremely bulky, the trade-off studies should attempt to establish whether less demanding requirements can be met using modules derived from the higher-performance unit, or that a separate lower-performance system should be developed that would indeed be readily transportable from ship to ship with minimized interface requirements.

In conclusion, it is evident that underway water sampling at a depth of 800 m and 8 knots towing speed is technically feasible, but may not be very practical, owing to the bulk and cost of the towed gear.

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DISCUSSION

HERR: Would you comment on the combination of cable and depressor? For a pumping system, it would be advantageous if the pumping depth did not change drastically as the ship manuevers, as might occur with a a dead-weight depressor or bomb-type depressor.

We have had some experience with dynamic V-pin depressors, but in matching a V-pin depressor with a faired cable system, we have experienced instabilities, kiting problems, and other problems. You have limited your talk to cables, but cables and depressors are somewhat linked, don't you think?

GAY: They are, in fact, linked. The depressor design has to be matched to the towing system. If you could find an already existing depressor that could be towed at the desired depths and speeds, you would certainly use it.

If you wish to keep constant depth, you should use dynamic depression. There will be some weight, and therefore some small variation in depth with speed, but not significantly great.

I do not know whether your problem with kiting was due to the depressor or due to fairing. I would suspect fairing. You mentioned stacking problems, for example.

We have towed the flexnose fairing at a depth of 100 meters at 30 knots without kiting by using support rings along its length, thus avoiding the buildup of tangential force that causes cocking and misalignment leading to severe kiting.

PUMPING TECHNOLOGY

Lee H. Courtemanche

Several pumps have been developed that can be used or adapted for use in underway water sampling.

Figure 1 shows a centrifugal-type pump that employs centrifugal force to create work (measured in terms of flow, gallons per minute, and pressure feet, and foot-pounds per pound of energy). The pump shown in Figure 1 is one of several types of centrifugal pumps available. It is a horizontally split case, double-suction pump. Centrifugal pumps can handle large flows--up to 100,000 gallons per minute or more--and differential pressures in excess of 200 psi.

Figure 2 shows the interiors of three such pumps. The parting, or access to the mechanical assembly, is on the horizontal plane, thus the designation, horizontally split case pump. The critical fit is that of the outer diameter of the impeller hub to the inner diameter of the casing ring. These units are packed-box versions. An option with this type of pump is to use a mechanical seal on both sides of the impeller. There are many combinations and varieties.

Figure 3 shows three versions of a horizontal end-suction pump used in some of the sampling systems we have been discussing. This pump has also been mentioned in reports of underway water sampling. The pump pictured is a back pull-out, horizontal pump, available off the shelf in cast iron, bronze, 316 stainless steel, Teflon, and titanium, with limitations, of course, in size and configuration particular to the materials used and the method of construction.

These pumps are electrically motor driven, and mounted on a bedplate, with a coupling and oil lubrication. Deflections at the face of the stuffing box, shown in Figure 4, are less than a couple of thousandths of an inch, to give the user optimum service.

The interior view of these pumps depicted in Figure 4 indicates the principle of their application: reliance on the impeller to create a centrifugal force that causes flow at a certain pressure. Various sizes and configurations of this pump are available (those pictured are employed in the chemical, petrochemical, and brewing industries), and some have been used for water sampling.

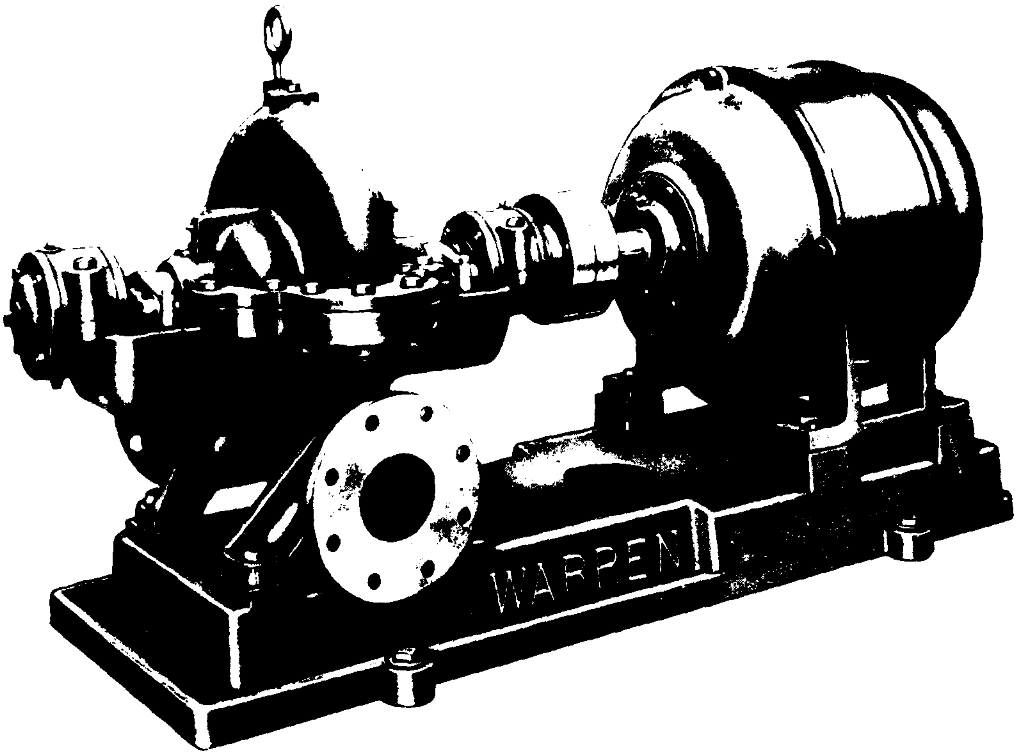

Figure 1 Single-stage, double-suction centrifugal pump.

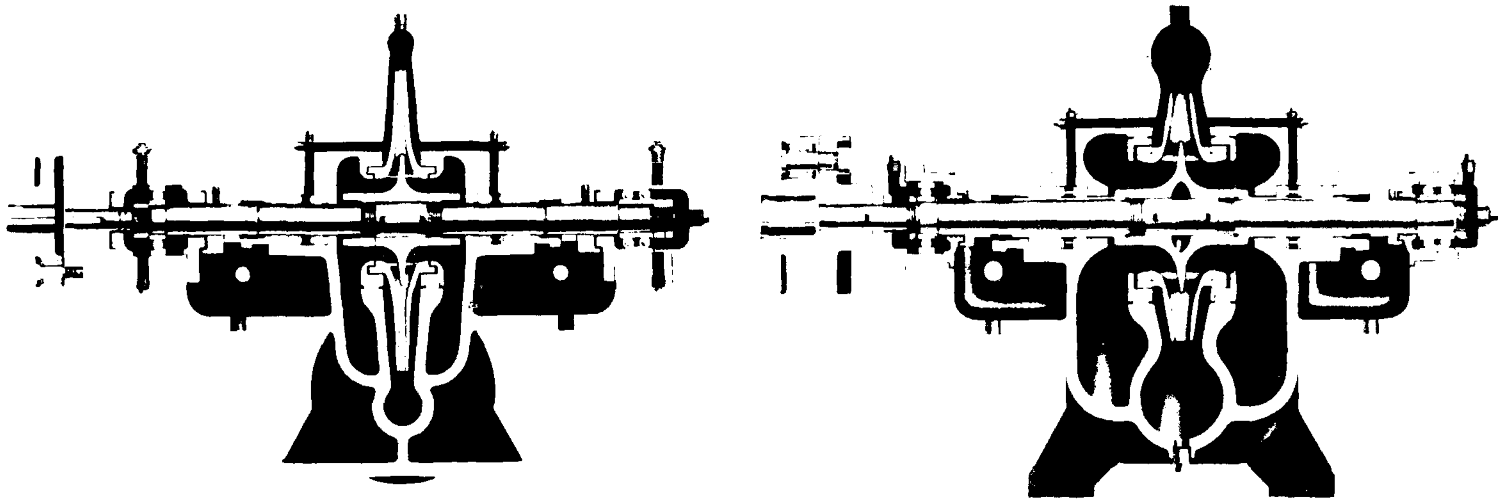

Figure 2 Sectional views of three versions, single-stage double-suction centrifugal pumps.

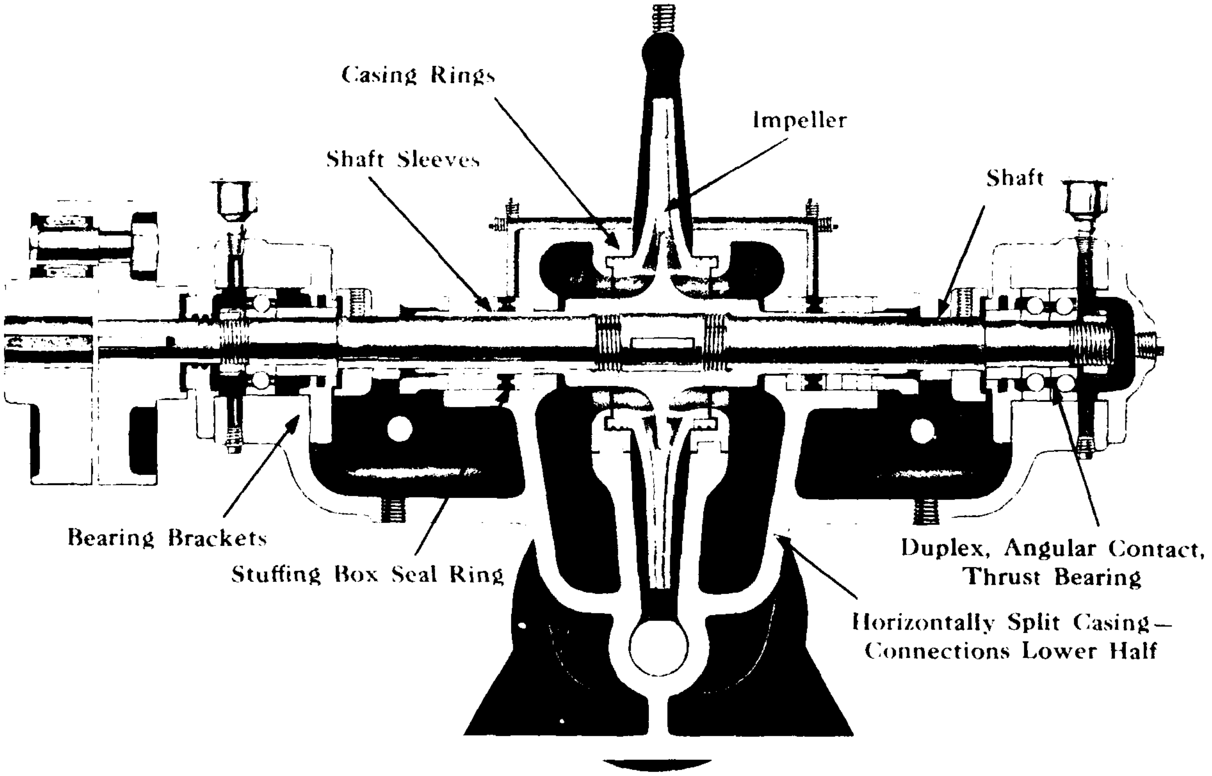
Casing Rings
Impeller
Shaft Sleeves
Shaft
Bearing Brackets
Stuffing Box Seal Ring
Duplex, Angular Contact, Thrust Bearing
Horizontally Split Casing—Connections Lower Half

Figure 2

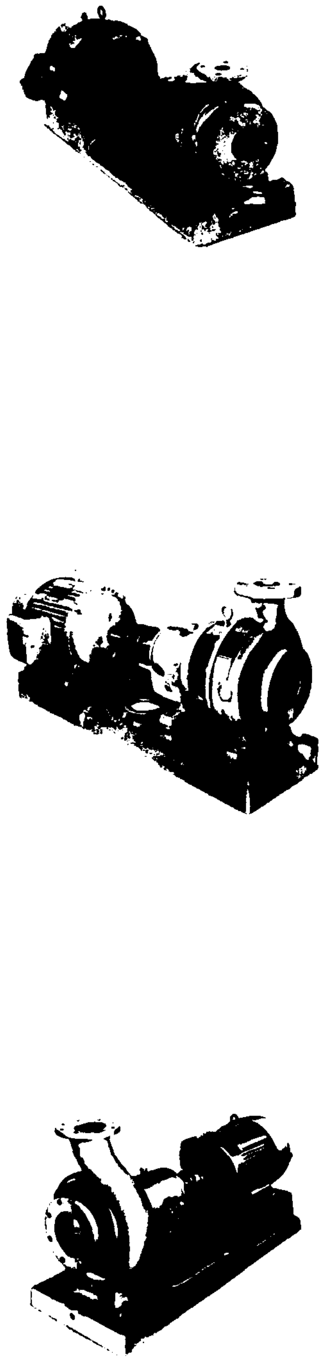

Figure 3 Three versions of horizontal end-suction pumps.

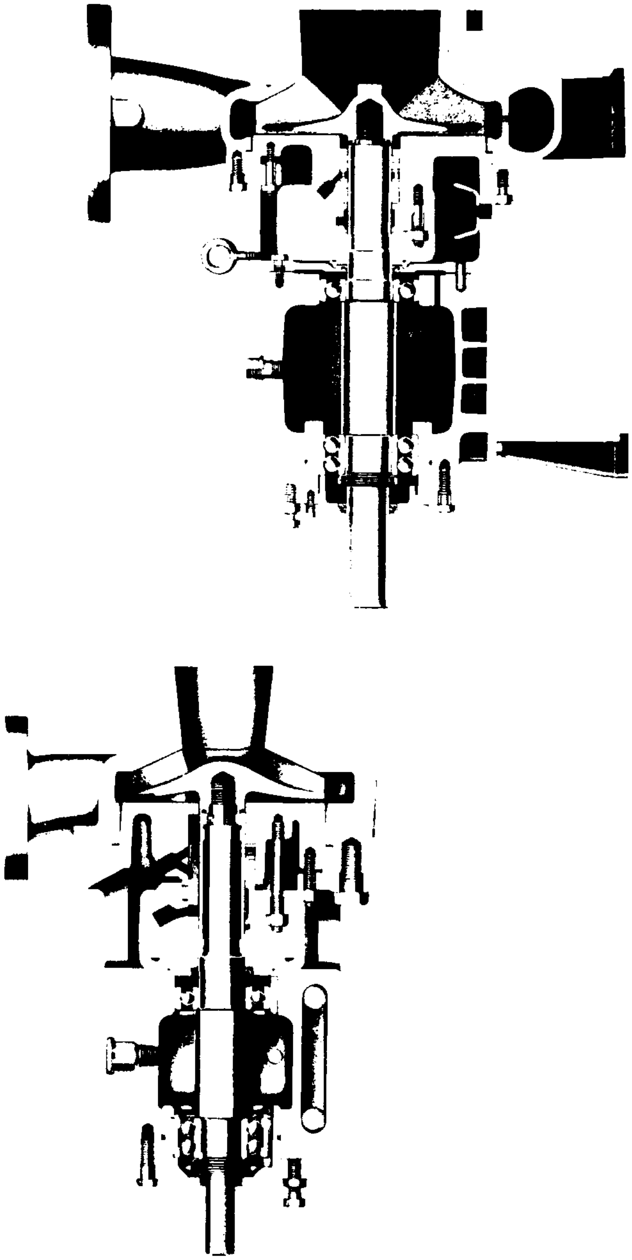

Figure 4

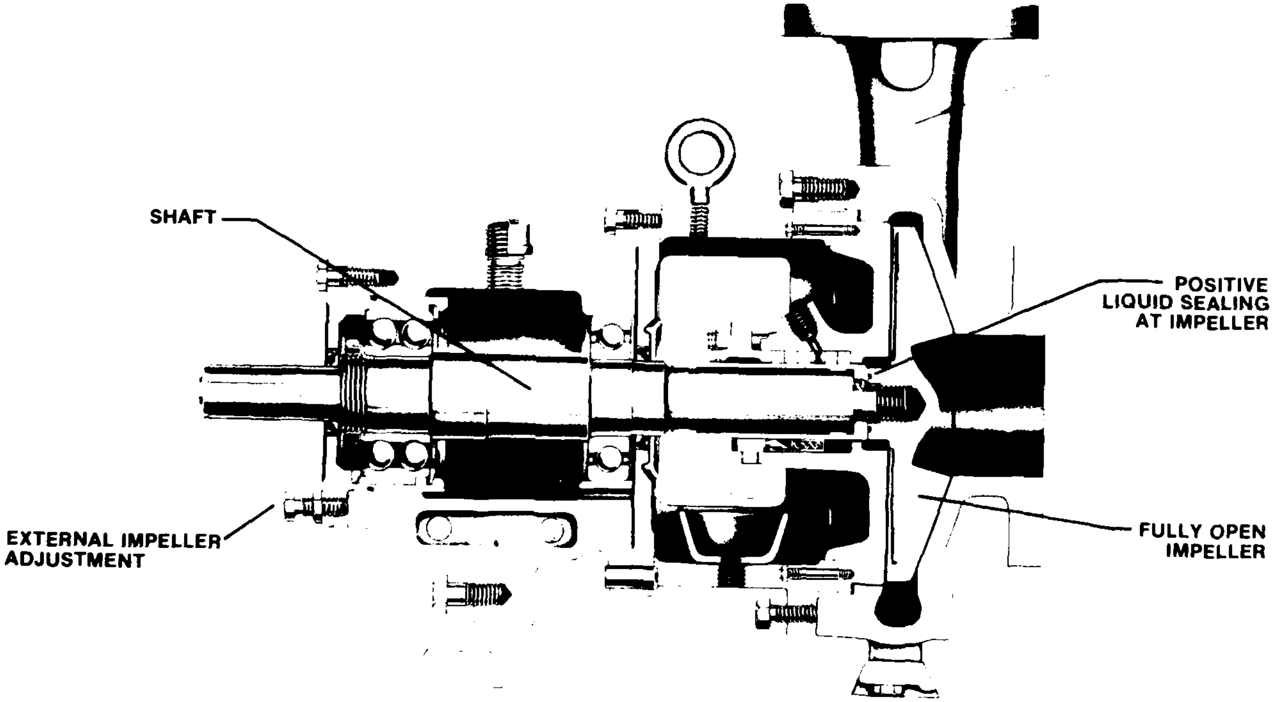

Figure 4 Sectional views, horizontal end-suction pumps.

Figure 5 shows a similar pump designed for higher working pressures. This centerline support pump, manufactured to standards of the American Petroleum Institute, will work in environments of 850°F and at pressures 600 to 700 psi.

The design of the vertical turbine pump in Figure 6 may be suitable for very deep sampling in a submersible unit. The principles of its design are evident: relatively low flows and relatively high pressures. The flow rate can be raised to 5000 or 6000 gpm, or maintained at 10 gpm or less. Depending on the bolting and metallurgy, pressures of 1000 psi, perhaps 1500, are possible.

A submersible single-stage centrifugal pump is pictured in Figure 7. The capacity of these pumps can be varied from 30 to 40 gpm to more than 5000 gpm. These pumps are usually made of cast iron with bronze fittings, but could be made of 316 stainless steel. Impellers for such pumps have been made of non-metallic materials such as nylon, fiberglass-reinforced polyester, and Teflon for particular applications.

The particular units shown are equipped with tandem-type seals or oil buffer zones to prevent leakage into the driven passageways. If the inboard seal fails, the outboard seal would protect the pumped fluid against contamination. The pumps are typically equipped with a seal sensor to detect the presence of a liquid passing through the oil barrier and signal a control panel.

The rotary-type positive displacement pump (Figure 8) has also been used for water sampling. The pump pictured is a spur-gear unit that yields constant (positive) displacement at a given shaft speed. These pumps can create flows up to a couple of hundred gpm or more, and pressures up to 500 psi. There is a Vickers rotary pump capable of pressures from 1000 to 3000 psi. The functional limitations are those of materials and construction. Off-the-shelf pumps of this type are bronze-fitted cast iron or 316 stainless steel, and the rotors and gears are made of nylon, Teflon, or specialty materials.

The duplex piston reciprocating pump pictured in Figure 9 can also be classified as a positive displacement pump. As indicated in the figure, the two pumping elements are arranged side-by-side, and their discharges overlap, thus reducing pulsation.

Another type of positive-displacement pump used in water sampling replaces the electric drive with compressed air. A shaft-diaphragm assembly moves back and forth between two chambers (air is compressed into one), displacing the liquid. For users who specify non-metallic materials and construction (such as chemical and pharmaceutical manufacturers), Teflon balls, Viton, neoprene diaphragms, and Teflon diaphragms are available.

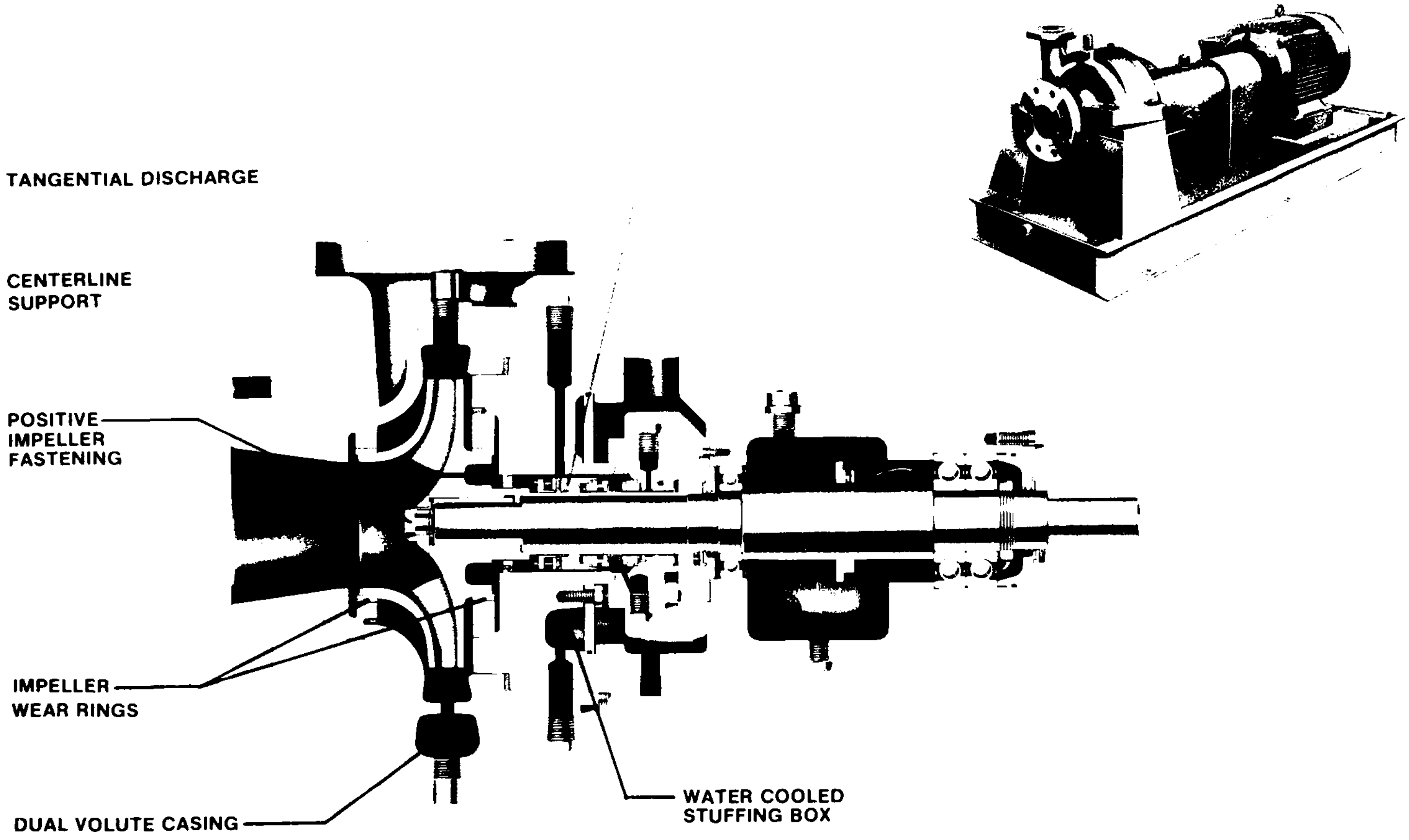

Figure 5 Exterior and sectional views, high pressure process pump.

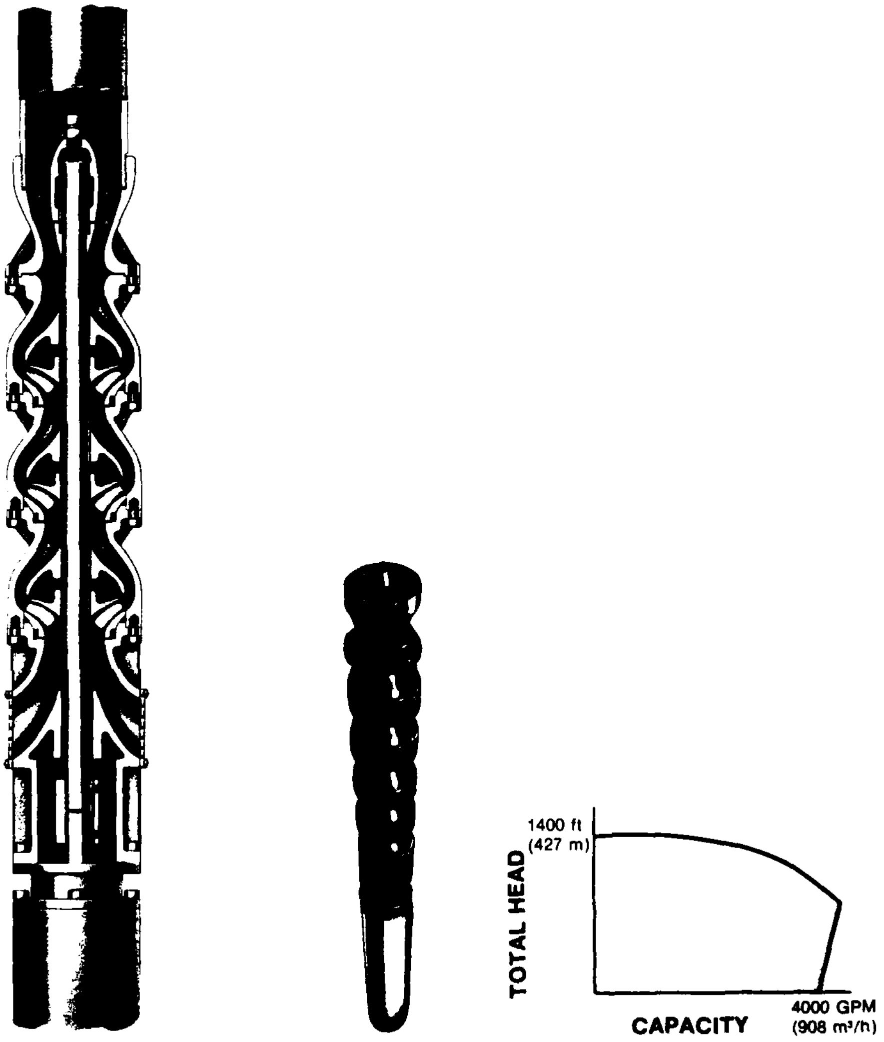

Figure 6 Submersible vertical-turbine pump.

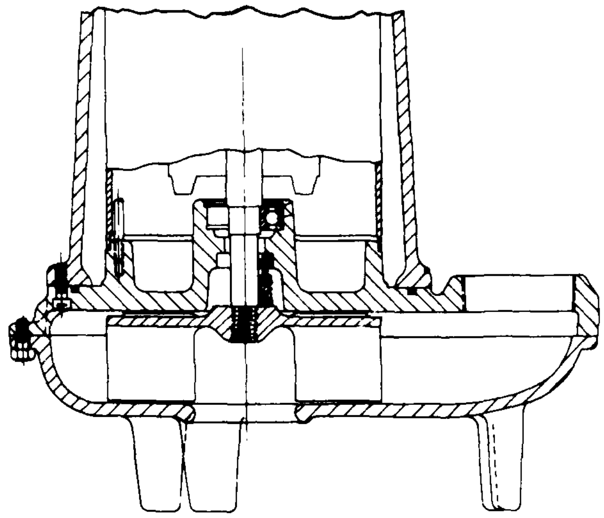

Figure 7 Submersible single-stage centrifugal pump.

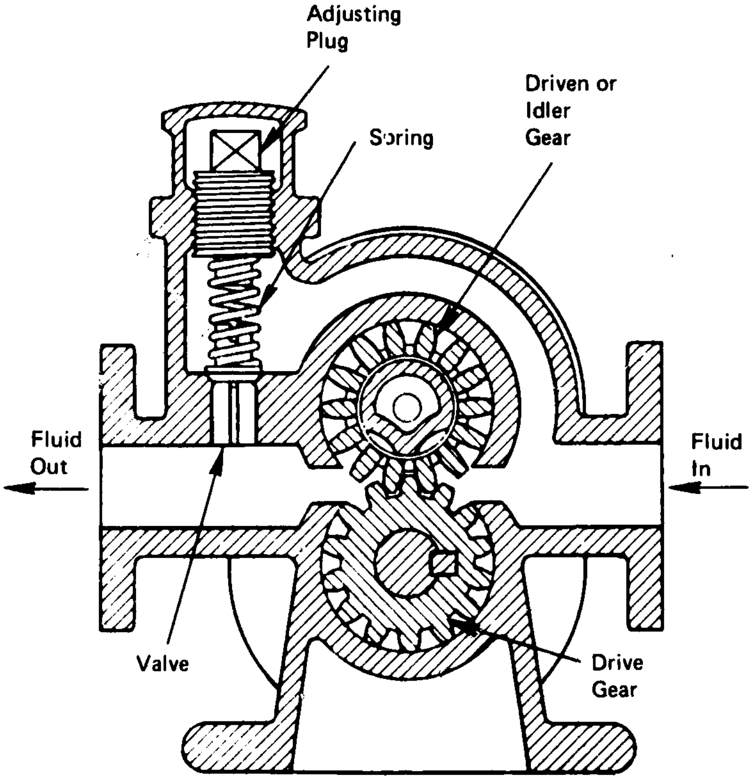

Figure 8 Rotary spur-gear pump.

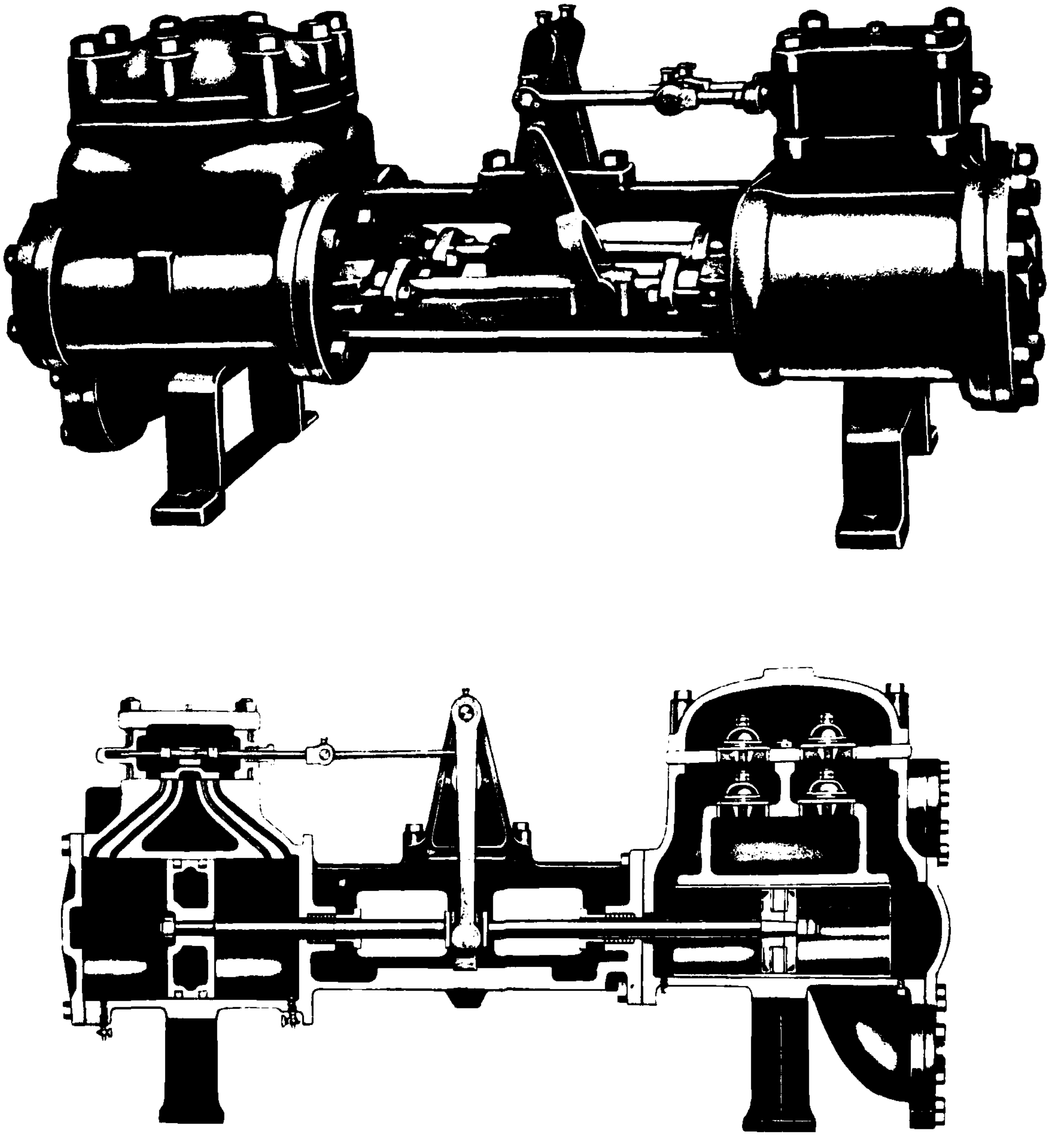

Figure 9 Exterior and sectional views, duplex piston reciprocating pump.

Performance Curves

Pumps operate at the intersection of pump curve with the system head curve. Vane losses and shock losses depend on the point of the curve of operations. For water sampling, the turbulence within the unit should be minimal. In a centrifugal pump, because of normal operating velocities, the suction-line velocities might be from 3 to 10 ft/sec, and depending on rotating speed, might reach 80 to 100 ft/sec.

Mechanical losses can occur owing to deflection of the units; bearing losses and leakage losses can occur between the face of the impeller and a casing, or for a double-suction pump; e.g., between the outer diameter of the impeller hub and the inner diameter of the casing ring. Recirculation losses occur under low flow conditions, and of course, this is undesirable for water sampling, as material can be picked up from the pump chamber, impeller, volute, or stuffing box cover.

A typical pump curve for a horizontally split case pump is given in Figure 10. The pump has a 10-inch diameter impeller (the range is 8 in. - 9-5/8 in.). This particular unit generates up to 390 feet total head, and the capacity could be as great as 5500 gpm.

The net positive suction head (NPSH) required at the suction center line of the pump ranges from 10 ft to 30 ft. As indicated by the lines of isoefficiency, this particular unit's best efficiency is 74 percent, but under low flow conditions, it could be less than 61 percent.

The performance curves of rotary and centrifugal pumps are plotted in Figure 11. Operating at a set speed at a certain amount of flow, slippage occurs in the rotary pump, increasing as a function of pressure and brake horsepower, and of course, as a function of the pressure differential required. (The effects of viscosity are unimportant for seawater.) The rate of discharge varies little with these pressure differences (as indicated by the curve for head capacity [a]) in a rotary pump, but drops rapidly with decreasing pressure in a centrifugal pump. The efficiency of a centrifugal pump used for water sampling would be relatively low because of low-flow conditions.

The greater the number of vanes in a centrifugal pump, the more total head can be achieved at top design efficiency, but for low flow conditions, the effect would be minimal. The width of the impeller also affects the general capacity at design efficiency: increasing the width enhances performance.

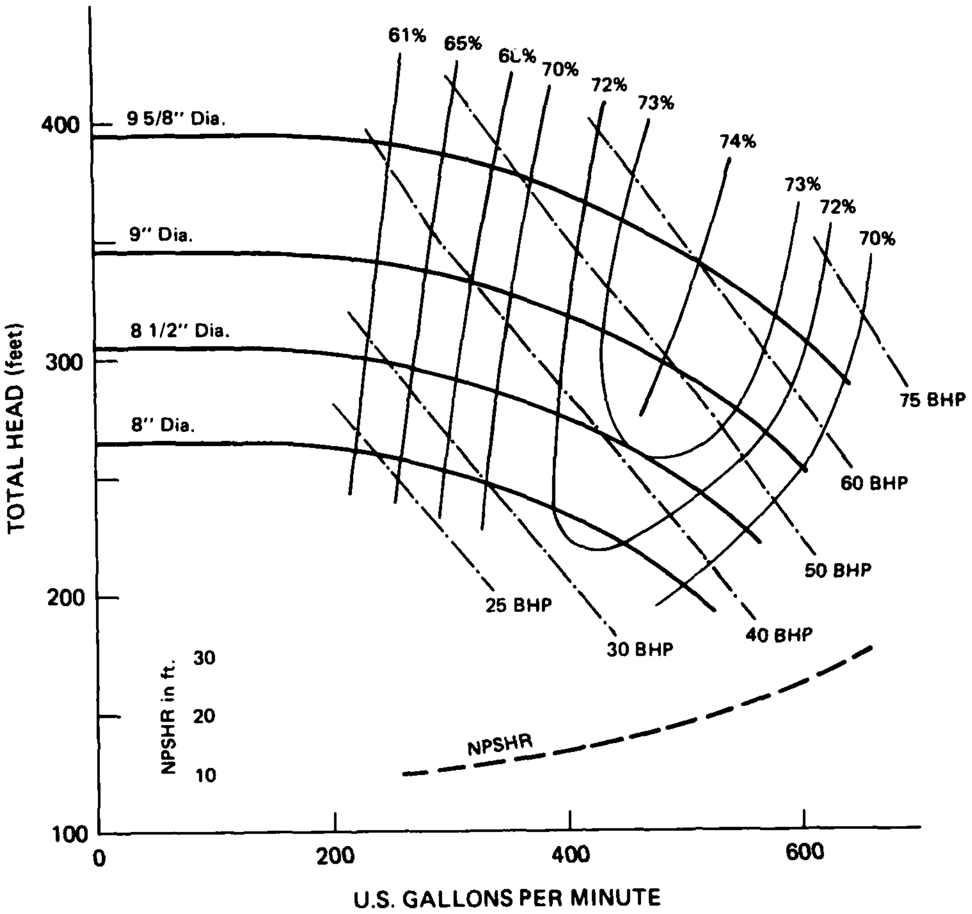

Figure 10 Performance curves for a centrifugal pump.

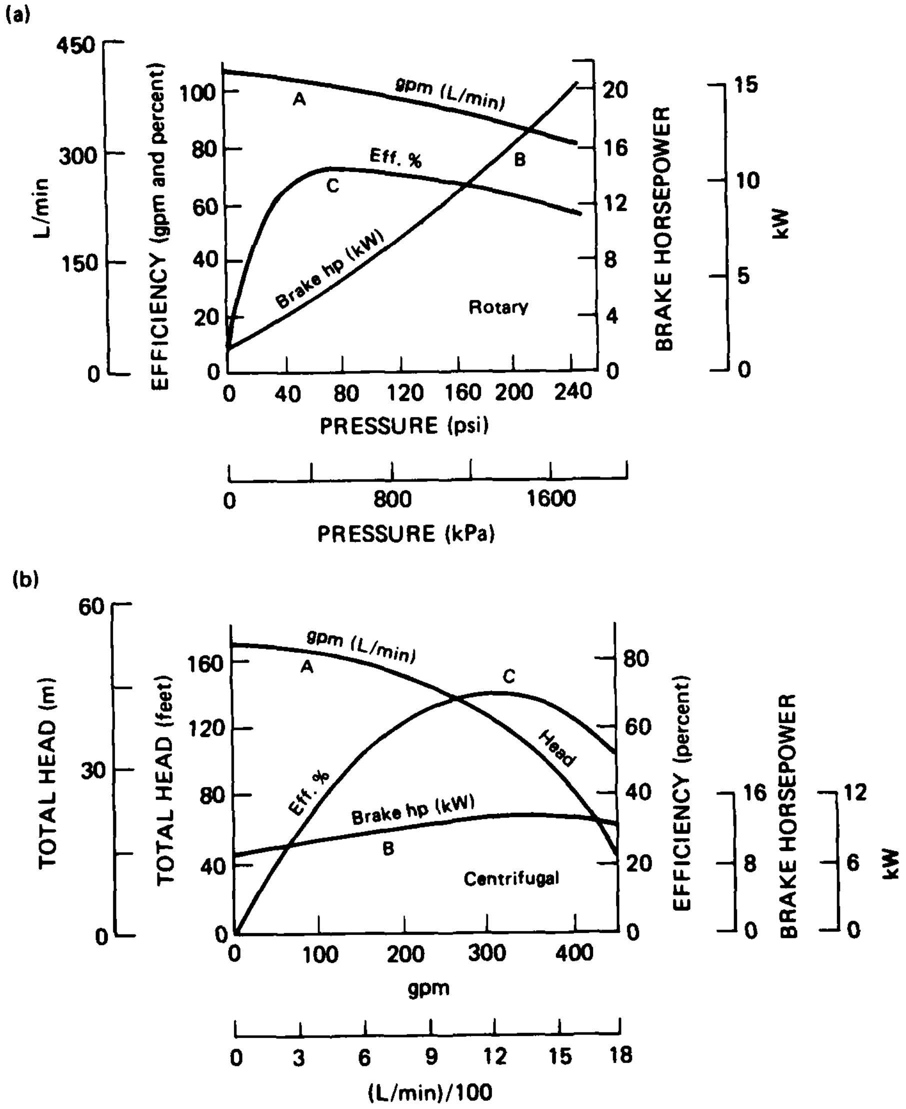

Figure 11 Comparison of rotary (a) and centrifugal (b) pump-performance curves.

Operating Conditions

As mentioned earlier, a pump operates in a section of its pump curve and a system curve. Artificial head could be imposed on the system just by throttling to increase the total head, and of course, reducing the flow.

The system head depends on the suction conditions of the unit--whether a tank is full or empty, whether the pump has a pressurized chamber or a non-pressurized chamber, and so on. For any particular pump, the operating conditions, and the points on its specific curve at which operations occur, will vary.

Pump speed is another factor in performance. Positive displacement pumps would operate at lower velocities and create less turbulence within the unit than variable displacement pumps.

Oversizing pumps could be a problem under low flow conditions. It is important that the safety factors not be abused. Shock losses may occur under conditions of low flow or inefficient operation, or in cases of high turbulence if the pump is oversized.

Users sometimes ask what happens when two units are operated in parallel. Capacity is basically increased at a certain total head. For water sampling, a vertical-turbine pump might be used, or a couple of units stacked in series to obtain higher differential heads, and this might enable sampling at 1000 meters depth.

Testing

Among the tests conducted on pumps are several to rate their efficiency. The suction at discharge head is measured, and by Bernoulli's theorem, there will be a differential head to overcome. If there is a difference in the suction discharge flange sizes or openings, velocity head components must be calculated. These are relatively insignificant, but cannot be ignored. The suction discharge pressure is measured by picking up the brake horsepower on a torque shaft or a meter, and the efficiency calculated as a function of speed. The flow is a function of the flow out of the tank which is detected by a manometer, Venturi, or weight tank.

Cavitation analysis is conducted to establish the pump's NPSH, or the velocity required for movement from the suction opening to the entrance to the impeller vane. The friction of turbine losses between the suction opening and those vanes must be overcome. Tests have also been conducted to determine the resistance of various pump materials to cavitation. Steel is superior to aluminum and bronze, cast iron, and lead.

The NPSH requirements of most pumps range from 1 foot absolute to 9 to 10 feet. Some pumps require essentially flooded suction conditions, but most centrifugal, reciprocating, and rotary pumps can pull a significant lift; for example, 25 inches of mercury, or an NPSH that is easily handled. (The NPSH required by an actual pump is included in the pump curves given in Figure 10. It is evident that under low flow conditions, NPSH would be perhaps 10 feet; under wide-open conditions [at the end of the curve], it could approach a requirement of essentially flooded suction of 28 to 30 feet.)

Cavitation

You have probably seen some of these units after they have been in operation under cavitational conditions, and wondered what causes the spongy appearance at the eye of the impeller, or on the casing of the volute itself. It could be cavitation, or the implosion of bubbles exceeding the tensile strength of the materials of construction.

As mentioned in other presentations, users have operated units under slight cavitational conditions and achieved adequate performance. As a manufacturer, I would advise against this, as the degradation eventually shortens service life. The implosions of bubbles exert forces that cause very rapid changes of moments on the shaft or other parts; as a result, the service lives of bearings and packing seals are cut short.

The lift of the units mounted on the bows of ships to pump water samples is affected by the static lift conditions, frictional loss through the suction piping, and the pump's required NPSH curve. Beyond the maximum, an audible noise will be heard as the cavitation occurs. There is just so much you can pull from a lift of these units.

The number of feet would depend on the pump curve, but the pull is probably limited to 10-20 feet. Users have attempted 25 feet; at this point, they can expect entrained air.

Figures 1, 2, 9, 10, courtesy Warren Pumps, Inc.
Figures 3, 4, 5, 6, 7, courtesy Goulds Pumps, Inc.

A SIX-PORT UNDERWAY WATER SAMPLING SYSTEM

Marshall H. Orr* and Clifford L. Winget**

A six-port seawater sampling system that acquires uncontaminated water samples has been constructed. The water samples are taken from a moving ship (0-2 m/s) with a vertical resolution of 1 m over a 5 m vertical range. The depth of the water sampling ports is adjustable (0 to 100 m) while the research vessel is under way. The system has been deployed three times at Deepwater Dumpsite 106 (Figure 1) to obtain seawater samples for chemical or biological analysis from sections of the water column contaminated and uncontaminated with industrial chemical waste.

The water sampler's vertical resolution and range of operating depths were specified from the results of high-frequency acoustic backscattering experiments (Orr and Hess, 1978; Orr, Baxter, and Hess, 1979) which had shown that particles in the releases of industrial chemical waste at the dumpsite, or subsequently formed were:

- Distributed throughout the seasonal mixed layer;
- Sharply limited in their vertical distribution by the density structure associated with the base of the seasonal mixed layer;
- Found in layers of limited vertical extent (less than 5 m) which were associated with the fine structure sometimes found at the base of the mixed layer;
- Temporarily displaced vertically by the local internal wave field, and
- Affected by the vertical shear in the water column.

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*Presenter

**The authors thank F. R. Hess, who provided the electrical engineering necessary to install the pressure and temperature sensors in the pump housing. E. Pratt prepared the figures and A. Soussa prepared the manuscript. This work was supported by the National Oceanic and Atmospheric Administration Grants 04-7-158-44054, NA79AA-D-00050, and Ocean Dumping Grant 04-8-M01-43.

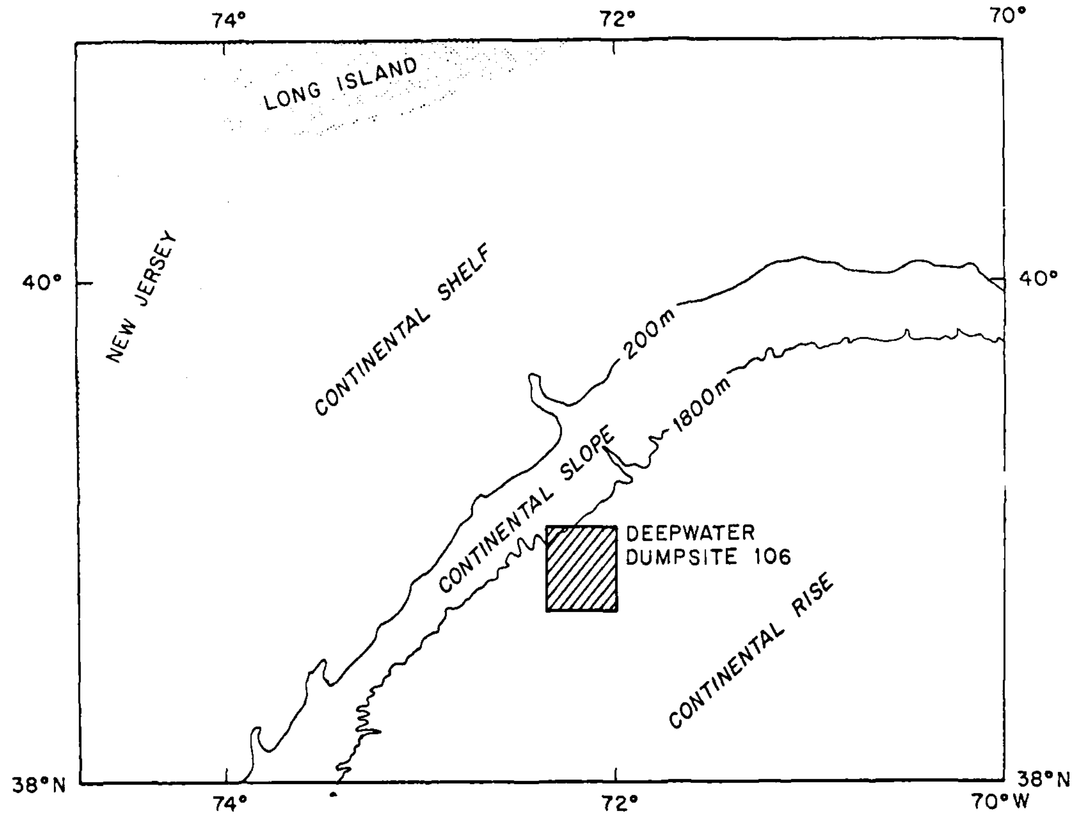


Figure 1 Geographic location of Deepwater Dumpsite 106 (DWD 106).

Of particular importance was the observation that the waste particles would accumulate on isopycnal surfaces in narrow horizontal layers that were sometimes less than a meter in thickness, and separated vertically by about one to a few meters. A section of 200 kHz acoustic backscattering data illustrating some of these features is displayed in Figure 2. The dark, heavy scattering area (arrow 1) and the lighter scattering area beneath it (arrow 2) are areas of heavy particle concentration associated with isopycnal surfaces within the seasonal thermocline. The particles associated with the base of the mixed layer were being vertically displaced about 10 m by the local internal wave field. The data were taken from a ship moving at 1.9 m/s, hence the period of the internal wave field is doppler-shifted. The period of the internal wave field was about 20-40 minutes.

The acoustic data indicated that a multiport, high-resolution, vertical profiling seawater sampling system was necessary to provide chemical and biological water samples with sufficient vertical resolution to determine the vertical distribution of chemical waste fields. It was specified that the water sampling system be capable of actively following--from a moving ship--the vertical displacement of an industrial chemical waste field by the local internal wave field. The water sampler constructed to these specifications has been (or will be) used to:

- Determine the sharpness of the vertical and horizontal distribution of chemical waste fields;
- Determine if the effluent phase of the chemical waste is distributed through the same section of the water column as the particle phase, and
- Accurately measure the dispersion characteristics of the effluent phase of the chemical waste in the open ocean.

The sampling system has been used during interdisciplinary experiments in conjunction with high-frequency acoustic backscattering systems and automated loran-C navigation systems in attempts to make these determinations and measurements.

System Design

An artist's sketch (Figure 3) of the water sampling system indicates its configuration and a typical deployment arrangement from an oceanographic research vessel. A winch (arrow 1) driven by an electric motor is used to raise and lower the water sampling tubes and

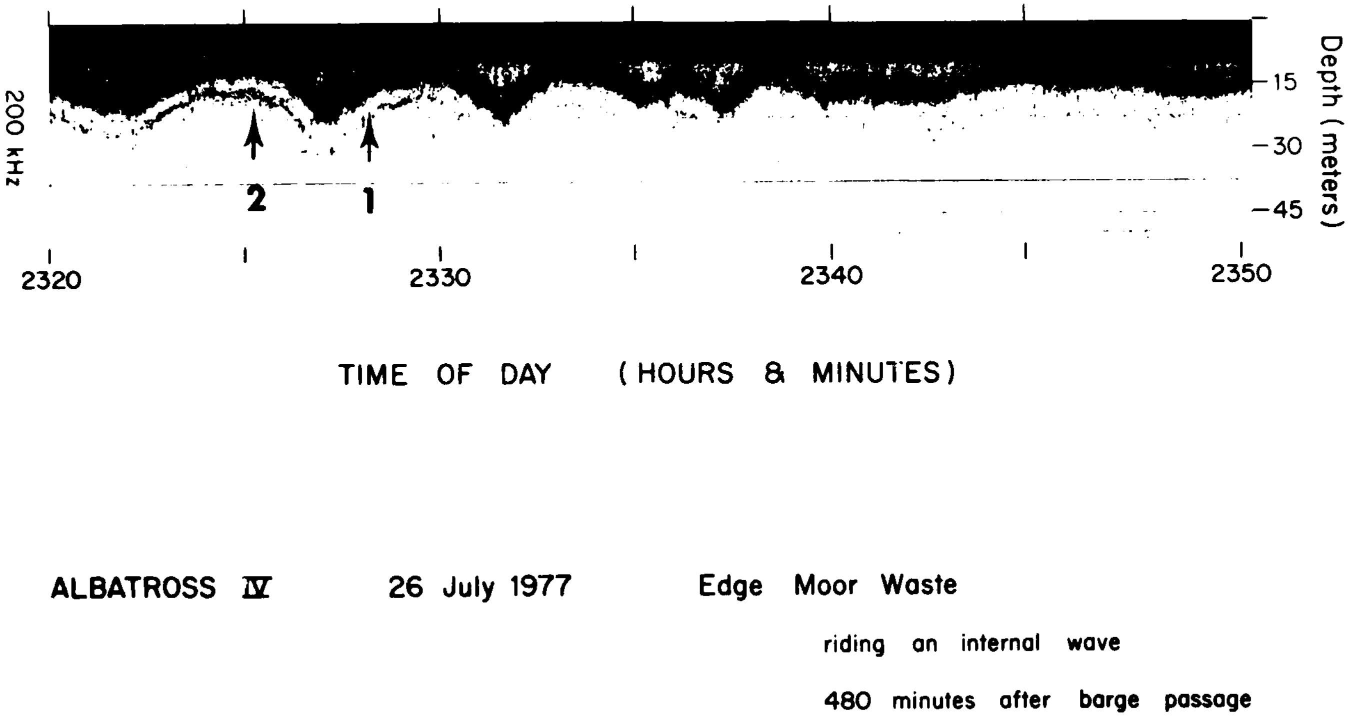


Figure 2 A 200-kHz acoustic backscattering record of the vertical and horizontal distribution of hydrous ferric oxide particles distributed on the isopycnals associated with the base of a layered summertime seasonal thermocline. The double layer of particles (arrows 1 and 2) on two surfaces and the limited vertical extent of lower layer is clear. The influence of the internal wave field on the vertical displacement of the particles is apparent. Acoustic records of this type pointed to the need for a high-resolution water sampling system which could be vertically displaced from a moving vessel to compensate for water mass motion during biological and chemical sampling of the water column.

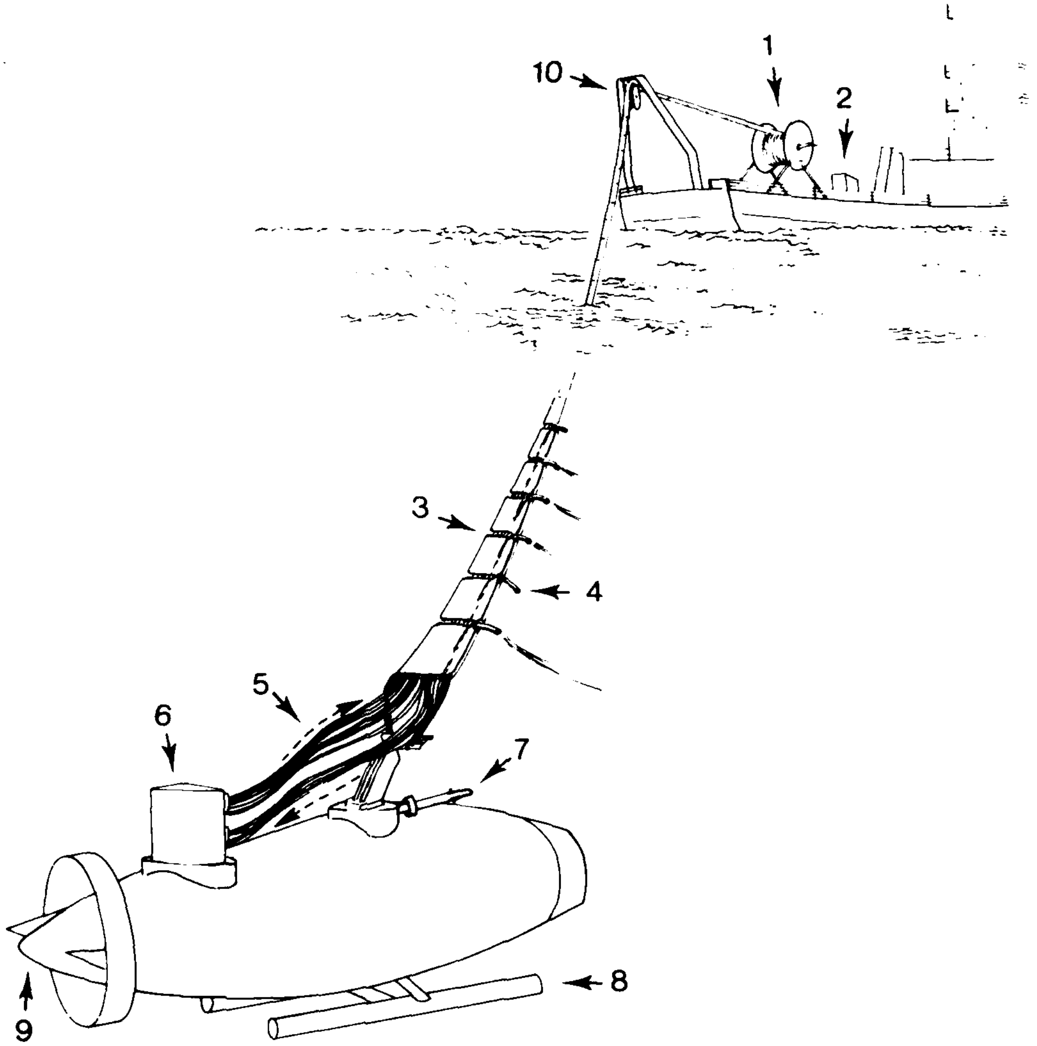


Figure 3 An artist's sketch of a typical arrangement of the multiport water sampling system aboard a research vessel. The sketch indicates the position of the winch (arrow 1), air compressor (arrow 2), fairing (arrow 3), water intake ports (arrow 4), Teflon intake and outflow lines (arrow 5), housing for intake and outflow lines (arrow 6), thermistor (arrow 7), weight (arrow 8), pump housing (arrow 9), and sheave (arrow 10).

pump housing (arrows 4 and 9). The winch is generally mounted on the fantail of a ship. A pliant polyurethane fairing (arrow 3) is passed over a sheave (arrow 10) attached to an A-frame. The fairing is used to house and separate two steel wire strength members, electrical conductors for providing the power necessary to run the water pumps, located in the pump housing, the six TFE Teflon tubes through which the seawater is pumped to the surface, an air line to provide the high-pressure air to compensate internal pressure in the pump housing, and a temperature-and-depth-sensor conductor cable. The pressure-compensated pump housing (arrow 9) contains six water pumps, a seawater temperature sensor (arrow 7), a leak detector, a ground fault detector, a pressure sensor, and an air-pressure regulator to allow the internal pressure of the pressure housing to be maintained at the same pressure as the surrounding water. The internal pressure regulation prevents the water pumps from rupturing during exposure to seawater pressure at the depth of operation. The water sampler's pump housing has a bottom weight (arrow 8) to sink and act as a stand onboard the ship. The water-intake hoses (arrow 4) are attached to the pliant fairings, as shown in the figure. On the ship's fantail, six TFE Teflon water lines are led from the winch to a variety of experiments, and an air compressor (arrow 2) supplies pressurized air to the pump housing. In the laboratory, analog recorders maintain a record of the depth of the pump housing and seawater temperature during the pump-deployment period.

The multiport water sampling system was designed, fabricated, assembled, and deployed in less than three months. The winch was constructed from a surplus frame and drum, a surplus 10 HP motor and a surplus positive mechanical brake (Figure 4). The mass of the winch with a full complement of fairing, tubing, wire-rope strength members, etc., is about 1820 kg. The dimensions of the winch are 1.55 m wide, 2.13 m deep, and 2.03 m high. The 10 HP motor is operated with 240 volt, single-phase, 60 cycle power. The motor raises the entire pump and fairing assembly at ship speeds of 2 m/s. A cross-sectional view of the pliant polyurethane fairing housing the six 12.7 mm ID Teflon tubes, plus a variety of electrical conductor cables, strength members, and air hoses, is also shown (Figure 4, arrow 1). Each is 46 cm long, 5 cm thick, and 23 cm wide, and has a mass of 2-3 kg. A picture of the water sampling system taken during a typical deployment operation indicates the positioning of the various components of the system on the deck of a ship (Figure 5).

The subsurface pressure housing is a modified torpedo body (Figure 6). The mass of the pressure housing and its attached weight is 682 kg.

The water pumps are March Manufacturing Company Model TE5C-MD. They operate on 240 volt single-phase, 60 cycle power and are capable of pumping at 132 l/min. with a 15 m head. Each pump is individually

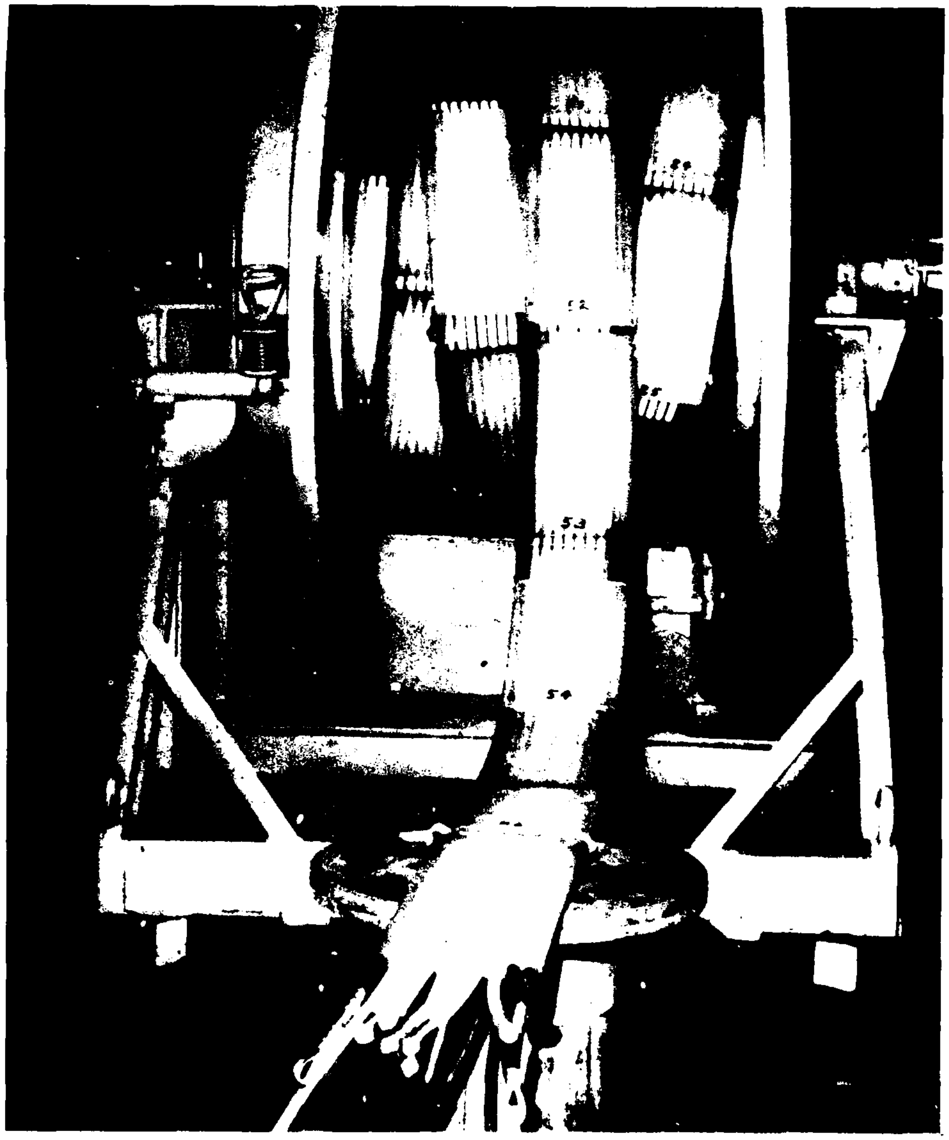


Figure 4 The winch used to deploy and retrieve the subsurface pump housing. The six white Teflon water sampling tubes, steel wire strength members, and assorted electrical conductors can be seen protruding from a polyurethane fairing (arrow 1).

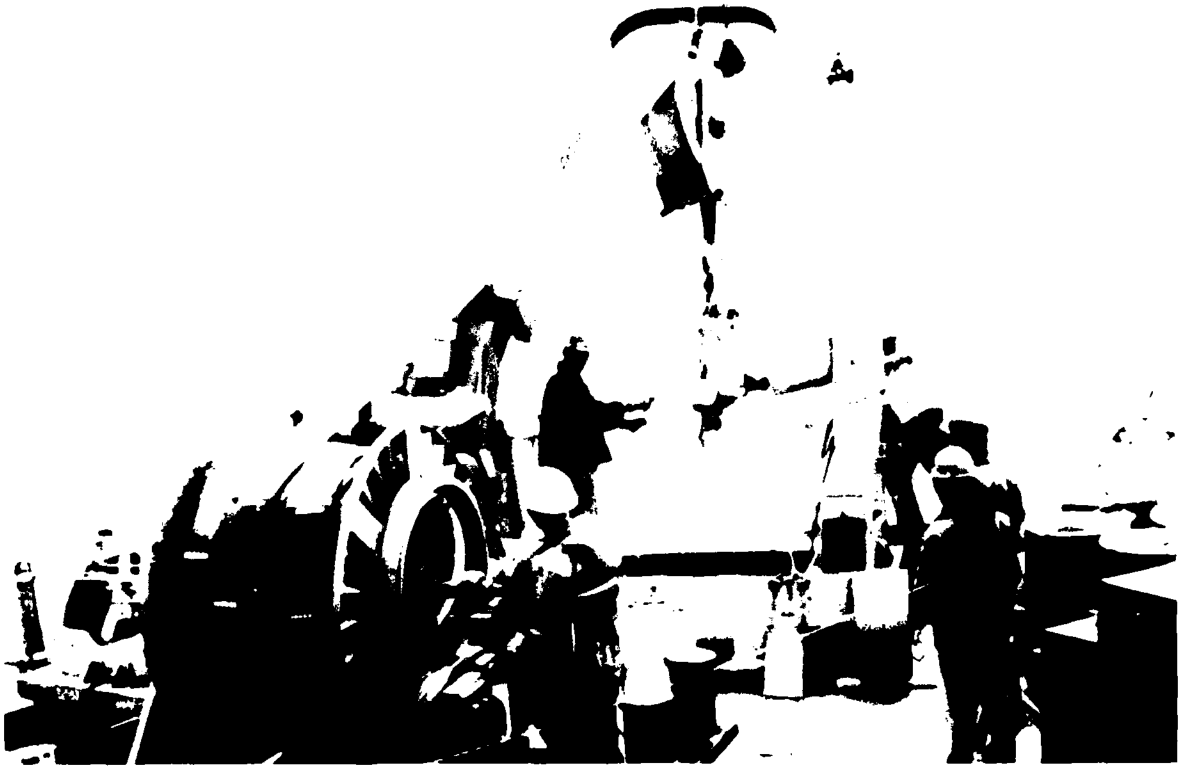


Figure 5 Water sampling during a launch from the NOAA ship MT. MITCHELL.

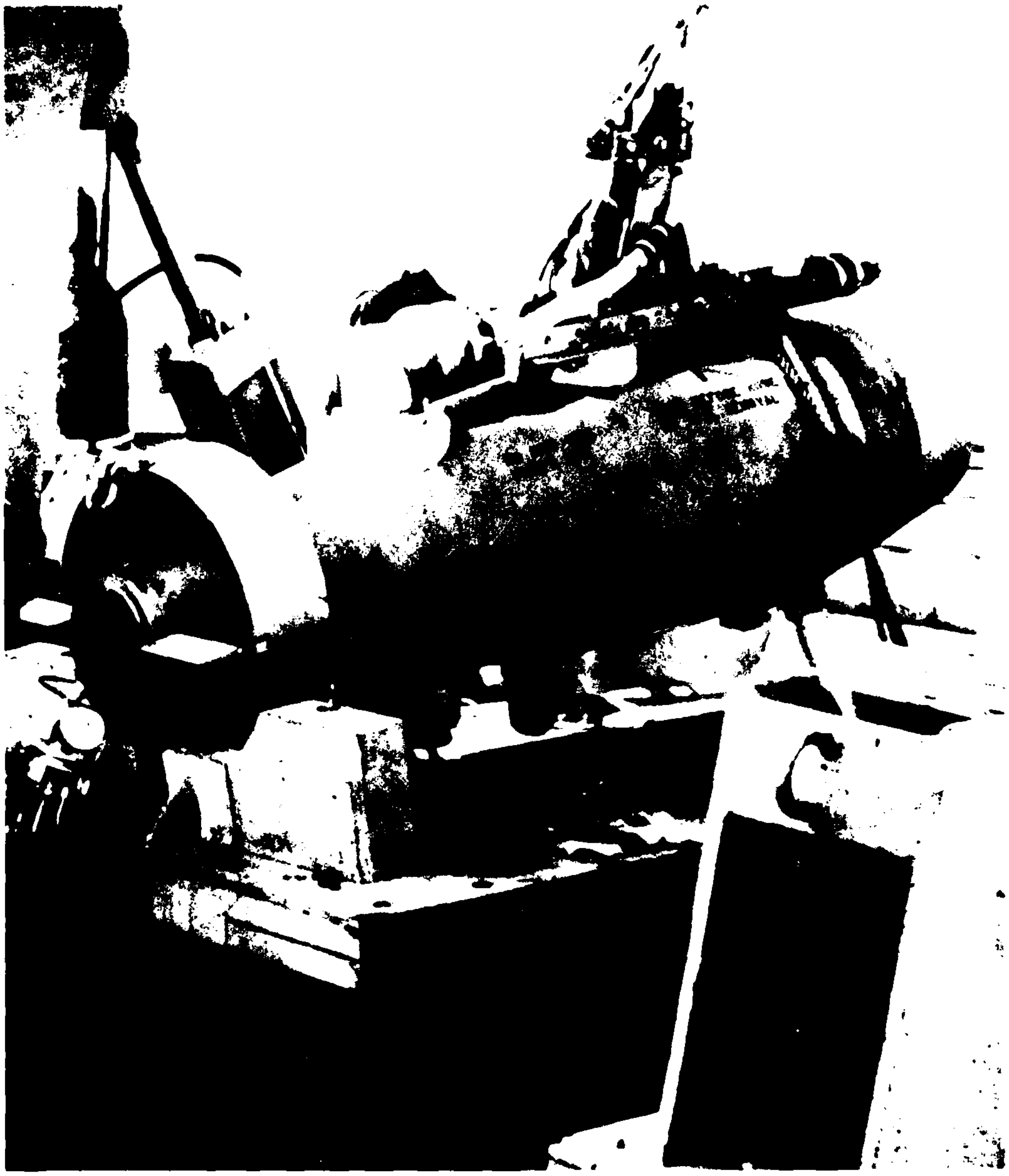


Figure 6 Closeup view of the pump housing. The pressure compensation air regulator has been removed to permit inspection of the pump housing.

fused. The loss of one to five pumps does not prevent water sampling from continuing. The pump housing is made of polypropylene. The impeller is magnetically driven. The impeller is polypropylene, and the impeller spindle and thrust washers are ceramic. These components are the only sections of the water-handling system not constructed of TFE Teflon.

The water pumps are mounted in two triangular stacks, one after the other, on a frame (Figure 7) which slides into the torpedo body. The seawater samples are taken through six hoses that enter the top of the torpedo body. The fairings for the various hoses and conductors are also attached to the top of the torpedo, as are the six 150 m length Teflon tubes. It is believed that a fully developed turbulent flow occurs in the pumps and Teflon tubing. The flow rate of seawater through each 150 m length Teflon tube is 5.6 l/min. The water takes about 3.4 minutes to flow through the Teflon tubing. The system seems to flush itself in approximately four minutes. No quantitative measurements of the flushing characteristics have been made.

Discussion of Operational Characteristics and Limitations

The water sampling system has been deployed three times. A typical plot of the surbsurface pump housing's depth during an April 1978 deployment is presented in Figure 8. Rhodamine WT dye was detected by James Bisagni of the NOAA National Marine Fisheries Service in Narrangansett with fluorometers attached to each of the six ports (Figure 9) during the monitoring of the dispersion of Du Pont Grasselli Plant waste. The waste had been tagged with the rhodamine WT dye prior to release. Note the sharp cutoff of the dye distribution near the deepest intake at 1330 hrs. This port was near the base of the mixed layer. The data indicated that the waste field did not penetrate below the mixed layer. During the time these data were taken, the research ship was repeatedly crossing a line dump of the waste plume at a nearly normal incident angle to the plume axis.

There are several limitations to the efficient operation of the water sampling system. The limitations are the lack of a complete slip-ring assembly, hydrodynamic lift from the fairings, and the need for a large research vessel with adequate fantail space to accommodate the system.

The system uses slip rings for the 230 volt, single-phase, 60 cycle power which is applied to the water pumps. It does not have slip rings for the temperature and depth sensor, nor the output of the six water sampling tubes. The vertical range over which the subsurface pumping housing can be raised or lowered without stopping to disconnect the temperature, pressure, and water sampling tubes is thus

Figure 7 A view of the six-pump assembly contained in the pump housing.

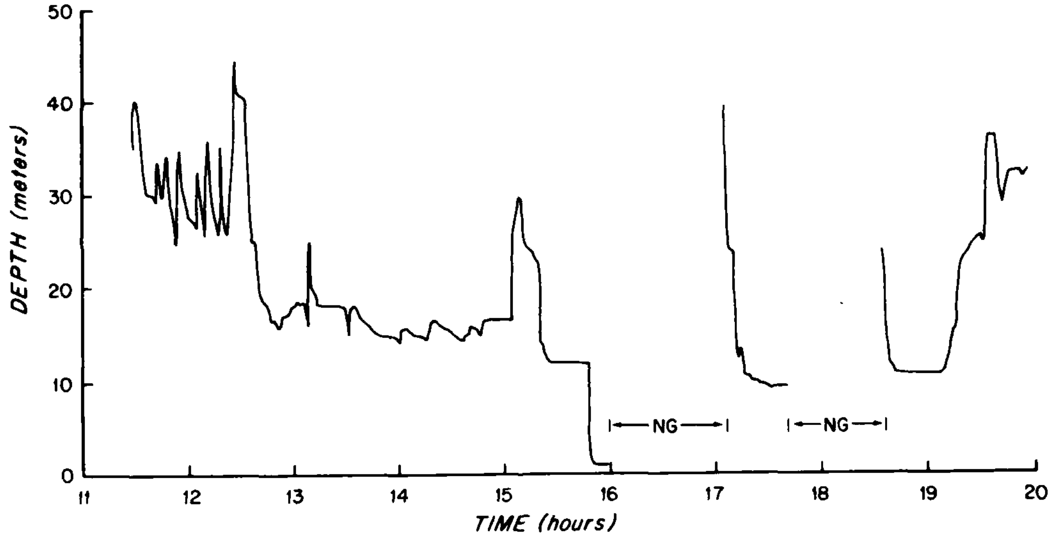
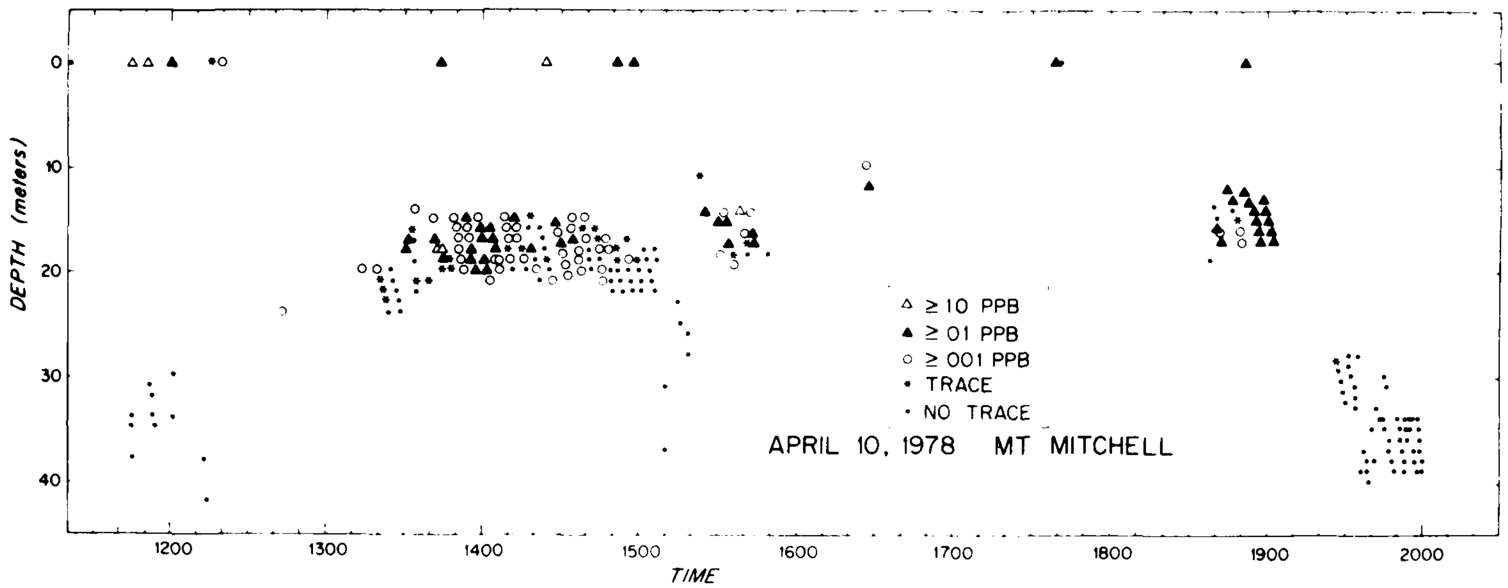


Figure 8 A typical record of the depth excursions of the water sampling system's pump housing during a 20-hour deployment. Those sections of the records labeled NG were missed due to the failure of a chart recorder.



DEPTH AND CONCENTRATION VS TIME OF DYED GRASSELLI WASTE
AS MEASURED BY FLUORIMETER ON WATER SAMPLES FROM PUMP FISH

Figure 9 An 8.5-hour record of times at which rhodamine WT dye was detected during the deployment of the multiport water sampling system. The data in the 1300-1500-hour period indicate a sharp cutoff of the distribution of the dye in the vertical. The water sampler was being towed such that some of the ports were just at or below the seasonal thermocline.

limited to about 10 m. The depth and pressure-sensor problem could be solved with the addition of another set of slip rings. The water sampling system could also be provided with slip rings. This has been purposely avoided because cross-contamination might occur within the slip ring assembly between the various water lines. Sewage sludge monitoring operations have been the primary concern: it was felt that particles associated with the waste field could get into the slip ring assemblies, mar the surfaces, and cause cross-contamination between the various water lines.

The fairings were designed as a protective device to hold the cables and tubes together. The water sampling system was also originally designed for deployment from the side of a ship such that the fairings would enter the water with their narrow aspect in the direction of motion of the vessel. During stern deployment, the fairings enter the water broadside and thus provide hydrodynamic lift to the system. Consequently, for stern launch at tow speeds of 2 m/s, the maximum depth at which the system will operate is limited to about 20 m. At slower ship speeds, greater depths can be obtained. A solution to the problem is to bundle the water sampling tubes and electrical conductors into a no-lift configuration.

A research vessel that has adequate fantail space and deck equipment is necessary to handle the system safely: the vessel must be 150 feet or more in length.

One of the great needs in realizing the system's capabilities for scientific applications is for adequate real-time chemical analysis techniques that can handle the volume of water pumped to the surface. In addition, if a system of this type is to be used routinely at sea, a full-time technician who is trained to use and maintain the system should be onboard. If it is to be used 24 hours a day, at least two technicians will be needed to operate the system. A scientist attempting to monitor chemical waste disposals during the Deepwater Dumpsite 106 cruises, for example, is very much involved in making decisions concerning the ship's navigation and his or her own research, and does not have the time to operate the water sampler in addition to running experiments.

Conclusion

A six-port water sampling system that can acquire samples over a vertical range of 5 m in one-meter steps, and that can be raised or lowered over a depth range of 0-100 m has been constructed and used during interdisciplinary cruises to monitor the dispersion of industrial chemical waste. The system performed reliably, having been continuously deployed on two occasions for 24- to 48-hour periods. The principal limitation to operating the system over the 0-100 m depth range with ship speeds of 2 m/s is the hydrodynamic lift of the fairings used to protect the electrical conductors and Teflon water sampling tubes. The lift limits the depth of the water sampling ports. This problem could be corrected by packaging conductors and water sampling tubes in a no-lift configuration.

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1. Orr, M. H. and F. R. Hess (1978), Remote acoustic monitoring of natural suspensate distributions, active suspensate resuspension and slope/shelf water intrusions, Journal of Geophysical Research, 83: 4062-4068.

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DISCUSSION

FARRINGTON: Something I neglected to mention in my presentation bears on what you said: It is nice to have a port available for someone who is not occupied with the analysis being conducted. If a signal comes back indicating that more samples should be taken, this person can start filling up various sampling containers, even if the analysis will be done back in the lab.

The problem we often have is that we have to do a very detailed profile because we do not know where the event is that we want to sample. If a sensor gives you the information that something very interesting is going on with the chemicals in some area, then you can get larger samples for analysis back at the lab.

ORR: Yes, that is a good point. There are a couple of other points about these systems I should mention. I am an experimental physicist, so I have to go to sea with a rather large acoustics system. When the interdisciplinary group visits a dumpsite, we take this multiport system as well.

Engineers can be interested in building the systems, but not in maintaining them or going to sea with them. If you plan to build such a system, you will need a technician who knows the system, who is available to go to sea with the system, and who will maintain it before and after cruises. These people are hard to get. They are expensive and cannot always be incorporated into the rest of your research effort. A system such as this one is not just a suitcase that you can throw overboard. It requires a technician who can go to sea with it, who understands how it works, and who understands how to support a heavy operation.

GREEN: Are you talking about one person or a group of people?

ORR: Well, if you are involved in a dumping operation, you like to monitor 24 hours a day. You are talking about two or three people to roll the system up and out and to watch it, allowing the scientist to take a broader view of what is happening.

HERR: Have you solved the problems of Teflon and the slip rings?

ORR: We recognized the problem, but we have avoided it. When we rolled the system up or down, we pulled the plugs out from the chemistry van, moved it up, and plugged it back in.

HERR: Essentially, then, you cannot profile with this system and pump. You have to stop and--

ORR: If you have enough length of cable, you can profile, say, 10 meters or so, before unplugging and unwrapping. If you wanted a true profile in terms of raising the system up and down every 20 or 30 meters, every 3 or 4 minutes, or every 5 minutes, then you'd have to have a slip-ring assembly built for it, and make sure that it is built so that there is no cross-contamination between the ports.

KESTER: Is it necessary to have the intervals between the multiple ports fixed, or can a system be designed that would allow you to modify them as you are using it, or at least within a matter of an hour or two of deployment?

ORR: The way it is now, it is fairly rigorous because of the way the metal has to go together to hold the Teflon. I think if you put the problem to the designer, he could devise an attachment to the fairings with three or four entry points, all of which are plugged but one. Then, if you do not want that separation, plug it and pick another. It is probably a pretty simple problem.

TULIN: In connection with that question, I want to ask a question of you, Shelton Gay, and Reece Folb: would it suit your purposes to have a body with a single port whose depth could be programmed for a time scale that would give you the resolution you need, and is it possible?

ORR: The answer is, it depends on the application. In the dumpsite where you are trying to cross a plume which may be only 50 or 75 meters wide, the response may not be fast enough, and you want this fixed grid so that you can slice the material.

If you are just interested in going across a front and doing a yo-yo across it, that is a different problem, and what you describe may be suitable. NOAA built a single-port system for smaller craft as well as the bigger boats.

FOLB: The six-port system could be designed as a controllable body, although it would entail additional complications in the system. The single-port system could be designed for variable height, although it may not be possible to get data samples fast enough with it.

ORR: To add to the complexity, in dumpsite work where you are out in the open ocean with just the loran-C to guide you, you try to cross the site to get an idea where the plume is acoustically, then turn around and come back over it. It is often difficult to estimate the exact time when you will come back onto the plume because most ot the time you do not know the shear in the water column, nor the advective field.

In analyzing the acoustics data, we have had a great deal of difficulty just trying to get the width of the plume as a function of time until we can account for shear. Then we have to estimate shear from the loran rates. One would like to have a better estimate than that.

GAY: Most of the technological problems that have been described --mechanical problems of towing, winching, and overboarding--are solvable, given some engineering, a little science, and a little money. They are not insurmountable.

THE GULF MARINE HYDROCARBON SAMPLING AND ANALYSIS SYSTEM

Richard J. Mousseau* and William H. Glezen

Introduction

The Gulf Science and Technology Company has been involved in underway water sampling since 1967, when it commissioned the M/V GULFREX. Early efforts with this ship were limited to taking near-surface samples through a hull penetration. Since 1974, when the R/V HOLLIS HEDBERG was commissioned, Gulf has continuously operated one or more subsurface sampling and hydrocarbon analysis systems. Our use of these systems stems from our oil and gas exploration efforts, and a very simple concept. The concept is based on the association of naturally occurring oil and gas seeps, and oil and gas discoveries. In 1952, Link[1] stated, "A look at the exploration history of the important oil areas of the world proves conclusively that oil and gas seeps gave the first clues to most oil-producing regions. Many great oil fields are the direct result of seepage drilling." Dickey and Hunt[2] also attested to the association by noticing that, "It is probable that more oil fields have been discovered by drilling on or near seeps than by any other prospecting method." Seeps do not prove the existence of commercial oil and gas accumulations, but their presence increases the probability of success, and shows the existence of the first requisite for successful exploration: the presence of a source.

Unless they are very active, seeps are not easily detected at sea. Hence, we use chemical means to locate them. We analyze seawater for the light hydrocarbon gases and interpret increased or anomalous concentrations of these compounds as the results of seeps.

The R/V HOLLIS HEDBERG

The R/V HOLLIS HEDBERG (under long-term charter to Gulf) was commissioned in 1974, and we have conducted the majority of our subsurface underway sampling on this vessel. In addition, other vessels have frequently been engaged to perform surveys of one or two months' duration. The HEDBERG is 204 feet long and 45 feet wide.

A block diagram of the R/V HOLLIS HEDBERG geochemical system is shown in Figure 1. This ship has the capability to sample and analyze seawater from three different inlets simultaneously. The mid and deep inlets are both towed systems operable at normal seismic survey speeds.

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* Presenter

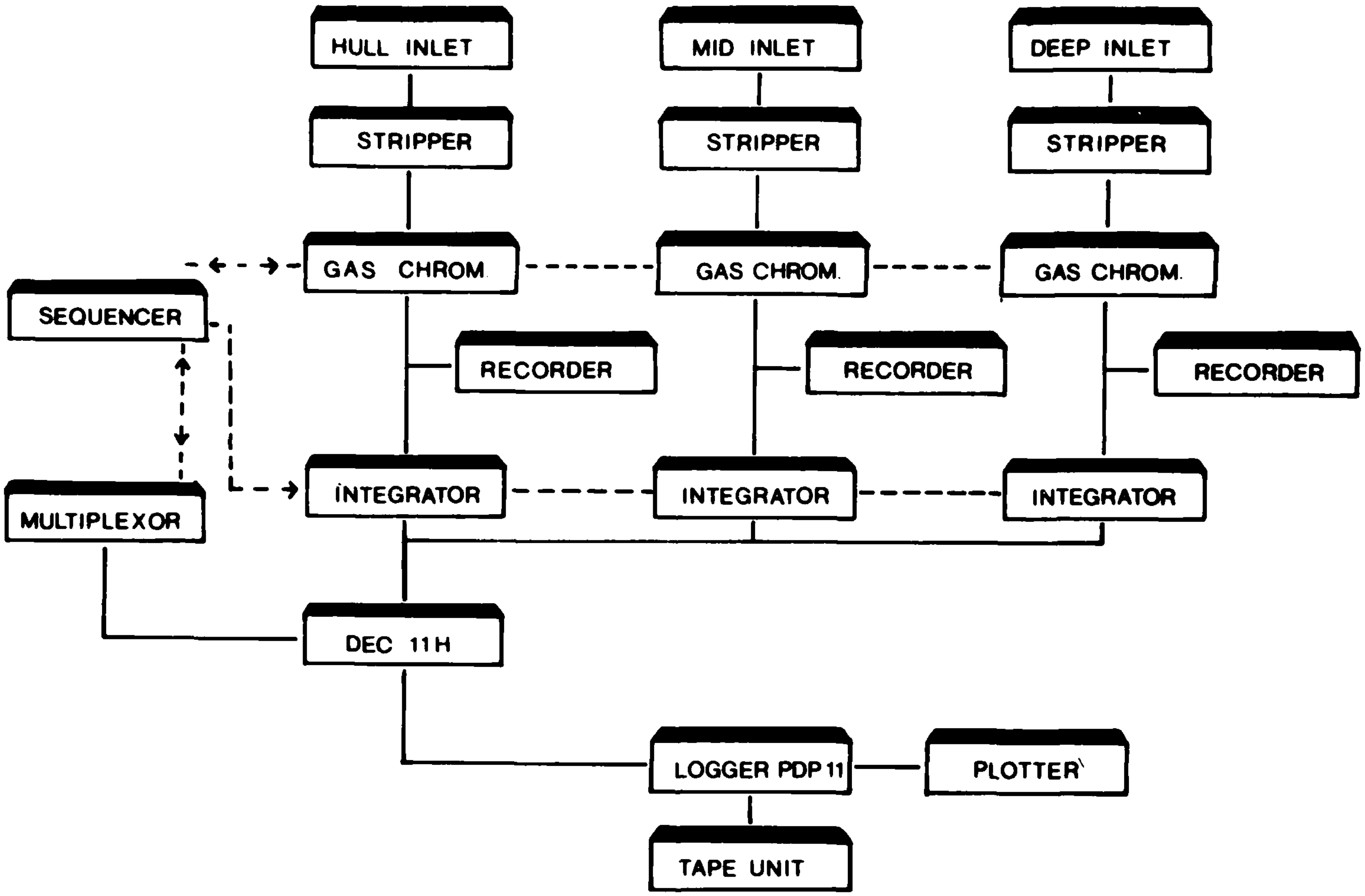

Figure 1 Block diagram of HOLLIS HEDBERG geochemical system.

The deep tow has 565 feet depth capability and the mid tow can sample to 450 feet. Water from the inlets travels to the strippers, where the hydrocarbons are partitioned into a stream of helium gas. The emerging gas streams are sampled once every three minutes by the chromatograph. The chromatograph data are displayed in analog form on a strip-chart recorder, and recorded digitally on 9-track magnetic tape along with ancillary information such as inlet depths, inlet temperatures and system configuration. The data can be processed and displayed in profile form onboard the ship in an offline batch mode.

Sampling System

The major components are shown on the block diagram. Both the mid and deep inlets employ a torpedo-shaped tow body, 5 feet in length and weighing 500 lbs. Within the body are an electrically driven water pump and sensors with circuitry to measure temperature and pressure. The pump we use is a standard 12-stage residential deep-well submersible pump manufactured by the A. Y. McDonald Pump Company. It is powered by a 230 volt, single-phase, two-wire, 1/3 HP Franklin electric motor. The length of tubing through which the sample travels lowers flow through the pump far below its open-flow capacity.

Figure 2 shows the pressure and flow-rate performance of this pump in the region in which it is operated. The deep inlet aboard the R/V HOLLIS HEDBERG delivers about six liters per minute onboard the ship, requiring about 110 psi pressure at the pump outlet. This is approaching the cut-off pressure of the pump. We are well into the turbulent-flow regime with a Reynolds number of 15,000. The pump is constructed with Delrin impellers and Lexan diffusors mounted on a stainless steel shaft. Bronze or brass fittings complete the pump construction. This construction minimizes the potential for contamination of the sample stream with hydrocarbon gases, but might seriously interfere with trace-metal determinations.

Figure 3 shows the construction of the electro-hydraulic cable used to tow the inlet body. This cable, supplied by the South Bay Cable Division of Consolidated Products Company, has a half-inch outside diameter and three-eighths inch inside diameter nylon tubing core. The core is surrounded by 21 No. 18 AWG wires. Each is made up of nineteen copper strands with 600 volt, 105°C PVC insulation. Ten of these conductors normally supply the motor; the remainder serve as spares, or service the instrumentation. The wires are surrounded by filling compound for moisture- and crush-resistance, and wrapped with a Mylar film. This entire bundle is covered by a polyurethane jacket. A braid made from .015 inch stainless steel wire surrounding the cable provides a tensile strength of 7000 lbs, and a yield strength of 3500 lbs.

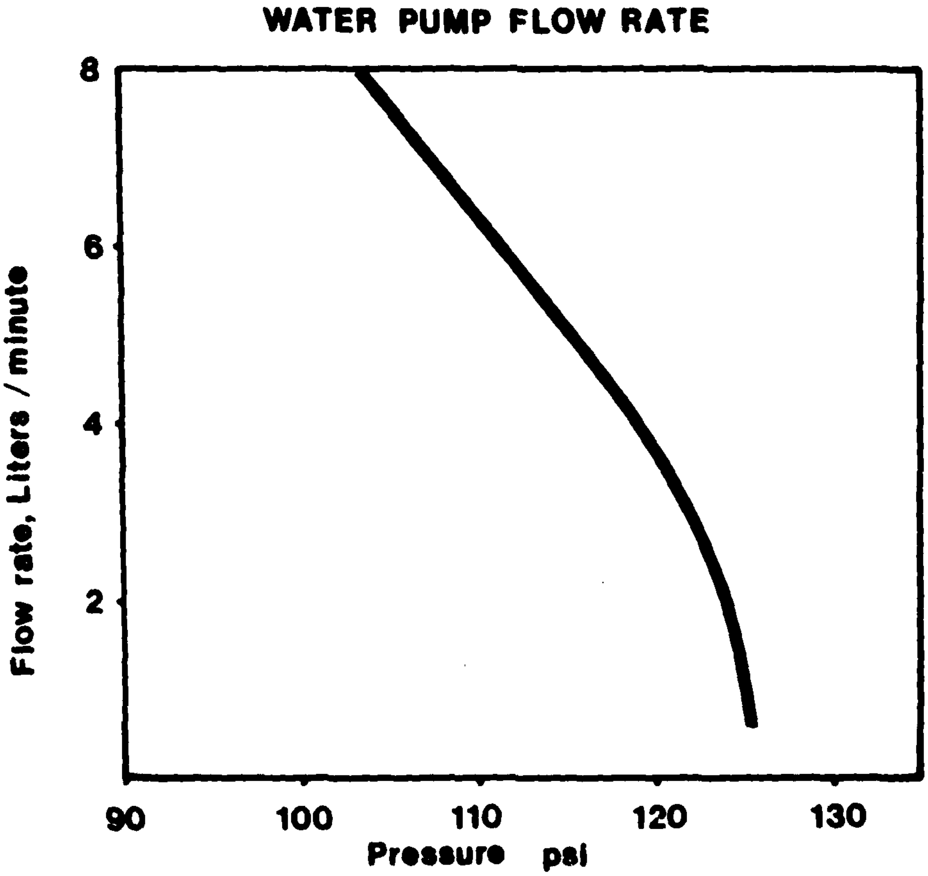

Figure 2 Water pump flow-rate near cut-off pressure.

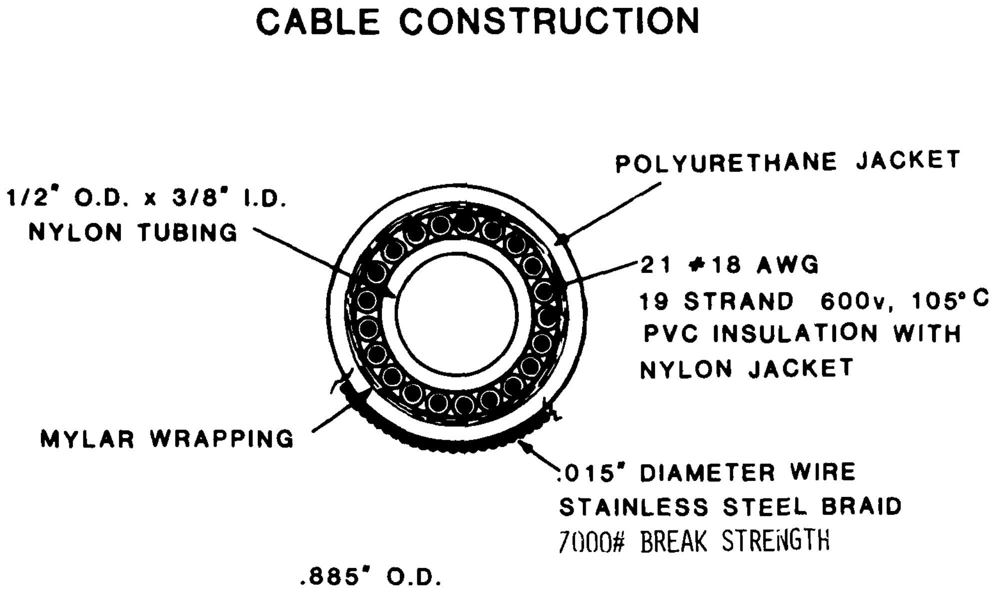

Figure 3 Electro-hydraulic cable construction.

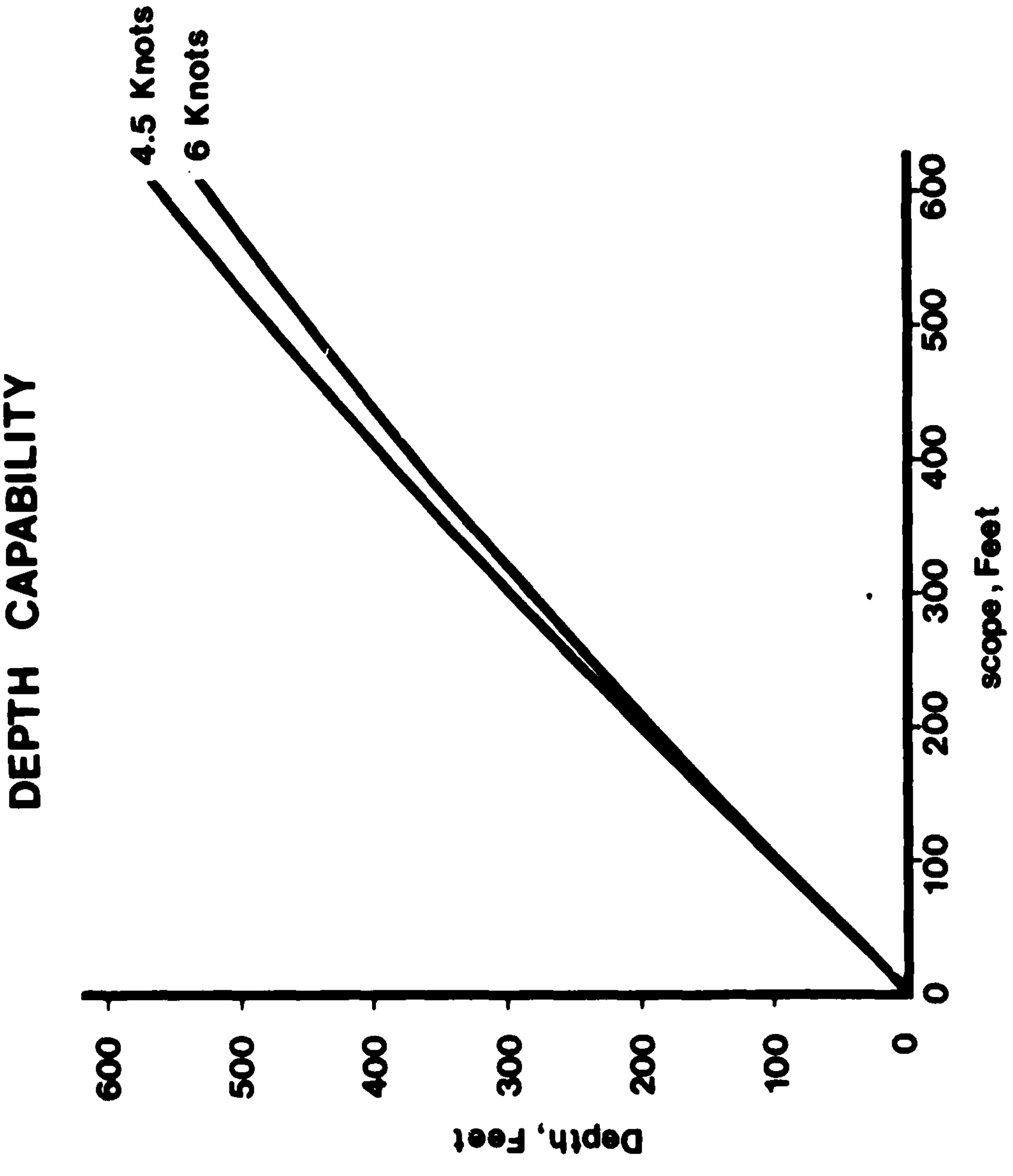

Figure 4 Cable scope-depth relationship at survey speeds.

Air-foil-shaped flexnose plastic fairing rides over the stainless steel braid, reducing the drag of the cable when towed through the water. The fairing reduces the drag on the cable to about 10 percent of the drag on a bare cable of the same diameter. This results in obtaining a sampling depth that is a large percentage of the deployed cable length, as shown in Figure 4. At 4-1/2 knots, a typical seismic ship survey speed, 600 feet of cable in the water yields a sampling of about 565 feet. Increasing the speed to 6 knots causes the body to rise about 40 feet. At this speed, the cable tension is just under 1000 lbs. The cable reel, sheave, and tow-point rigging complete the sampling system.

Figure 5 shows the mid tow reel installed on the R/V HOLLIS HEDBERG, with a flange diameter of 5 feet and hydraulic drive. Electrical slip rings and a water swivel joint mounted on either end of the axle permit continuous sampling while the depth of the tow is changed. A level wind is mounted on the front of the reel. An identical reel is used in what we call our portable system: although not something you could pack in your suitcase, it is frequently moved from ship to ship to perform geochemical surveys at various sites around the world.

The deep tow reel mounted on the R/V HOLLIS HEDBERG has a flange diameter of 6 feet 3 inches, and on this, the level wind is mounted on the back side of the reel, to increase the run of cable from reel to sheave.

Figure 6 shows the davit and spring-mounted sheave we normally employ with our portable system. It is seen here mounted on the forecastle of a seismic ship. Hydraulic cylinders drive a rack and pinion mechanism that rotates the davit in a vertical plane. The photograph shows the sheave supported by preloaded springs to absorb the shocks that can occur when operating in rough weather.

Analysis System

Figure 7 is a close-up of one of the two dual analyzers employed on the R/V HOLLIS HEDBERG. Each will handle two sample streams. The strippers are in the bottom of the rack, the chromatograph portion of the analyzer is at the top, and the analog recorders are in the middle.

The operation of the strippers is shown diagrammatically in Figure 8. Actually, "stripper" is a misnomer, for we'll see that no attempt is made to completely strip the gases from the water. Instead, we employ the same principle discussed in Herr's[3] paper. That is, we attempt to equilibrate a gas and water phase. Water under pressure enters the stripper chamber through two spray nozzles, exposing a large surface area on the entering water. At the same time, a stream of helium enters the chamber. The helium maintains the water level near

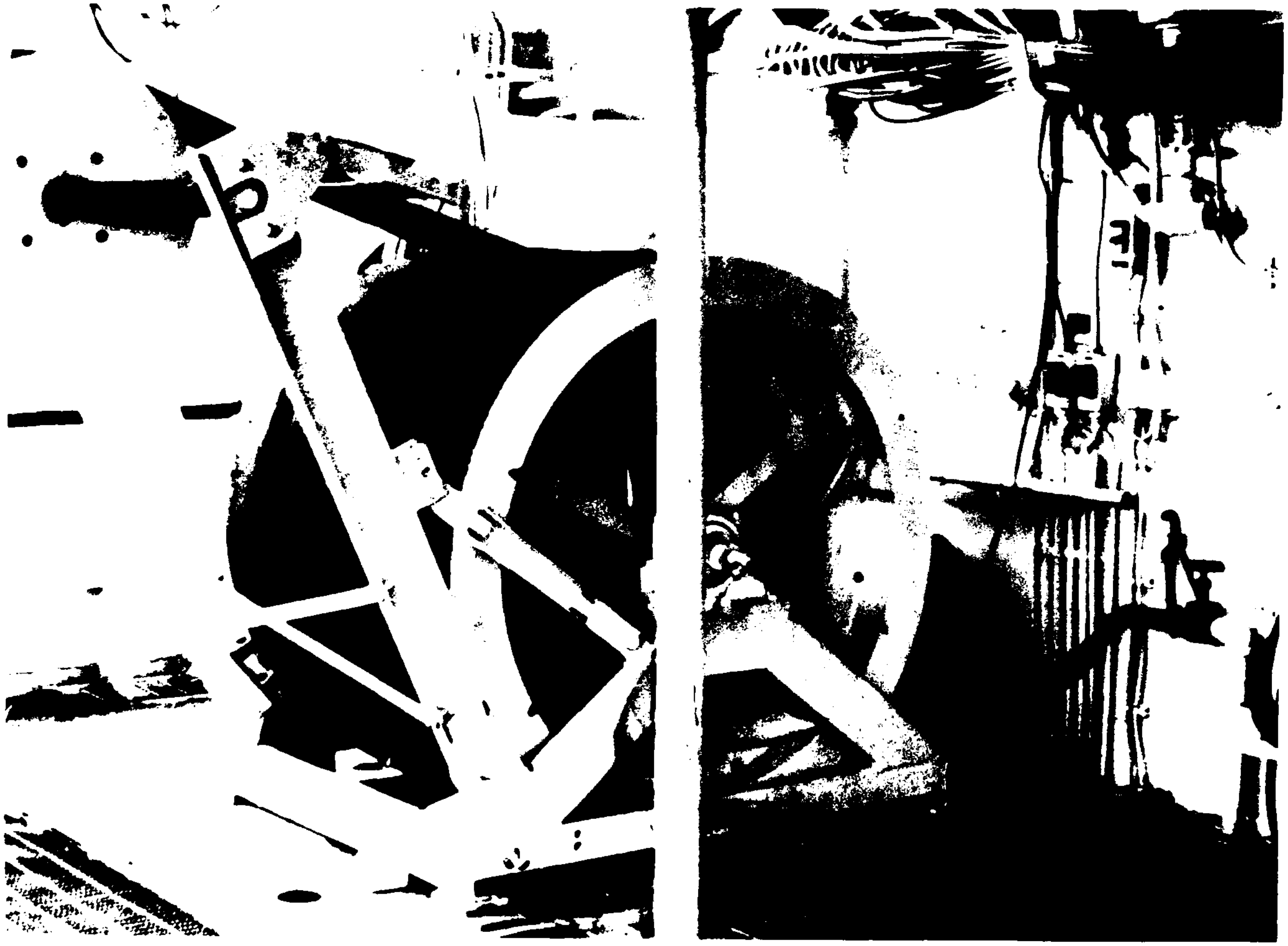

Figure 5 The R/V HOLLIS HEDBERG mid tow cable reel.
This design is also used with the "portable" system.

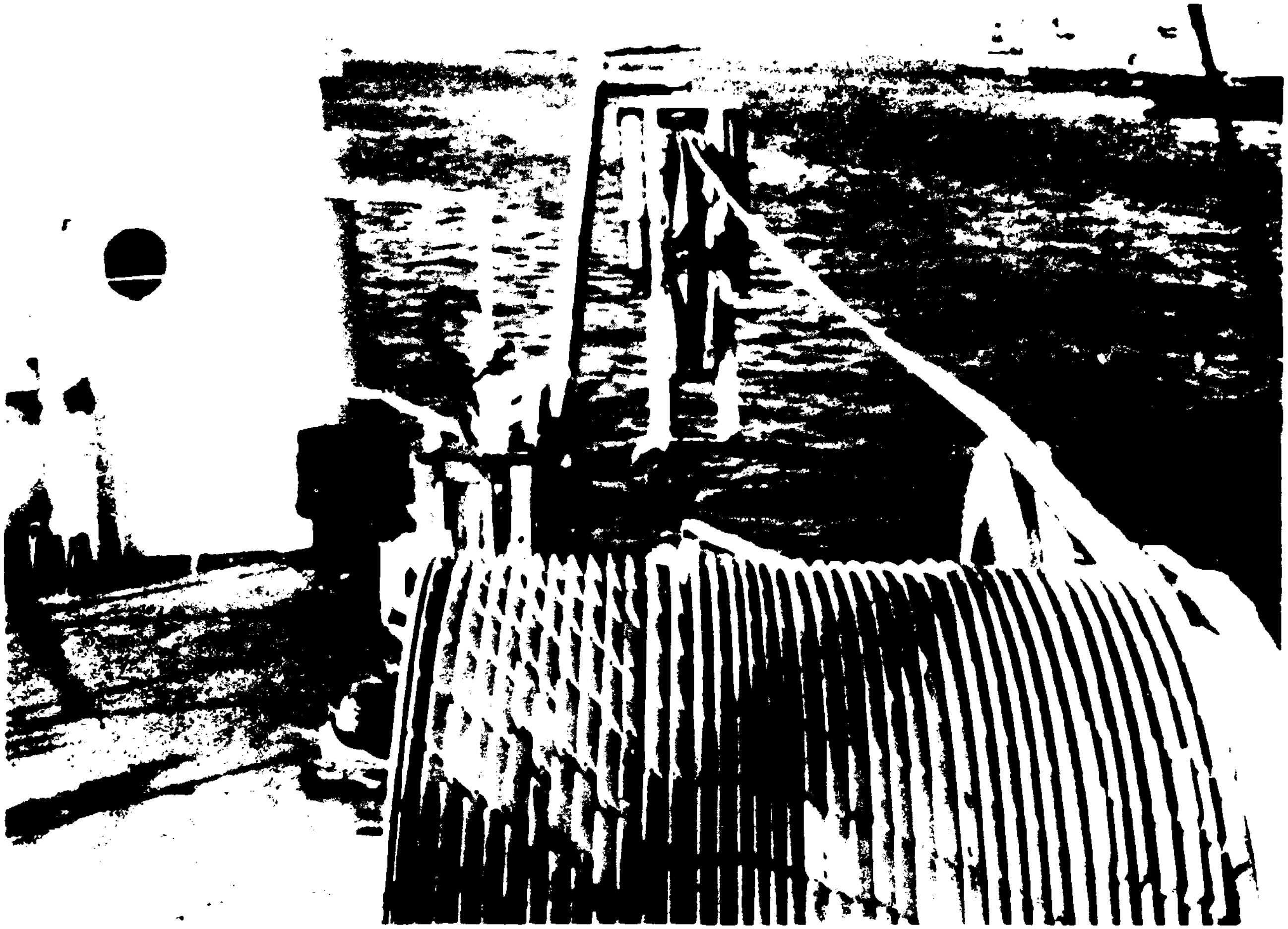

Figure 6   Portable system tow point rigging.

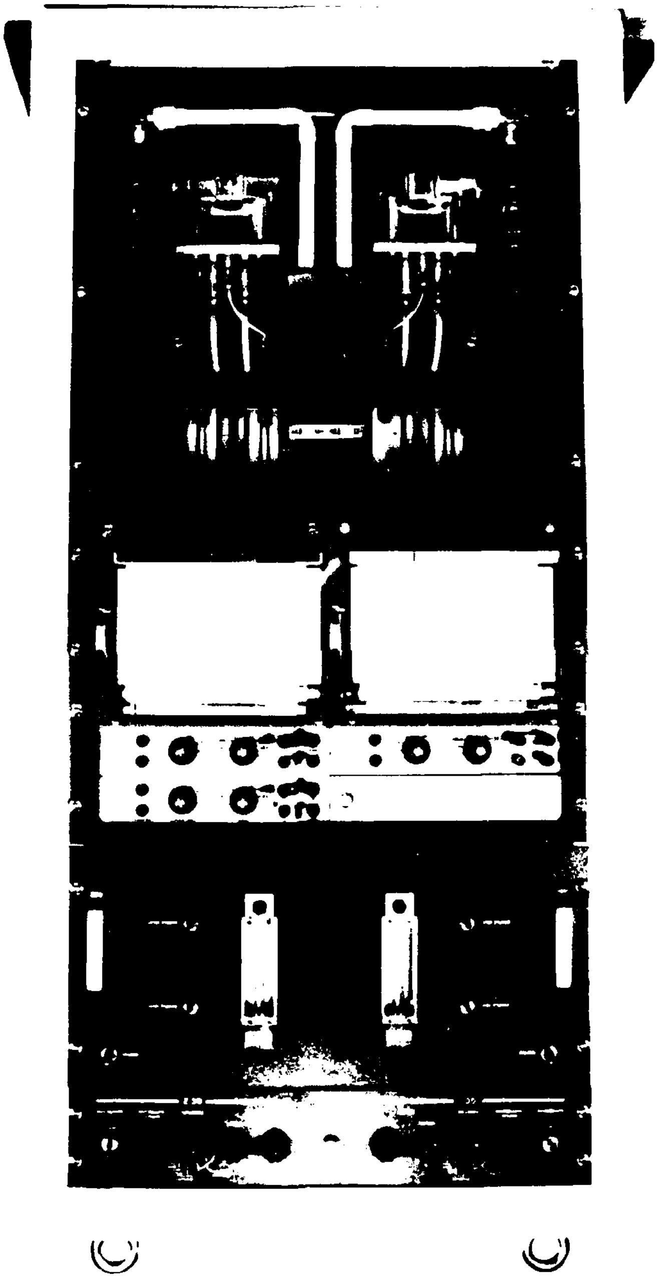

Figure 7 The dual marine hydrocarbon analyzer.

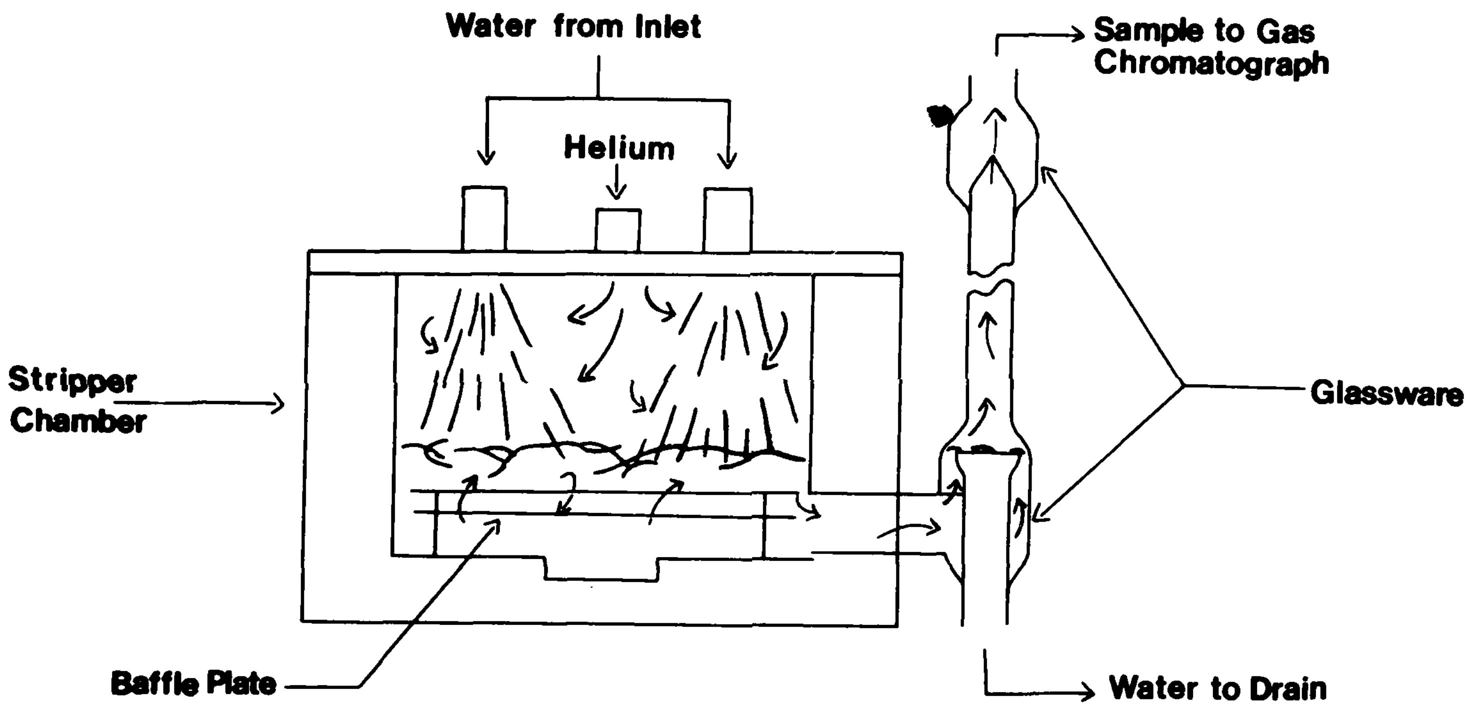

Figure 8 The gas "stripper" schematic.

the bottom water outlet and provides a gas phase into which the volatile components of the sample stream can be partitioned. The mixture of gas bubbles and water emerging from the stripper chamber is separated by gravity in the glassware on the right. The processes occurring within the stripper can be described by the following pair of simultaneous differential equations:

$$V_g \frac{d\,C_g}{dt} = (C_w - \frac{C_g}{K})\,P - C_g\,v_{go} + C_{gi}\,v_{gi} \qquad (1)$$

$$V_w \frac{d\,C_w}{dt} = -\,(C_w - \frac{C_g}{K})\,P - C_w v_w + C_s\,v_w \qquad (2)$$

where:

V_g is volume of gas in stripper
V_w is volume of water in stripper
C_g is concentration of component in gas within stripper
C_w is concentration of component in water within stripper
C_{gi} is concentration of component in gas entering stripper
C_s is concentration of component in water entering stripper
v_{go} is volumetric rate gas leaves the stripper
v_{gi} is volumetric rate gas enters the stripper
v_w is volumetric rate water enters and leaves the stripper
K is distribution coefficient for component (at equilibrium $C_g = KC_w$)
P is rate coefficient for the transfer of component across the interface between gas and water.

The first equation accounts for the amount of any volatile component in the gas phase. The term on the left is the total rate of change of a component in the gas phase within the stripper. The second and third terms on the right describe respectively the rate at which material leaves in the gas phase and the rate at which materials enter in the gas phase. The remaining term represents the rate at which the component transfers from the water phase to the gas phase within the stripper. It is given by the difference in concentration between the water and the gas, and a transfer coefficient P. The gas concentration is divided by the partition coefficient, K, to make it comparable to the water concentration as a measure of the driving force. The coefficient, P, contains most of our ignorance about the actual details of what goes on in the spray. It must depend upon the component's diffusion coefficient, and the amount and rate at which new surface is exposed in the spray. Solutions of these equations for two sets of conditions are shown in equations (3) and (4).

Steady State:

$$\frac{C_s}{C_g} = v_{go}\,(\frac{1}{P} + \frac{1}{v_w}) + \frac{1}{K} \qquad (3)$$

Response to step change:

$$\frac{C - C_f}{C_o - C_f} = e^{-\alpha t} \qquad (4)$$

C_o = Initial concentration
C_f = Final concentration
C = Intermediate concentration

$$\alpha = \frac{\left(V_g + \frac{V_w}{K}\left(\frac{P}{P+v_w}\right)\right)}{V_g}$$

The steady-state solution (3) is used to convert the hydrocarbon concentrations we measure in the chromatograph to the hydrocarbon concentrations in the entering seawater. The conversion is seen to depend on the sum of three terms: one is the ratio of the gas flow rate to the transfer coefficient; the second is the ratio of the gas flow rate to the seawater flow rate; and the third is given by the distribution coefficient of the component in question. The latter two terms are well defined, or are easily controlled. The term involving the transfer coefficient is the one more likely to suffer variations as the spray changes in character. The nozzles are replaced every cruise to minimize this occurrence. Typical values of the three terms stand in the ratio of 1 to 1 to 3; hence, the rate term represents only about 20 percent of the computed value. Minor variations in the term do not seriously affect the final result. Response to a step change in concentration described in equation (4) provides a more sensitive measure of this term, and was used to evaluate the coefficient.

Figure 9 shows the result for one set of conditions. Our chromatograph is limited to running only one sample every three minutes; hence, the plot you see was obtained by making three separate runs with staggered times. The exponential response predicted by the equation is seen to be closely followed over two orders of magnitude.

The chromatograph is constructed in our own shops. A single 10-port Carle valve controls sample injection and backflush of the precolumn. The flow diagram is shown in Figure 10. The flow arrangement is conventional, with the flow switching to the backflush position after the components of interest have passed through the precolumn. The flame-ionization detector is our own design, and employs an integrally mounted electrometer, eliminating a cable and its attendant noise at the input.

The integrators shown on the block diagram are formed from voltage to frequency converters whose inputs are fed by the detector electrometer. Their output is fed to counters, which are linked to the computer. The GC detector signal is integrated continuously and recorded at two-second intervals throughout the three-minute cycle of the chromatograph.

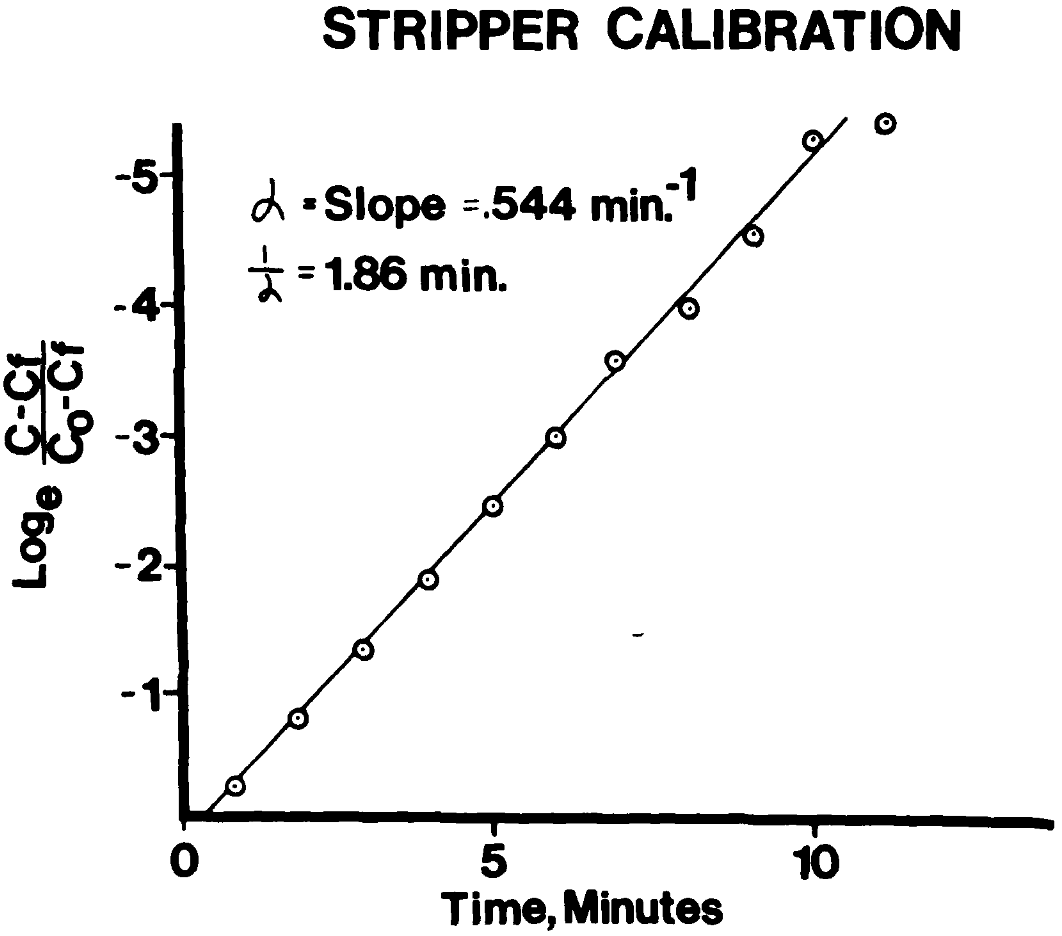

Figure 9 Stripper transfer coefficient calibration.

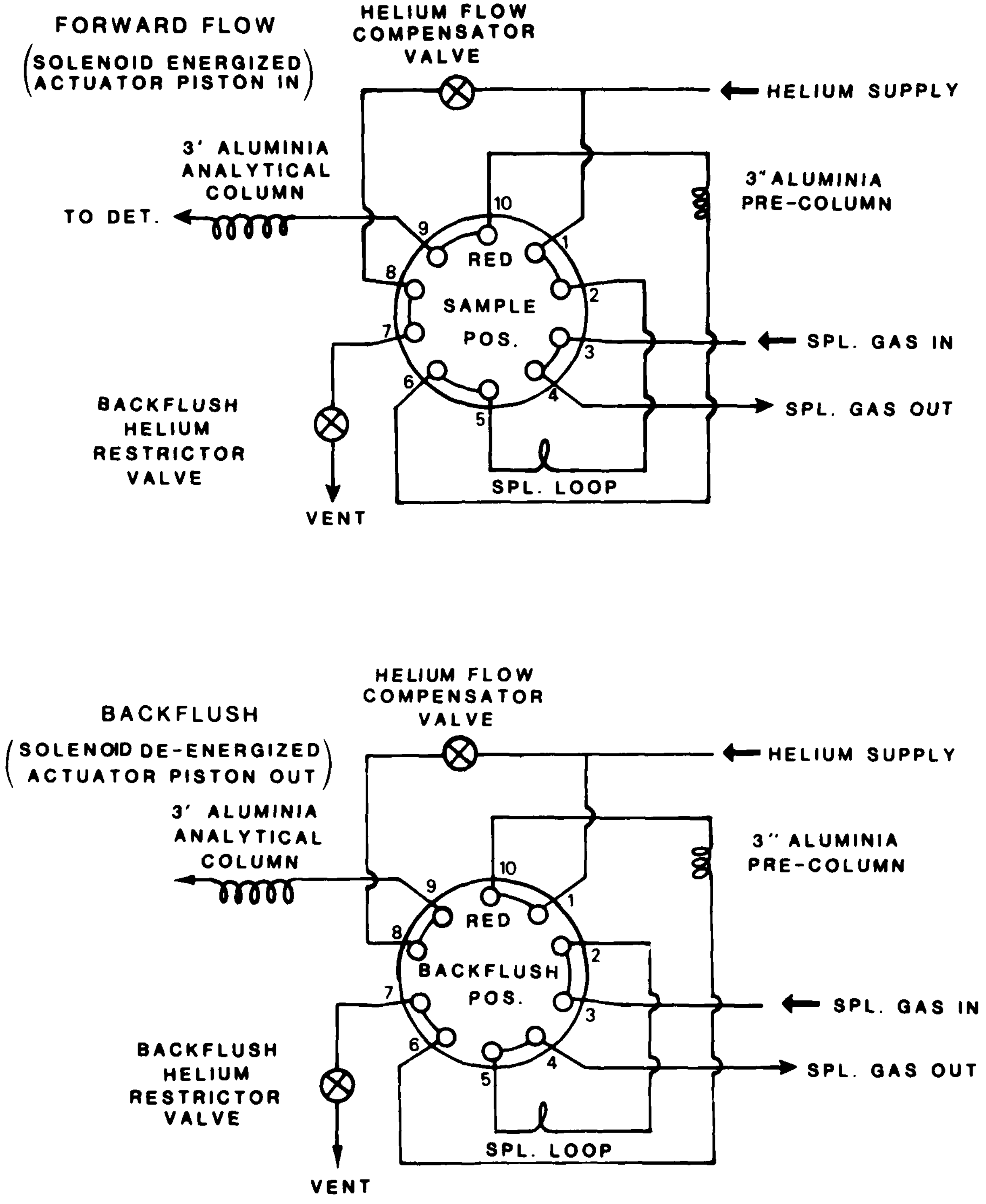

Figure 10 The chromatograph flow diagram.

Figure 11 illustrates the manner of recording the chromatograph signal. This figure is representative of the computer-drawn plots displayed at selected intervals during the in-house processing of the data. It is used in the quality control of the processing steps. The transformed signal scale allows identification of the retention times of even the largest peaks, and still gives a vertical displacement at the baseline approaching that of the analog recorder on its most sensitive scale. The upper trace in this plot presents the actual two-second integrations of the signal. The bottom trace is the baseline calculated by the processing program.

Coastal Hydrocarbon Concentrations

Let me show you a brief sampling of some data that the system has generated. The first examples are taken from a paper presented last April.[4] Figure 12 compares propane concentrations measured with the Gulf system in three offshore regions of the United States to the worldwide concentrations reported by J. W. Swinnerton and R. A. Lamontagne.[5] The worldwide data cover a wide geographic area. The histogram shows their measurements for 132 open-ocean sites. Sites they considered to be contaminated have been eliminated. The open-ocean average propane concentration derived from these measurements is .34 nanoliters per liter. However, the average is not very typical. Actually, half the samples are .15 nanoliters/liter or less. Our data for coastal waters in these three regions are similar to the worldwide data in that all show a significant number of samples containing concentrations at the low end of the scale. There are differences, however, from region to region.

The Atlantic Coast has a median concentration of .14 nanoliters/liter, almost identical to the worldwide median, but there are only four samples out of 13,000 exceeding 1.2 nanoliters per liter.

The Gulf of Mexico data clearly show evidence of petroleum. Twenty-two percent of the samples have in excess of 2 nanoliters/liter. Half the samples have more than .5 nanoliters/liter. The mean concentration is 2.7 nanoliters per liter, or eight times the open-ocean mean. The offshore Louisiana area is a prolific petroleum producer and our data reflect it. Swinnerton's data support this interpretation. All 11 samples that were eliminated because he classified them as contaminated were from the Gulf of Mexico, and 10 out of 16 of his remaining Gulf of Mexico samples have more than .5 nanoliters per liter.

The Pacific Coast data are intermediate. There are quite a few samples with more than 1.2 nanoliters/liter. There is petroleum production and seepage on the West Coast that appear to be showing up in our data.

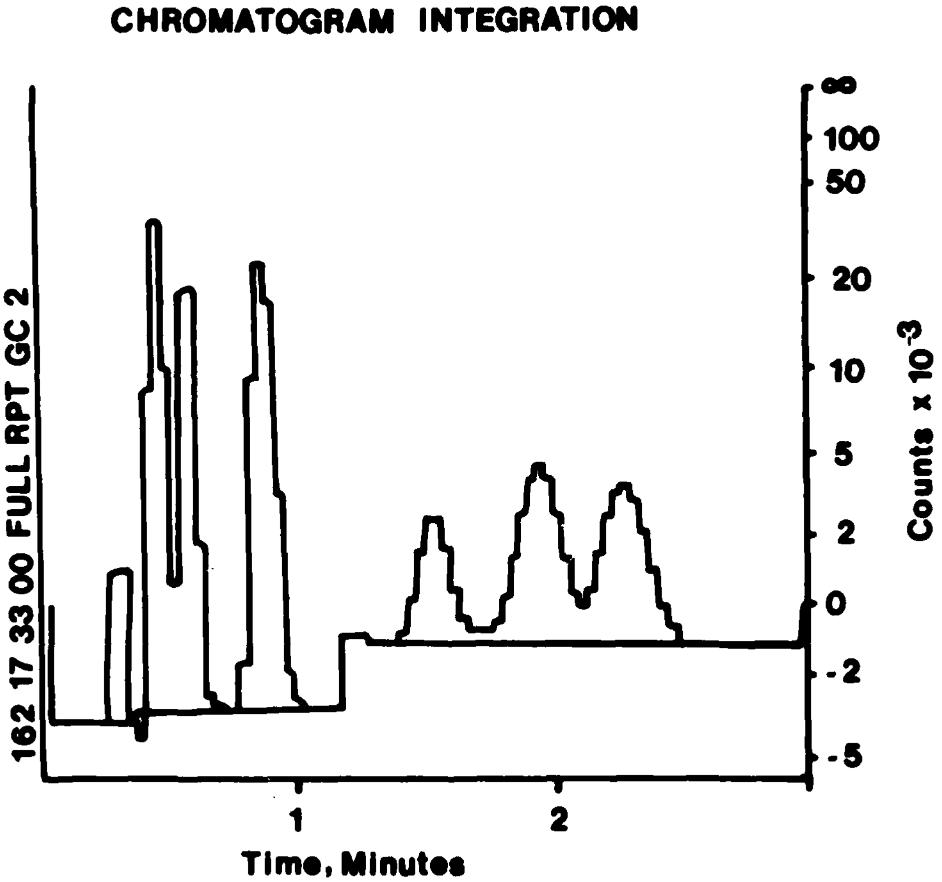

Figure 11 A chromatograph detector signal recording.

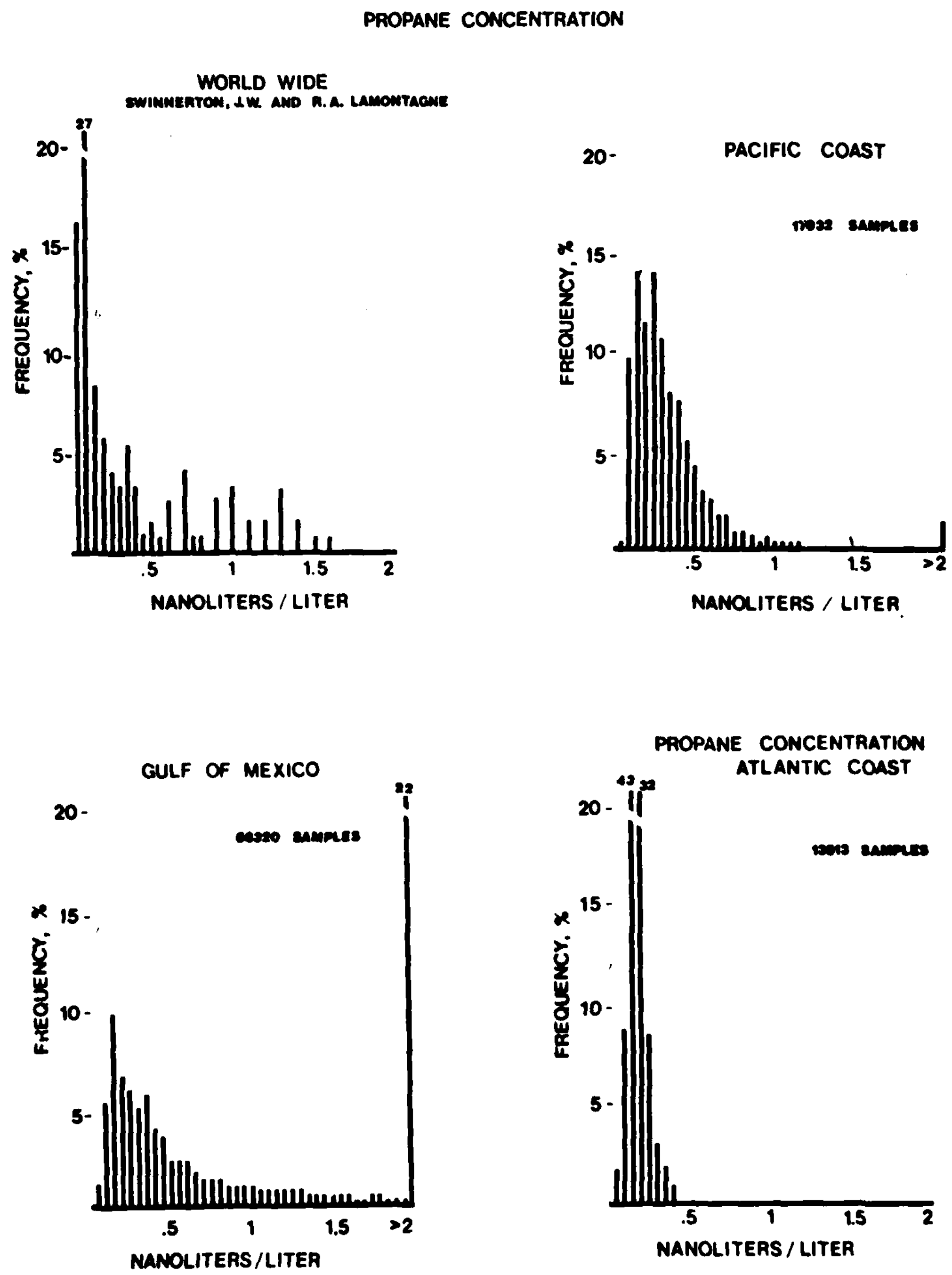

Figure 12 Seawater propane concentrations worldwide and in three offshore United States regions.

Figure 13 shows the same type of data for methane. The open-ocean values cluster closely between 30 and 80 nanoliters/liter. The median is 50 nanoliters/liter, and only 8 percent exceed 100 nanoliters/liter. Compared to the open oceans, the Pacific Coast data lack the samples containing between 30 and 60 nanoliters/liter. The median concentration is 140 nanoliters/liter. Twenty-three percent have more than 400 nanoliters/liter, and are clearly anomalous by open-ocean standards.

Of the three offshore regions, methane concentration in the Gulf of Mexico shows the greatest departure from the open oceans. Eighty-six percent of the samples exceed 100 nanoliters/liter compared with only 8 percent in the open ocean. Only 7 percent of the samples have methane concentrations in the 30 to 80 nanoliters/liter range that occurs so frequently in the open ocean.

The offshore region most similar to the open ocean in methane concentration is the offshore Atlantic. But even here, there are significant differences. This region is similar in that a more restricted range of concentrations is observed, and hardly any of the samples have more than 400 nanoliters per liter. Yet the region is considerably richer in methane than the open ocean. The median concentration is 2-1/2 times that of the ocean, and 67 percent of the samples have more than 100 nanoliters/liter.

Apparently, methane is being added to the ocean water more frequently on the continental margins than is propane. Possibilities for sources of methane that do not also add propane include biogenic generation in the water column or shallow surface sediments, influx from rivers or dry gas seeps, possibly of biogenic origin, from accumulations of economic importance. Integration of geophysical data into the interpretation is necessary to indicate the latter.

A final example, Figure 14, displays the data in the form they are most frequently used. We examine the seawater hydrocarbon anomalies in conjunction with the subsurface, and make an interpretive judgment whether the anomaly reflects a commercial accumulation.

The seismic section indicates faulting and shallow-gas charged sediments at the site of the hydrocarbon anomaly. We frequently see an association of this type. Reitsema, Lindberg, and Kaltenback[6] in their paper describing results obtained with the Marathon System stress the same association of faulting and seeps.

Future Needs

What are the sampling requirements for the future? The hypsometric curve in Figure 15 reveals that if we are to double the area for which we can now sample near the bottom, we must have capability to reach

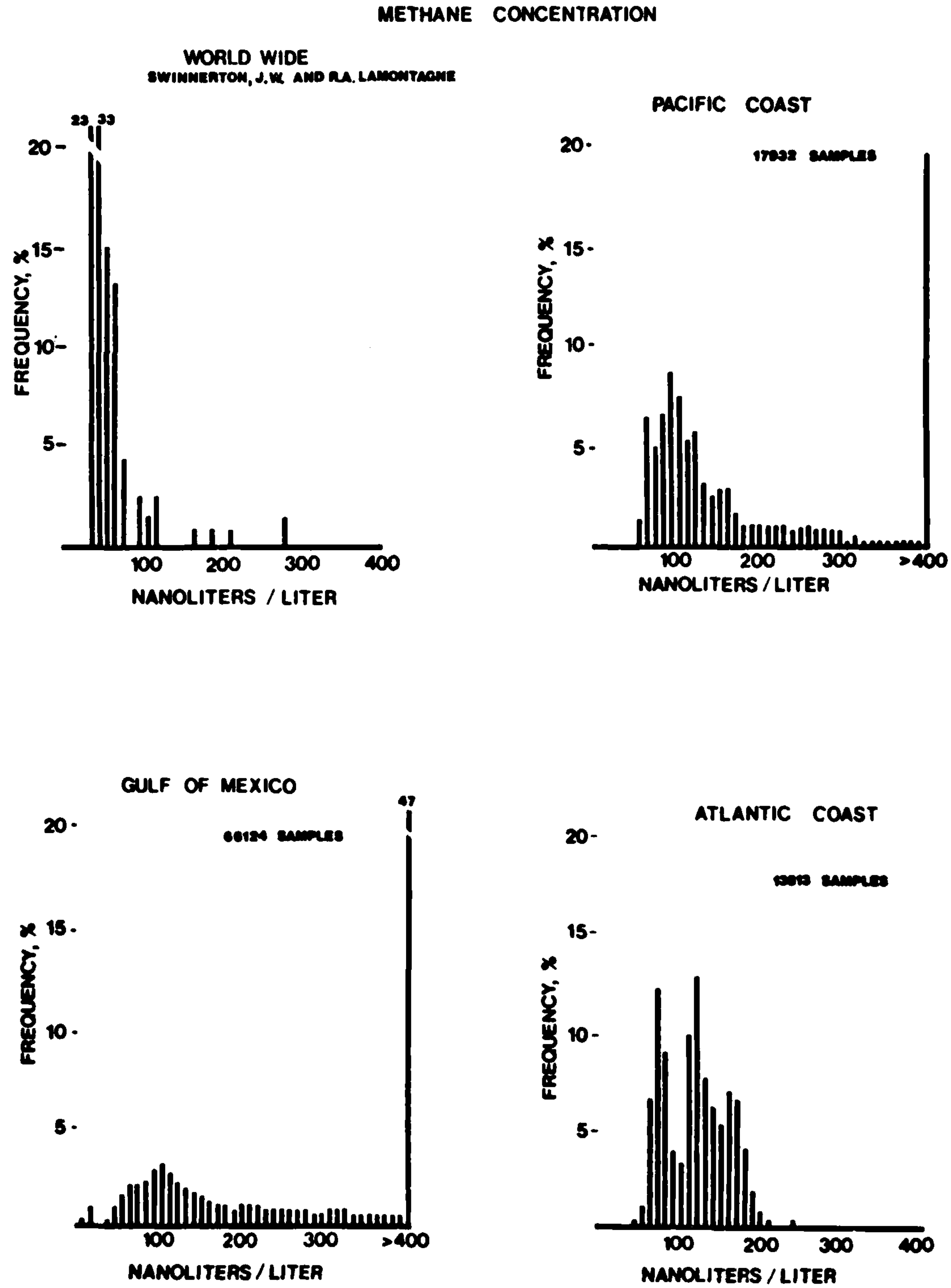

Figure 13 Seawater methane concentrations worldwide and in three offshore United States regions.

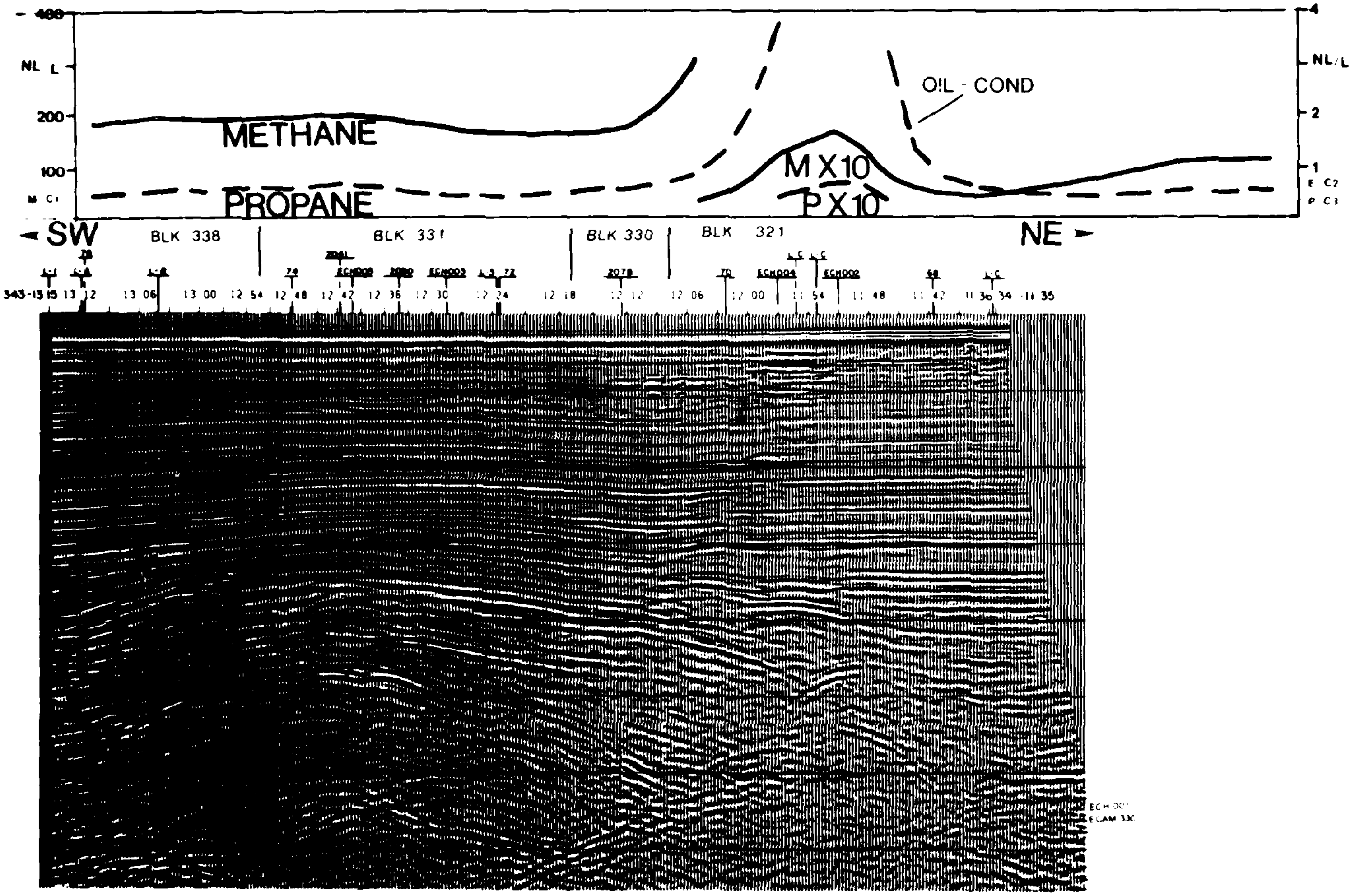

Figure 14 A seawater hydrocarbon anomaly associated with faulting and gas-charged sediments.

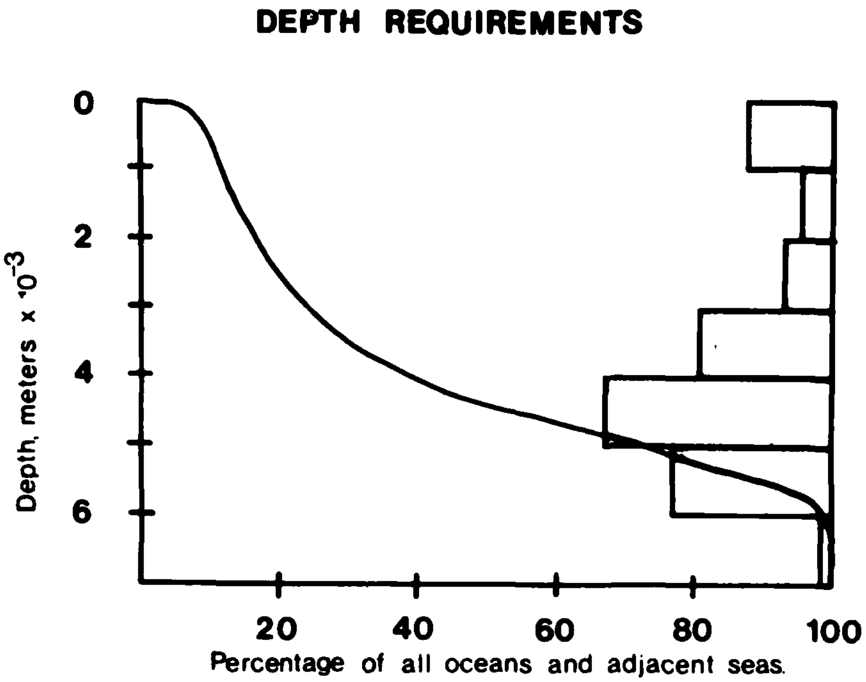

Figure 15 Depth capability requirements for extended seafloor coverage.

almost 2000 meters, and greater than 4000 meter capability to cover half the ocean bottom. To make more meaningful estimates of requirements for the petroleum industry, we should plot depth against petroleum resources. These data are not available, but we expect they would plot considerably above the curve shown, and that we can explore for more resources without increasing our depth requirements so rapidly.

Acknowledgment

We wish to thank the many Gulf personnel who helped during various phases of the development of this system, especially F. L. Spanbauer, who designed the digital electronic circuitry and computer interfacing.

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DISCUSSION

GUINASSO: What do you suppose it costs you to operate one of these systems?

MOUSSEAU: A lot of money. We have two people on duty all the time on our ship, just taking care of the sniffer system, and they are working out there 84 hours a week, so the expenses get quite enormous.

FARRINGTON: Do you have any measurement stability problems in your system due to the ship's rolling, or do you have a special electrical configuration?

MOUSSEAU: Well, we did experiment with the electrode configuration, and eliminated most of the motion sensitivity, but we haven't eliminated such problems entirely. The ship's roll has the same frequency content as some of the early peaks. You cannot just filter it out. The integration technique we use also reduces it appreciably.

FARRINGTON: Could you tell us about the relative down time on that instrumentation?

MOUSSEAU: It is very small. It is well below 10 percent of the survey time. The main trouble we had was with the tow or the cable system.

ORR: How much does it cost to build a system such as yours, and what is the cost of the cable?

MOUSSEAU: The cable itself runs about $8.00 to $10.00 a foot without the fairing. We do not really know how much the system costs, but I would estimate between $100,000 to $400,000 to build a complete system, the tow, the cable, the winch, the instrumentation, the computer data system, everything.

GUINASSO: I can answer part of that question. I just bought some cables: the cable cost about $7,000 and the fairing cost about $14,000.

HERR: Considering your flow rate, your pumping flow rate, and the stripping system that you have, what is the nominal gradient that you can measure in methane? That is, the number of nanoliters per liter per meter over ground that you can determine.

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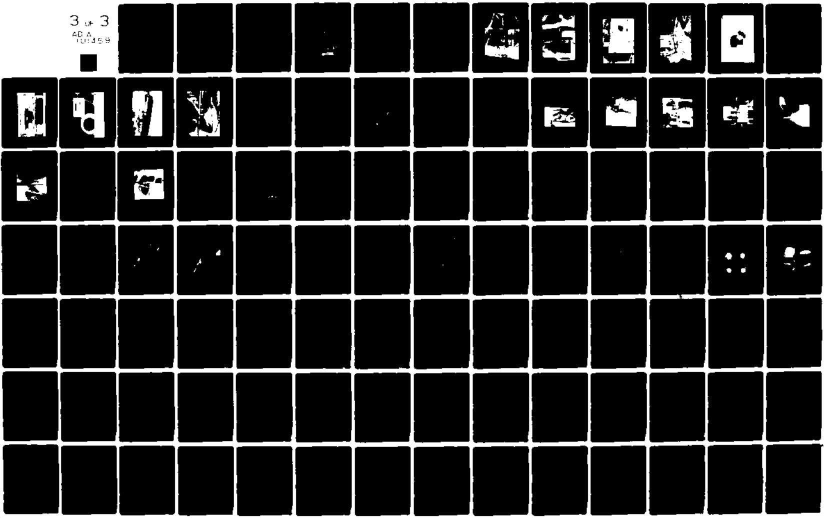


MOUSSEAU: Well, the spatial resolution depends on the ship's speed. The stripping system, or equilibrator, has a time constant of about two minutes for the bare stripper chamber. There is another chamber in the sequence, so the time constant, or residence time, is perhaps three minutes. You can figure that into whatever speed at which you want to travel. Normally, at 6 knots there is 3/10 mile between samples. For greater resolution, we'd have to analyze faster, use smaller chambers, slow down, or make other changes.

AN UNDERWAY TOWED PUMPING SYSTEM FOR TRACE-METAL STUDIES

Bob J. Taylor

The Engineering Development Laboratory has been working on its underway towed sampling system since the summer of 1978, at the request of the National Ocean Survey's newly established Ocean Dumping and Monitoring Division. That group had taken on the responsibility of monitoring chemical dumpsites--Deepwater Dumpsite 106 off the New Jersey coast, and a pharmaceutical dumpsite off Puerto Rico.

One objective the division had in mind in monitoring the dumpsites was to be able to investigate the concentration of trace metals in the dumped material as a function of time after the dump. Since the dumpsite plume will be affected by surface wind and currents, continuous sampling was required to meet this goal.

Design concept studies were started in 1978. We had completed the lab and field tests of the phase-one system by September 1979. The field tests were conducted on the Chesapeake Bay, and the first open-ocean cruise of the phase-one system was conducted in September.

We then initiated design of the phase-two system. The primary difference between the phase-one system and the phase-two system is the towed-body configuration. The phase-two system was completed and field-tested two weeks ago on the Chesapeake Bay. The open-ocean cruise for the phase-two system is scheduled for this summer at Deepwater Dumpsite 106 aboard the R/V GEORGE B. KELEZ.

We are going to use the remainder of this year to generate the specifications for upgrading the system, primarily increasing its depth capability from 50 meters to 150 meters. We are also going to take a look at adding additional intake ports and the possibility of integrating a data-acquisition system with the sampling system.

I will cover briefly the specifications for the pumping system. It has a depth range of 2 to 50 meters. We have avoided lowering on station because of twisting problems that might develop between the two-part towing-cable configuration. We can tow at speeds up to five knots. The pumping system delivers six liters per minute with a transport time of 200 seconds from the intake port to the delivery manifold. We have temperature- and pressure-sensing capability in the towed body. The entire system, including valves, connectors, delivery tube, and the pump itself, is either TFE or FEP Teflon.

The system can be divided into four basic parts: the towed body, the tube and cable assembly, the deck auxiliary equipment, and the control console and water delivery manifold, which are normally installed in the shipboard chemistry van.

The fish has in its lower section 430 kilograms of lead-plate ballast. The lead plates are encapsulated in a polyurethane potting material to help spread the load when the fish is positioned in its cradle.

We are using a Franklin Electric Company submersible pump motor that delivers 3/4 horsepower at 3450 rpm. It has a stainless steel case, and is pressure-rated to 2000 psi.

The pump that we are using is a Fluorocarbon Scientific centrifugal Teflon pump. It has a ceramic shaft and vitreous carbon bearings. The depth sensor is a Digiquartz 400 psi sensor, which is coupled to a Digiquartz pressure computer normally located in the control console inside the chemistry van.

The temperature sensor is a YSI precision thermistor. Multiplexing circuitry for the temperature and pressure signals is located in a pressure housing aboard the fish.

The tube and cable assembly is a two-part configuration using a separate wire rope to sustain the towing load, and a tube bundle containing the Teflon delivery tube, electrical cables for the pump motor, and two sensors. The tube bundle is overbraided with a nylon jacket and ribbon fairing.

The auxiliary deck equipment consists of the shipboard winch, which holds the towing wire rope, the cradle container for the fish, the A-frame with stoppers and tensionmeters, and a hand-cranked reel stand. Prior to the open-ocean cruise in May, we plan to switch to a flaking box arrangement instead of the hand-cranked reel stand.

The control console is located inside the chemistry van. It has digital readouts for temperature, depth, and motor current, and contains a strip-chart recorder for temperature and depth.

The water delivery manifold is also located inside the chemistry van. The fish we are using is a Fathom 1.5 meter passive towed body. It has clear Lexan shells on the top and bottom and an aluminum superstructure.

Figure 1 shows a sketch of the underway towed pumping system. Note the inlet port on the front part of the fish, the separate wire rope and tube-cable assembly, the reel stand storing the tube and cable assembly, the oceanographic winch, the water delivery manifold, and the control console.

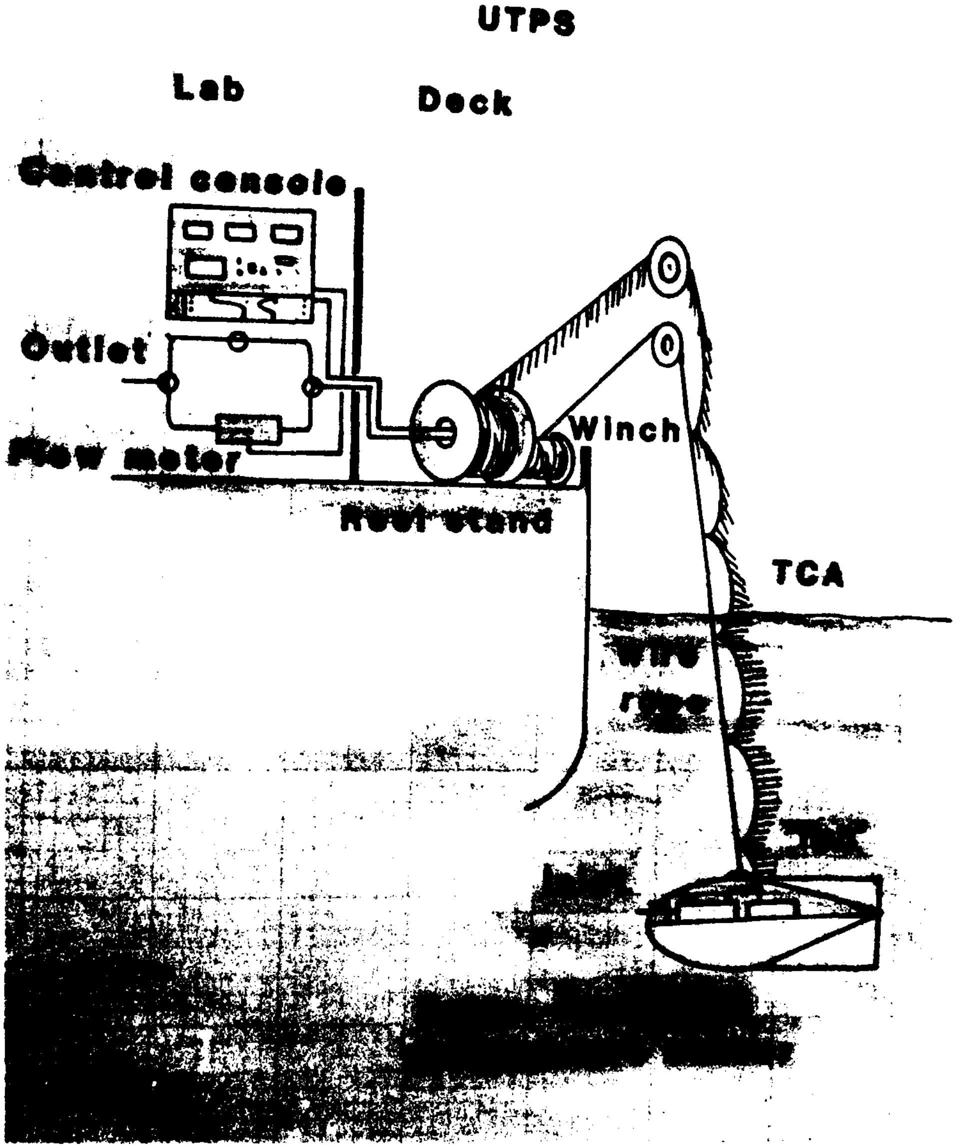


Figure 1 Underway towed pumping system.

Figure 2 shows the construction of the tube-cable assembly and the method of attaching it to the wire rope. Breakouts with shackles positioned at one meter intervals are snapped over the wire rope during deployment and removed during recovery. The entire assembly is covered with ribbon fairing. Copper sleeves are used on the wire rope to prevent the snap shackles from sliding, so during tow operations, presumably, there is no load on the tube-cable assembly at all. Note the construction of the tube-cable assembly: braided nylon rope fillers are used, and the entire assembly is overbraided with a nylon jacket.

Figure 3 shows the phase-one system suspended below the A-frame on the R/V JOHNSON. Note the cube-cable assembly with the fairing, the separate wire rope leading to the ship's winch and the block arrangement on the A-frame. The intake port, the pump, and the pressure sensor were installed inside the cylindrical housing. We did not have a temperature sensor on the phase-one system. Note the dead-weight depressor hanging below the stern of the vessel.

The underway towed pumping sampling system is routinely backflushed with nitric acid. One of the tests we conducted on the Bay was to set up the experiment and work through the backflushing procedures.

The first time the phase-one system was used operationally was aboard the R/V GEORGE B. KELEZ at Deepwater Dumpsite 106 (Figure 4). The towing arrangement was different from the arrangement on the R/V JOHNSON. In the case of the KELEZ, towing operations were conducted from an A-frame on the side of the vessel, rather than from the stern. Figure 5 shows the self-contained chemistry laboratory aboard the KELEZ.

Initially, we experienced the same problem as that of the Woods Hole project, in that we did not have electrical slip rings on our reel stand; hence, each time a depth change was made, we had to disconnect power to the towed body. An interim solution was found by flaking enough cable on the deck and leaving the connectors attached (Figure 6). Prior to the cruise in May, we intend to have a flaking box that will be used to store the tube-cable assembly. There is a risk in flaking the cable on the deck. The Teflon tubing inside the tube-cable assembly may be damaged if its bending radius around the figure eight is too small.

Figure 7 shows the Fluorocarbon Scientific Teflon pump. The pump has a ceramic shaft and vitreous carbon bearings. Note the impeller and the magnetic coupling.

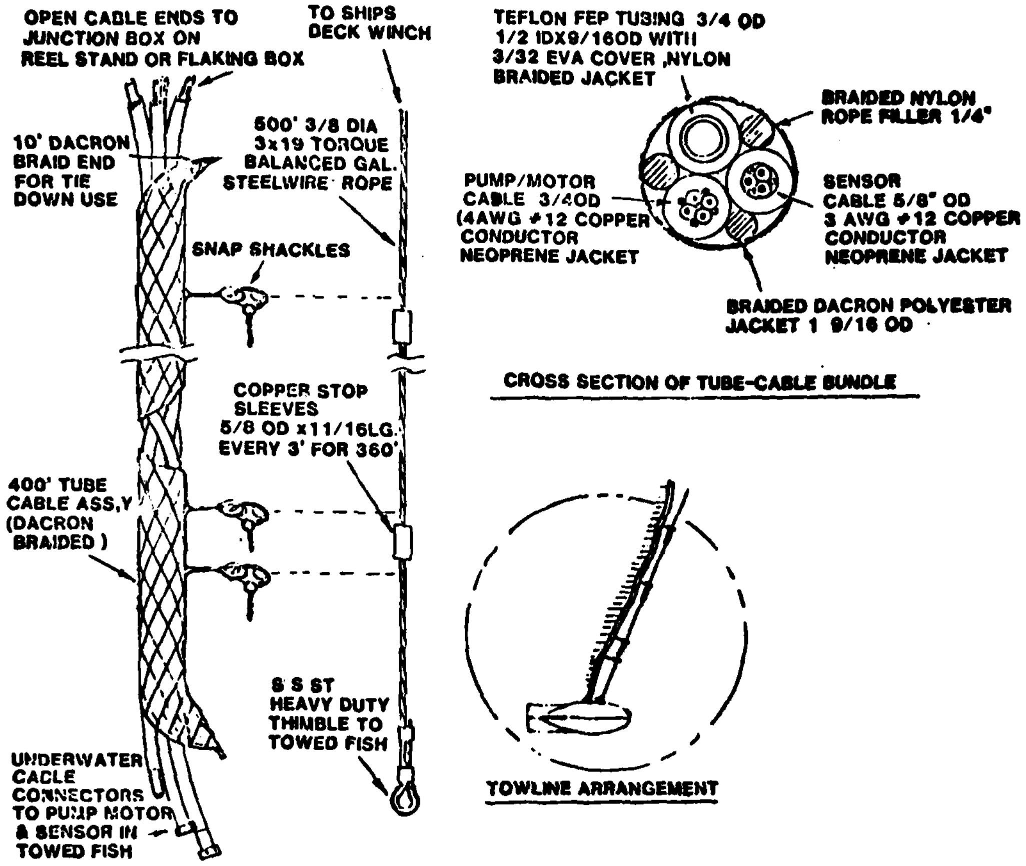


Figure 2 Schematic of towline-tube-cable assembly (TTCA).

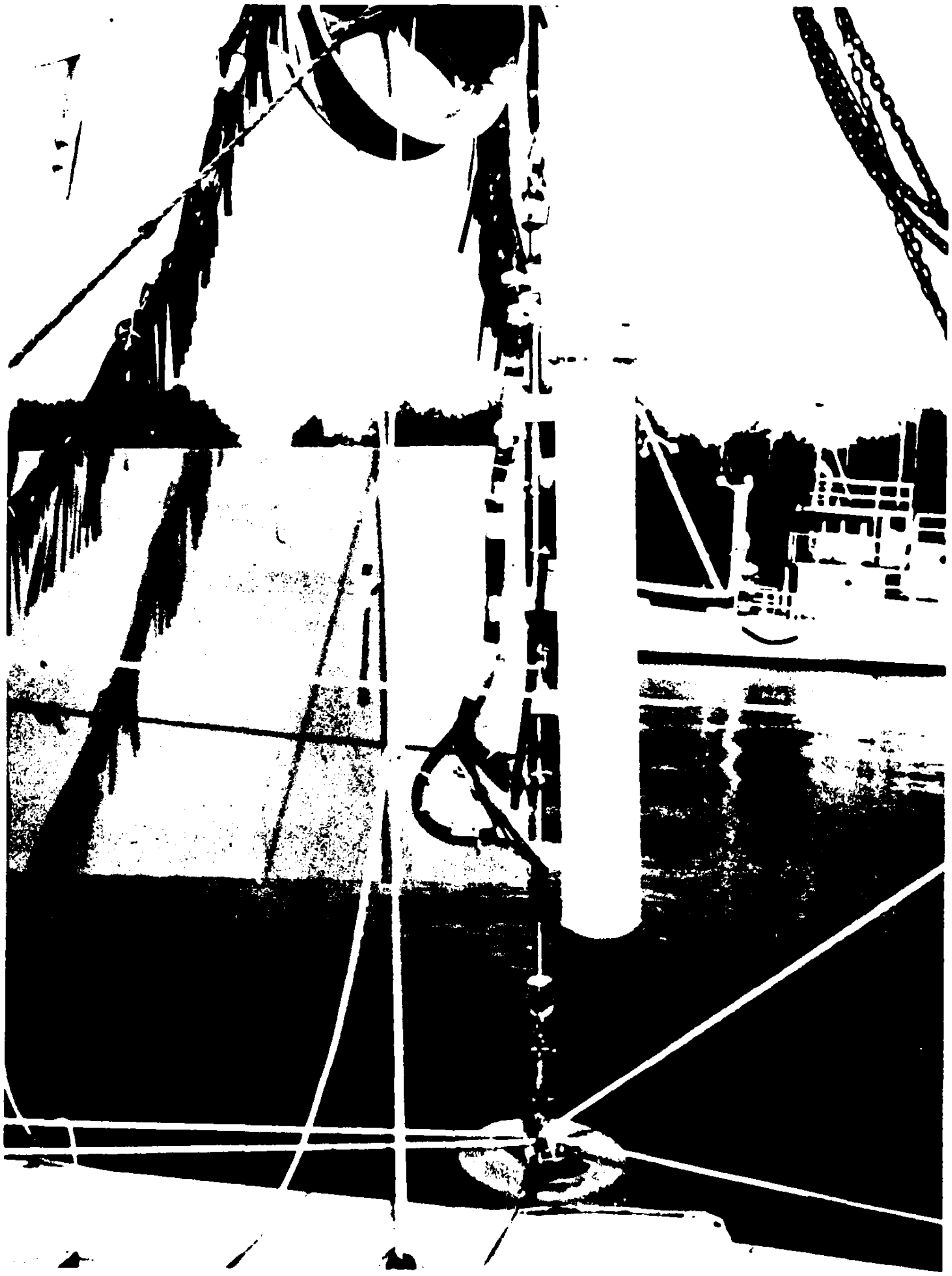


Figure 3 Phase I system suspended from R/V JOHNSON.

Figure 4 Phase I system aboard R/V GEORGE B. KELEZ.

Figure 5 Chemistry laboratory.

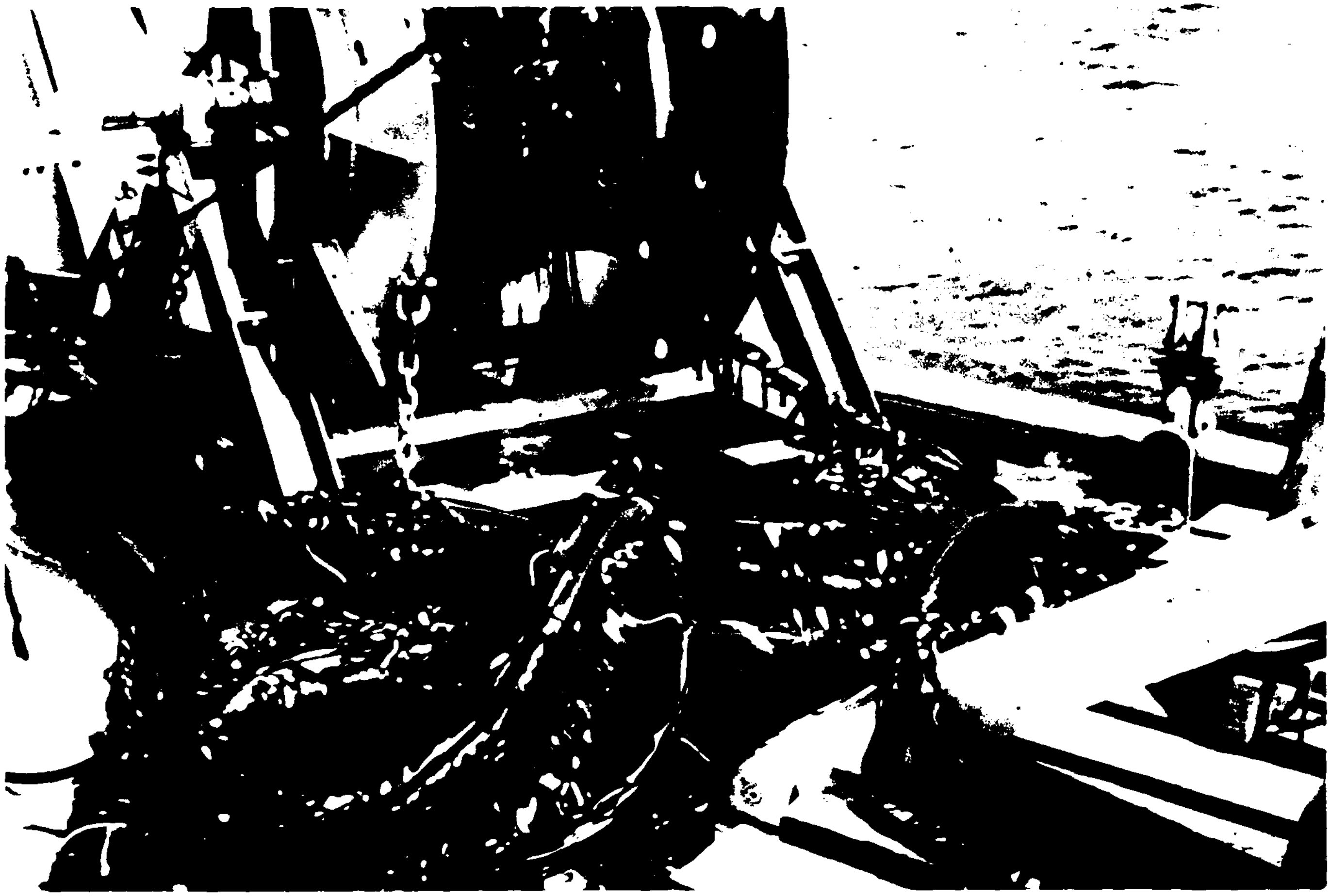


Figure 6 Cable flaked on deck to allow electrical connectors to remain attached during depth changes.

Figure 7 Pump.

Figure 8 shows the control and monitoring console. Readouts for flow rate, temperature, ground fault current for the motor, the motor current, time, depth, and strip-chart recorder are located on the front panel.

Figure 9 shows the water delivery manifold, which is normally mounted inside the chemistry van on the towing vessel. During sampling operations, water flows over the top loop of the manifold. Flow rate is measured by rerouting the water through the flow sensor in the lower loop.

Figure 10 shows the system installed onboard the R/V LAIDLY for the phase-two field tests. The towing configuration aboard the LAIDLY utilized a crane rather than an A-frame.

Figure 11 shows the phase-two towed body, the Fathom fish. Note the water intake port, the temperature sensor, the pressure sensor on the port side aft of the fish, and the housing for the multiplexing electronics. The pump and motor are located on the starboard side of the fish. The lead ballast is also visible in the lower section. The tube-cable assembly and the towing connection are visible at the top of the fish.

The Engineering Development Office is interested in the quality of the water samples collected by the underway towed pumping system. During March, tests will be conducted to address sample contamination and smearing by the system.

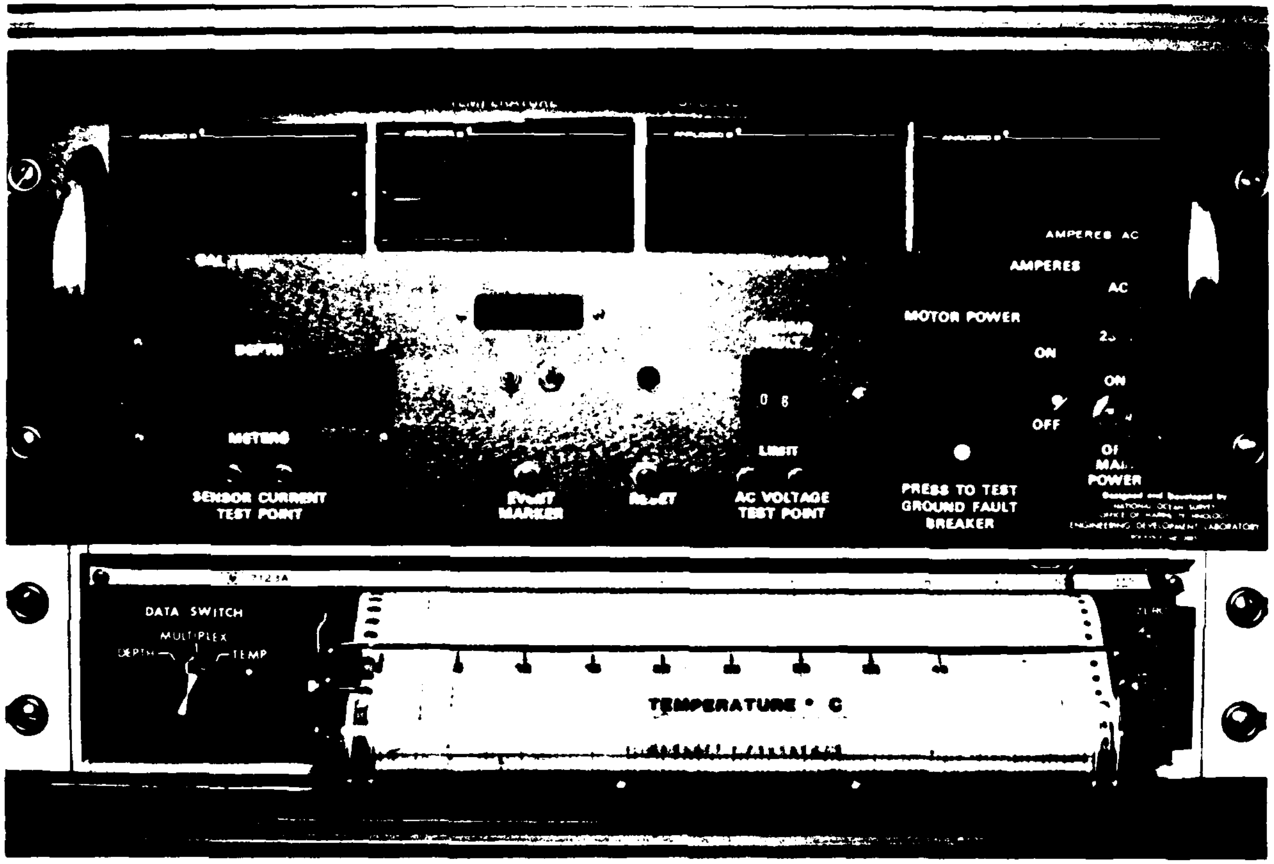


Figure 8 Control and monitoring console.

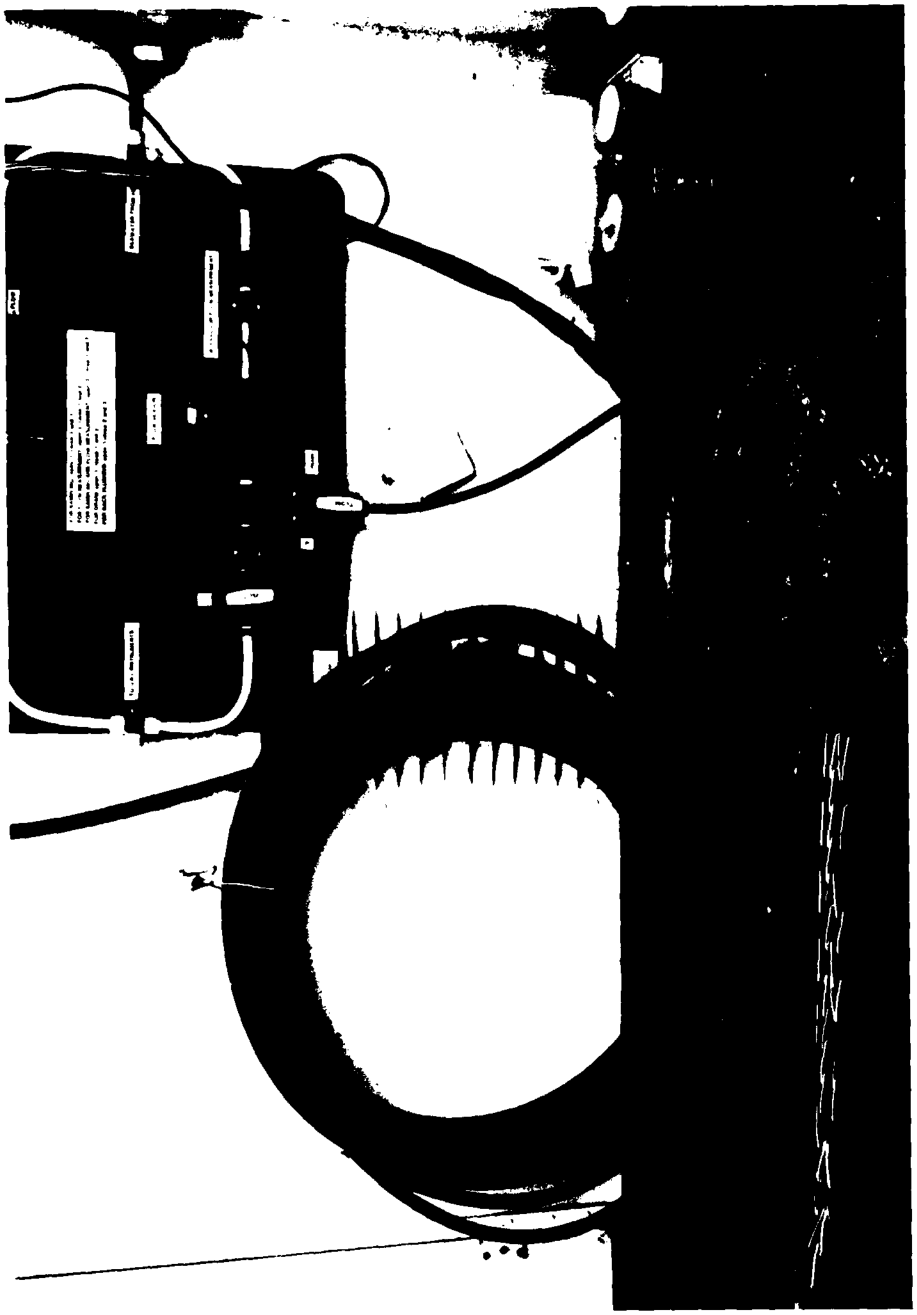


Figure 9 Water delivery manifold.

Figure 10 Phase II system aboard R/V LAIDLY.

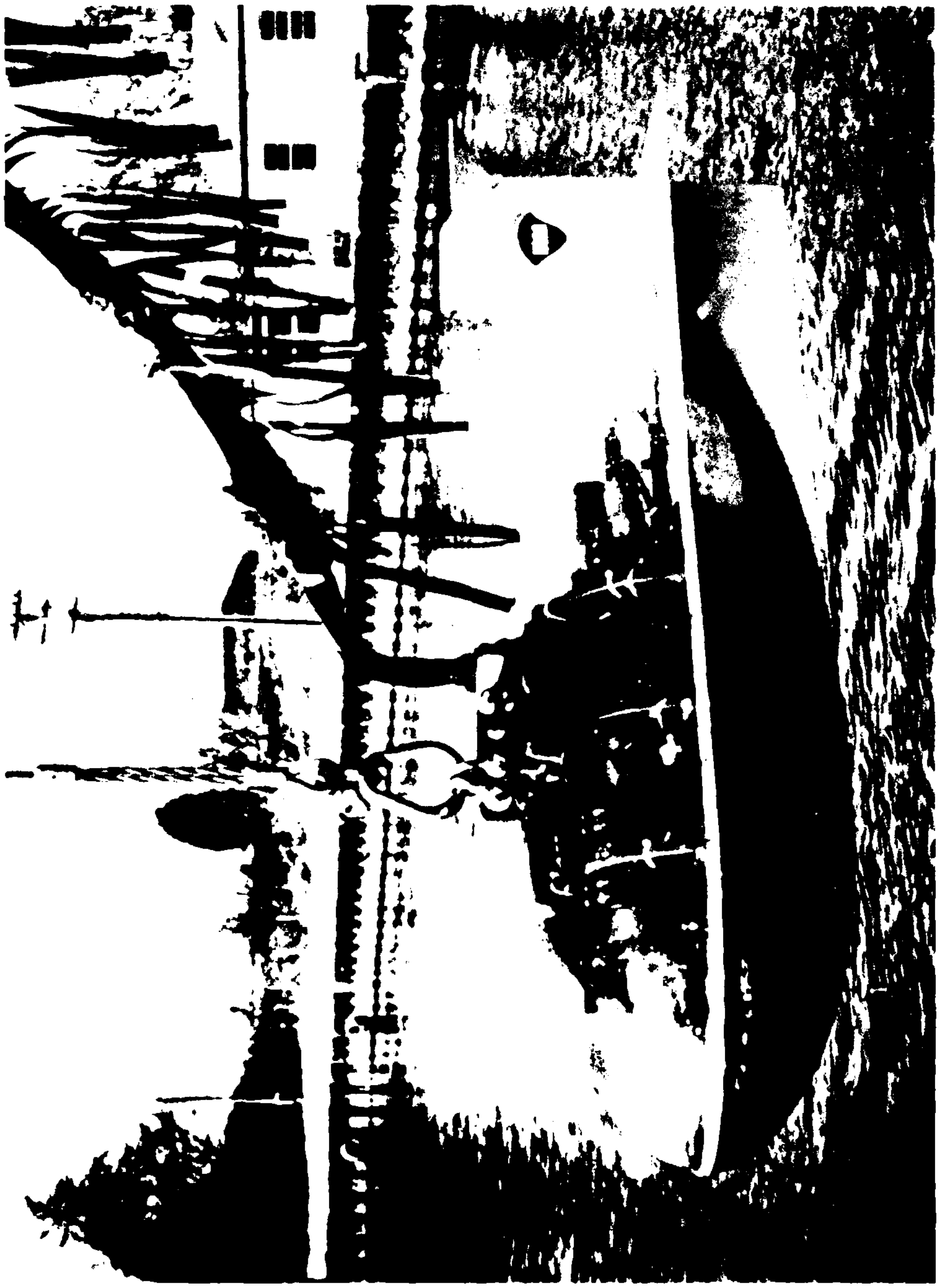


Figure 11 Phase II towed body.

DISCUSSION

FARRINGTON: There is a question that occurs to me, thinking about your towed system and the speeds at which you are towing. What is the bow wave effect in front of this and turbulence in front of these towed vehicles? In other words, how can we be sure of where we are sampling, and what kind of mixing regimes we have in front, especially when people are talking about wanting to take a look at very thin layers of particulate materials?

TAYLOR: We have not yet really tested the intake port effects in front of the fish, so we are not sure what sort of mixing we might be getting there.

IN SITU SAMPLING WITH A BATFISH VEHICLE

Alex W. Herman

I am going to describe an in situ sampler called the Batfish vehicle. The Batfish, illustrated in Figure 1, is a rapid underway sampler, designed at the Bedford Institute of Oceanography. I will describe the operating mechanics of the system, how we use it, how we use it on a ship, and then show you some data from our biological sampling program to illustrate some of the space and time scales of sampling with the system.

The Batfish vehicle was designed to transport oceanographic sensors, and the three that are illustrated in Figure 2 are a Variosens fluorometer measuring chlorophyll a (that is the estimator of the standing crop of phytoplankton), a Guildline digital CTD measuring conductivity, temperature, and depth, and an in situ electronic zooplankton counter, a prototype unit. The electronics for the unit are mounted in the top shell. A small plankton net concentrates the animals and feeds them into the sensor. The problem with these plankton nets is that they become clogged with phytoplankton when towing them for any length of time, say 10 to 15 minutes. Therefore, we have oscillated the net from side to side, a very short stroke but very rapid, on the order of 5 Hz, and this maintains open mesh pores. We can now tow the system continuously and keep the nets clean.

The sampler net is actually quite small relative to the plankton nets usually used--about a square meter in size--but for measuring copepods (in the millimeter-size range) it is perfectly adequate. We have obtained adequate sampling statistics on particular Batfish dives: comparing the results to those of larger samplers, we find quite good correspondence.

The vehicle is towed in a sawtooth manner, porpoising, and in this way, we profile both the vertical and the horizontal. The maximum depth for the vehicle with all this biological gear is about 250 meters at speeds of six knots. With CTD alone, a considerably more streamlined system, it can be towed at 10 knots to 400 meters depth.

The towing cable is a 7-conductor armored cable with flexnose fairing, but we are moving more and more to ribbon fairing because of the simplicity of the handling system. For biological sampling, all we need to sample most of the time is the top hundred meters.

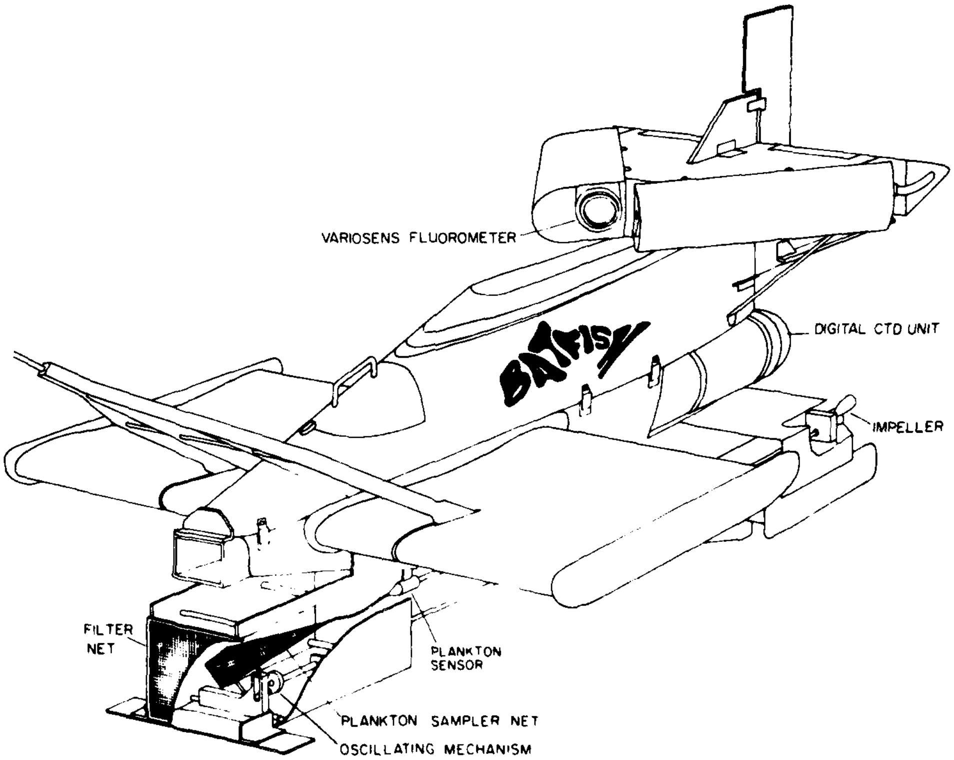


Figure 1 Batfish vehicle and sensors (vehicle length = 1.5 m).

The operating mechanism is illustrated in Figure 2. The Batfish will dive and ascend on command from the ship. The mechanical power that is used for driving the Batfish is hydraulic pressure. The source is the impeller. It maintains a constant pressure throughout the system. The wings are moved up and down by a hydraulic ram, and the hydraulic ram is controlled by the direction of flow of hydraulic pressure in this line. The direction of flow is then controlled by the servo valve, and that is controlled by an electrical signal. The signal is of the order of milliamps. The Batfish follows a feedback system using the rate of change of depth, rather than depth, which we originally used. The rate of change of depth ensures a constant sampling rate on both dive and ascent.

The mechanical system is pictured in Figure 3, indicating how we launch it from a ship. Basically, it sits on a platform which is connected to a trolley. The trolley runs on rails and is motorized. The trolley moves out on the rails to a pivot. The ramp tucks in under the stern, and the Batfish is dropped into the water (Figure 4). This is a very good system in rough weather because the Batfish can be picked up quite readily near the surface with this platform and brought onboard quickly. However, it is a sophisticated system. We are moving away from this, and using an A-frame and a roller block so that we move the A-frame or move the Batfish onboard. It requires more manhandling, but it is far less sophisticated than the system shown.

A rear view of the Batfish on the platform (Figure 5) indicates the location of the Variosens fluorometer, the CTD system, the zooplankton sampler, the impeller for maintaining hydraulic pressure, and the impeller used to oscillate the nets.

The zooplankton sampler system can be seen in Figures 6 and 7. Figure 6 shows the sampler net, and Figure 7 the conductivity cell used to measure zooplankton. The plastic tube in Figure 7 leads to a plastic bag. The zooplankton collected in the bag are counted, and the results compared.

A closer view of the top shell of the Batfish (Figure 8) shows the Variosens fluorometer and the prefilter net used to eliminate large zooplankton (> 1 mm) that would otherwise clog the sensor. The Variosens fluorometer is basically an optical electronic device. It focuses light from a xenon source on a 1 cc volume. The emitted light is blue between about 350 to 550 nanometers. The chlorophyl _a_ molecule is excited, and fluoresces; that is, it re-emits red light (685 nanometers), which is then focused on a photodiode. The resulting signal is therefore proportional to chlorophyll _a_ content.

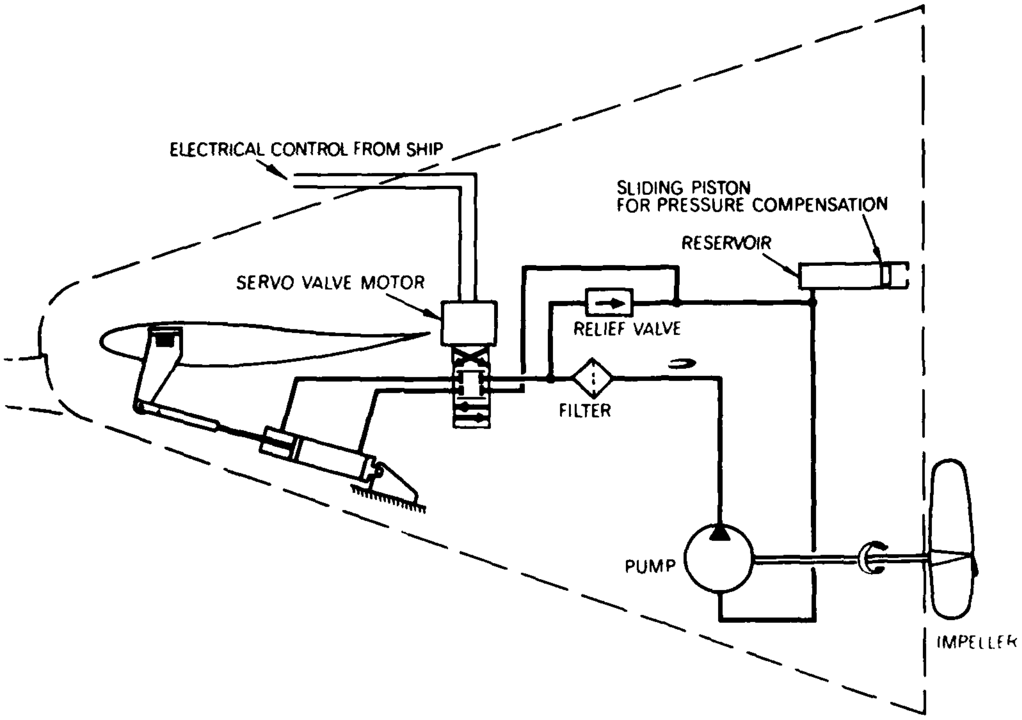


Figure 2 Electrohydraulic system.

Figure 3   Mechanical launching system.

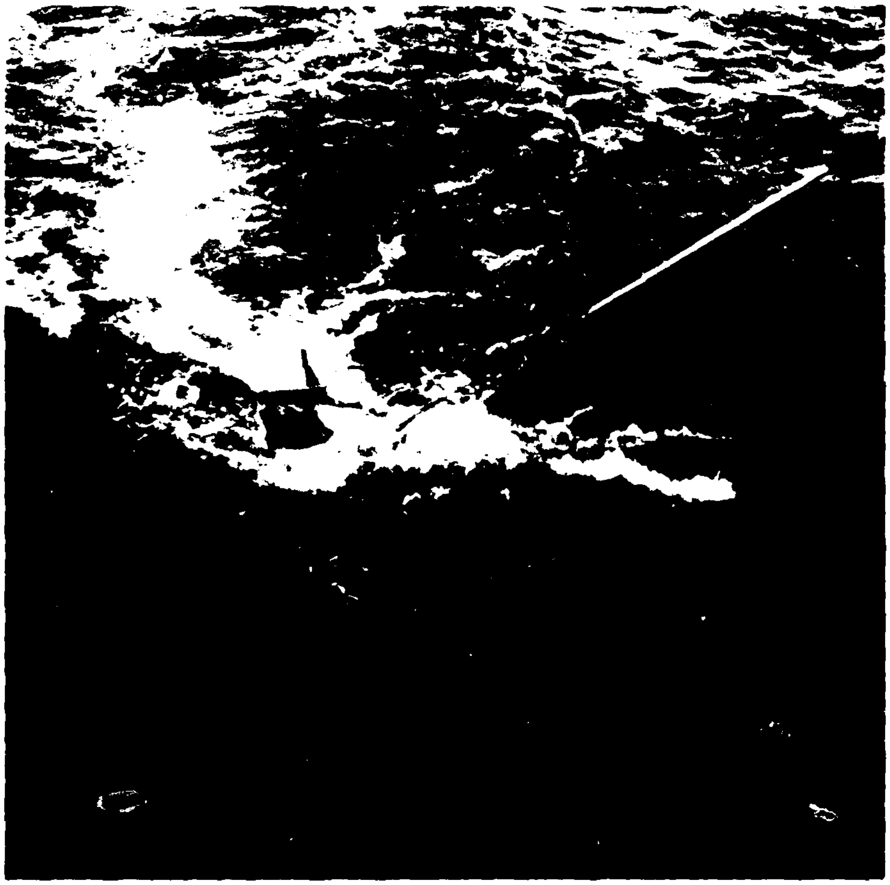


Figure 4 Launching the Batfish.

Figure [illegible] Rear view of Batfish showing impellers (black maintains hydraulic pressure; white oscillates zooplankton sampler net), and digital CTD unit.

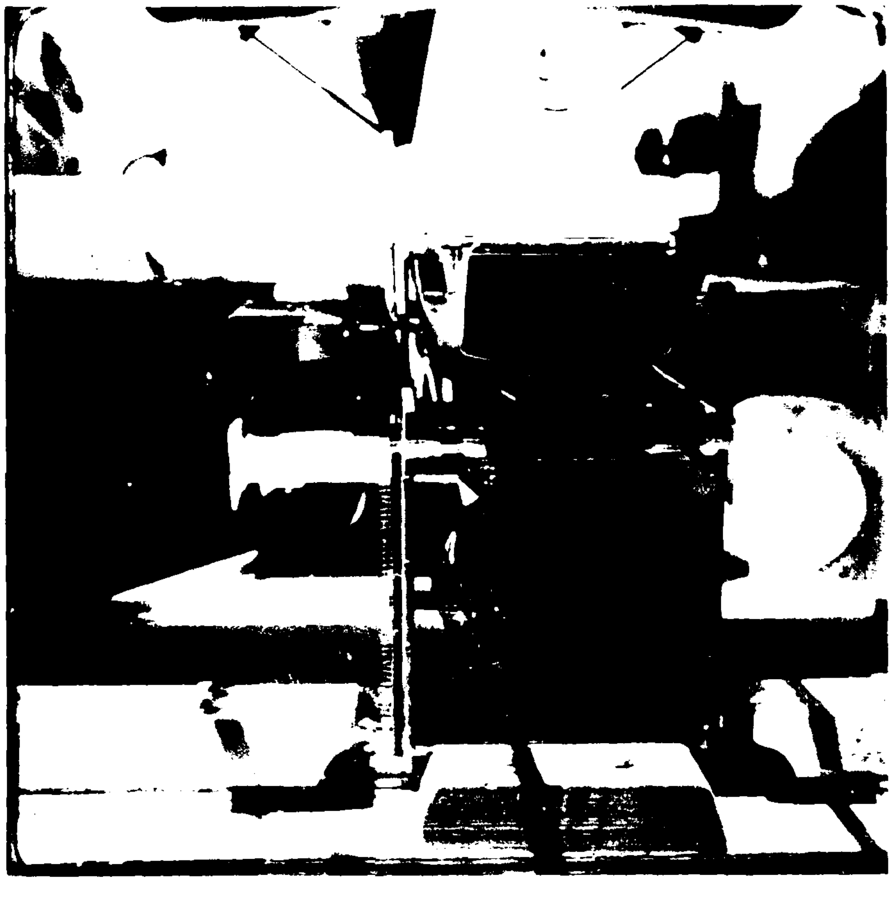


Figure 6. Front view of Battish, zooplankton sampler net.

Figure 7 Side view of Batfish, zooplankton sensor cell.

Figure 8. Top shell of Batfish, filter net and fluorometer.

A view of the winch in Figure 9 gives some idea of its size. The photograph shows the slip rings and flexnose fairing, and a sheave that will line up the fairings so the towing cable can be rolled on neatly. Again, we are moving away from the flexnose to ribbon fairing. This reduces the size of the winch needed, and makes the operation far more versatile.

The zooplankton counter is just a conductivity cell, a three-electrode system. It maintains a constant potential difference across the outer two electrodes. What happens is that when a small copepod passes through the tube--a copepod is itself an insulator--the total conductance in the cell changes, giving a signal proportional to its volume. We measure both its volume and length as it passes through the cell. The peripheral equipment associated with the counter consists of the deck unit which powers and decodes on the same line, and presents parallel 16-bit data that can be interfaced to any computer. A very inexpensive cassette recorder is used to record the transmission line. This system can be used in a small boat. A five-channel analyzer sorts small to large sizes, essentially yielding the number of animals over the size range.

The next step in sophistication would be a desktop calculator, the HP-9835, ideally suited for interfacing to peripheral devices. We simultaneously accumulate CTD and zooplankton data with this unit. The only problem is that we cannot work it up simultaneously with the tow.

One of the things we have built is a medium-size winch--a one-inch hose with power cable temperature-depth probe, and a Moyno pump. This consists of a helical rotor. We are using this system because we find experimentally that it treats the organisms very gently. This is especially important to phytoplankton, but there is some finite damage to be eliminated.

It will profile to 100 meters. It is primarily designed just for vertical station work, and is not yet meant to be towed. If the bottom section of the Batfish zooplankton sampler were removed and turned vertically, this would be the system to be used. Flow rates of 15 to 20 gallons a minute are obtained. This is about what we need for adequate statistics on copepods.

The next step or level in sophistication is the Hewlett-Packard 21-MX. It will process and contour all our Batfish data online. We can look at temperature on depth, chlorophyll on depth, density on depth, and some of the zooplankton as well. And, of course, we use it for the offline work as well.

Figure 9 Winch and towing cable (flexnose fairing).

Results

An example of some Batfish data, to indicate the scales we are working with, is given in Figure 10. The depth trace of the Batfish, the sawtooth, is separated by approximately one kilometer per cycle. Contoured on the depth trace are temperature, salinity, density, and chlorophyll for a frontal system off the Scotian shelf breakfront south of Nova Scotia. The system is formed in the springtime, and separates cold, fresh coastal water from warm, saline slope water to the south. Its signature is frontal contours moving to the surface where salinity and density are compensated.

Inspection of the chlorophyll signal (chart D of Figure 10) indicates that the highest concentration of chlorophyll exists at the front itself--the chlorophyll signal there was five times the value anywhere else on the shelf. This is a common feature of fronts.

One of the reasons we studied this area was because the shelf break is an area of high biological productivity. It is a very active fisheries area. Production is enhanced because of upwelling, or the transport of nutrients to surface, which are subsequently carried onto the shelf. One of the reasons we wanted to study it was to find out how these nutrients are vertically transported. One of the things we did know was that in this area the semidiurnal tidal signal, the M2 signal, is very strong.

We profiled with the Batfish in this section alone, towing the vehicle back and forth for a full diurnal period, or rather, about 30 hours. We performed eight tows, about three to four hours apart, to try to resolve the M2 signal. The Batfish dives were separated by one kilometer per cycle. What we observed was that the chlorophyll layer moved vertically and horizontally with the M2 tides.

Chart A maps the temperature measurements, approximately three to four hours apart. Viewing these charts together, we noticed a plume, an intrusion of warm, saline water rising to near-surface, and cold, fresh water, apparently moving down. The warm plume starts to retract, is fully retracted at the node of an M2 cycle, and reappears again. We found that the motion of this plume was highly correlated to the M2 cycle, as was the movement of the chlorophyll.

With considerably more data than shown here, we proposed that the movement of these plumes derives its energy from the M2 tides, the internal tides; thus, it transports nutrients to the surface, and this is the mechanism for vertical transport--one of the reasons one observes such high concentrations of chlorophyll at the front itself.

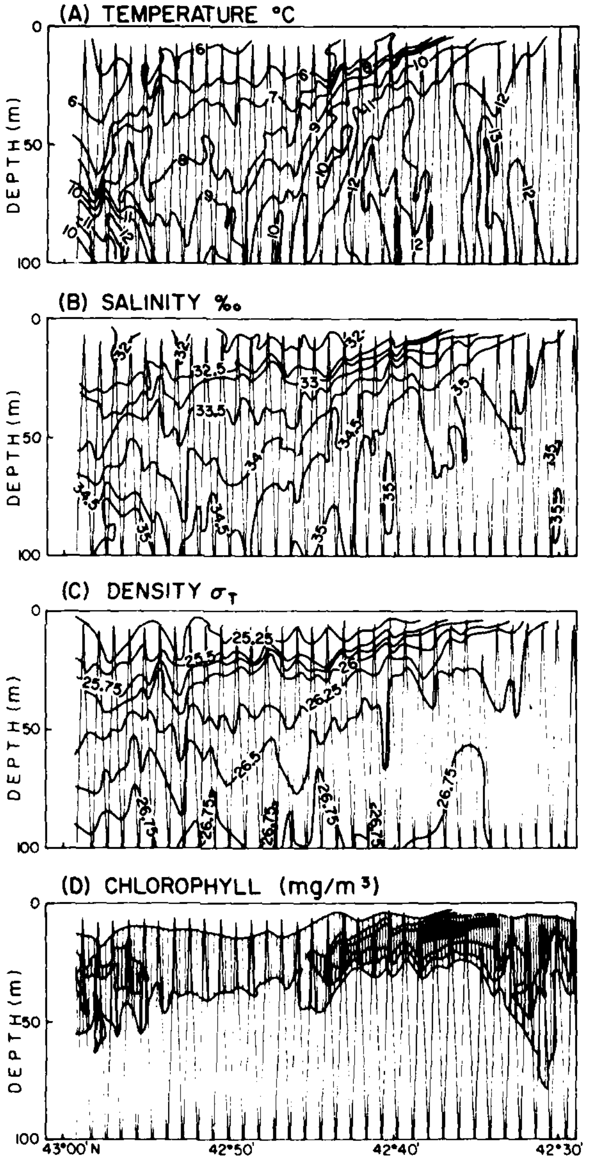


Figure 10 Contoured Batfish data for transect sampled at break front south of Nova Scotia.

Since this experiment was done, some theoretical basis has been laid for the movements observed: these are considered M2 internal waves, and they are propagated from the shelf break, that is, the very edge.

We have calibrated the zooplankton counter and we have calibrated the cell against known shapes. We can generate the dimensional parameters of every animal that passes through. At the end of each tow, we plot the number of animals or the frequency as a function of each of their dimensions--diameter, length, and volume.

The first thing we noticed was that we had a series of peaks that were more distinguishable for diameter than the other parameters. If we take the same sample that we have collected in our sample bag, analyze it microscopically, and plot the same sort of distribution, we can identify species with these peaks, and in fact, some of their stages.

Another method is to compare data in which the species are absent to those of another tow in which that species dominate.

In data acquired from the shelf of Peru, for example, we noticed peaks of very small copepods, a species called *Calanus chiliensis*, stage 5 (these are adults) and *Eucalanus inermis*, with depth. The animals migrate in the daytime, for reasons that are not yet known.

In the nighttime tow, the animals were seen to rise and aggregate at the same depth. They are known to rise to feed on the phytoplankton. The results of daylight and nighttime tows may be distinctly different.

Away from the front, the animals appeared to migrate, but the front seemed to act as a boundary: they did not at any time during our sampling period migrate through the front. Possibly they are migrating, and the mixing occurring below the front is actually dispersing the animals. We still do not know. Considerable work remains to be done.

I hope these examples indicate the space and time scales that we are actually working with: meters in the vertical, kilometers in the horizontal, and hours in the time scales.

DISCUSSION

SIMPSON: That was a very interesting set of data. The physicists who have used Batfishes before have always had the problem of package motion: it doesn't go up and down quite the way you would like. For some tests, it isn't very important, but if, for example, you want to calculate gradients (the horizontal gradient versus the vertical gradient), you have to separate the vertical from the horizontal component of the motion of the package. This means the package must be equipped with accelerometers and velocity sensors.

In a frontal experiment where the horizontal gradient, presumably, is of equal magnitude or larger than the vertical gradient, such calculations are even more necessary.

HERMAN: The sort of patchiness that one observes in chlorophyll on our shelf is on the order of 5 to 10 kilometers, so by cycling one kilometer of interest, one can draw at least the variability in chlorophyll. Certainly with reference to the plume that we saw, we were still within the internal wave structure that exists in the shelf. We did not know that before we profiled it, but fortunately, it occurred.

BIVINS: You showed your prefilter screen with which you said you filter out large zooplankton. How do you clean it?

HERMAN: That is our limitation right now. The animals beyond our measuring-size range compared to those within it are so few that the net does not become significantly clogged until about 6 to 8 hours of towing. We generally tow from 3 to 4 hours per transect. It is not yet a real problem, but it is our limitation right now.

BIVINS: Are you worried about avoidance response because of that?

HERMAN: One thing that is so difficult to measure is avoidance. We have compared our results to results obtained with a 1 m^2 net, with which one expects high performance. We detect a systematic error of measurement no less than 60 to 70 percent of the real catch; in other words, we may be pushing water out of the way at a rate of about 40 percent. So long as it is consistent throughout the tow, we needn't concern ourselves with it.

SHERMAN: What is the size limitation of your net with respect to components other than copepods in the zooplankton; for example, larval fish?

HERMAN: We could move into a sampling range the order of centimeters, and increase the size of the net to approximately 10 or 12 inches, but we could not oscillate it to clean it. This may not be necessary. We could use a large open-mesh net, and clogging would not be a problem, but I doubt if we could go much further with the Batfish vehicle. What scale did you have in mind?

SHERMAN: A scale from half a millimeter up to, say, 20 millimeters.

HERMAN: Oh, we are in that range now.

SHERMAN: And do you have results for fish larvae?

HERMAN: We have results that include fish larvae. The only thing is that the copepods dominate, and any signal that is small is effectively background, in our estimation. That is, Calanus finmarchicus would account for 50 percent of all the copepods there, and the peaks that we would see would overshadow any of the fish larvae.

So if you were in an area of very high concentrations of fish larvae or you knew where they were--near the surface, perhaps--and you were pumping in that region only or sampling in that region, you might get results.

FISHERIES ECOSYSTEMS STUDIES AND UNDERWAY SAMPLERS

Kenneth Sherman

Introduction

Through passage of the Fisheries Conservation and Management Act of 1976, the United States now has jurisdiction of fishery resources within 2.2 million square miles of the newly designated Fisheries Management Zone. The zone extends territorial waters from 3 miles to 200 miles off the coastlines of the continental U.S., Hawaii, Alaska, and island territories. The National Marine Fisheries Service (NMFS) is conducting surveys to monitor changes in the population levels of marine fish in approximately 200,000 square miles of the Fisheries Management Zone. Most of the effort is located off the northeast coast. Survey activity in the Gulf of Mexico and off the Pacific coast is limited.

The marine fishery resources off the northeast coast contribute 500 million dollars annually to the economy of the coastal states from Maine to North Carolina. To provide the kinds of fisheries and ecosystem information that will support the management and conservation of important fishery resources of this region, we have developed a survey approach that allows for investigation of not only the fish but also the plankton, the benthos, the hydrography, and the ecological regime that is producing the fish. Our strategy is to look at the major components of the shelf ecosystem, focusing on maintaining a time-series of observations of changes in fish stocks and their environments. The basic elements of the observational program include a system for recording vital elements of catch-statistics at major port facilities where fishermen land their catches. These data provide a means for estimating fishing mortality over the region, and represent an important cost-effective aid for monitoring the effects of fishing on changes in stock abundance. In addition, surveys of fish abundance are made by vessels of NMFS as fisheries-independent measures of changes in species composition and abundance. This report describes the ocean sampling program of NMFS off the northeast coast and includes comments on the role of underway sampling in marine fisheries ecosystems studies.

Except for the northeast coast, there are no large global areas of continental shelf where a multispecies fisheries ecology program is in place. The early history of fisheries ecology was developed in the North Sea. However, it has been difficult for the large number of countries bordering the North Sea and the northeast Atlantic to pull together and deal with closely integrated and coordinate time-series studies of the entire continental shelf bordering western Europe. There have been some very important joint activities through the International Council for the Exploration of the Sea (ICES). Rather good catch statistics for the region are reported to ICES and the European Economic Commission. But by and large, most of the fisheries studies in the eastern Atlantic have been short-term and conducted for a single species (e.g., cod, plaice, or herring).

The situation was much the same about 10 years ago on our coasts. Recently, however, it has been possible to integrate the research programs of some 25 fisheries laboratories in NOAA that were dealing with problems of coastal fish production. Since 1970, five major fisheries centers have been established, two on the East Coast, one on the Gulf Coast, and two on the West Coast through a large effort focused on the strategic fisheries areas. We are now dealing with the problem in a far more holistic manner than in the previous 70 years of fisheries investigations. The components of the fisheries ecosystem study that NOAA supports off the northeastern coast of the United States includes the activities of several laboratories that have been integrated into the Northeast Fisheries Center (NEFC). North, a laboratory in Gloucester, deals with the quality of the product from capture through processing. The laboratory at Woods Hole serves as the headquarters of NEFC, and deals with analysis of the catch statistics, including the recreational fish catch, which is not insignificant --it approaches the levels of the commercial catch, according to the initial estimates made recently. The fisheries assessment activities of the Center located at Woods Hole provide a continuing series of forecasts of the abundance of fish stocks off the northeast coast. This information is of immediate use to the development of management practices recommended by the Northeast and Mid-Atlantic Fishery Management Councils. Studies are also conducted on ecosystems models, fish stock recruitment, and benthic dynamics. The laboratory at Narranganset (R.I.) deals with the early stages of life history and problems of plankton ecology. Studies of apex predators (sharks, billfish, and tunas) and long-term fisheries ocean climate studies are also under way here. The Mid-Atlantic laboratories at Sandy Hook (N.J.) and at Milford (Conn.) deal with slightly different kinds of problems. The laboratory at Milford investigates shellfish aquaculture and disease problems associated with aquaculture operations, and coastal pollution problems. The laboratory at Sandy Hook is also dealing with continental shelf pollution problems, as is the laboratory at Oxford, Maryland, which is concerned exclusively with the disease problems of continental shelf fish and shellfish stocks. Administratively, the National Systematics Laboratory in Washington, D.C., is part of NEFC. This facility provides taxonomic support in properly identifying the fish and invertebrates of interest to NMFS.

The Northeast MARMAP Program

The research activities of NEFC dealing with fisheries assessments and fisheries ecology constitute a major program activity known as MARMAP, an acronym for the marine resources monitoring, assessment, and prediction program of NMFS. MARMAP provides a data base to support the management and conservation of the living marine resources on the continental shelves of the United States. The program itself depends largely on ships as the data acquisition platforms. This has been the tradition in fisheries. Recently, however, there has been greater use of aircraft and buoys, although their potential has not yet been fully realized. Submersibles are used in the program in a limited way to investigate benthic crustacean communities (e.g., lobsters and crabs), particularly on the edge of the continental shelf. As fuel costs rise, we are going to require sampling methods that significantly reduce the running time of expensive ships over that 200,000 square mile area off the northeast coast under investigation to support the fisheries management regime of the area. We need to look more closely at what satellites may be able to offer.

In the MARMAP program, we complete the information gathering and reporting cycle by moving from the acquisition of data, consisting of catch statistics and at-sea collections of fish and environmental data, to data reduction and analysis, and a series of quarterly to semi-annual fisheries abundance forecasts. MARMAP effort was begun about 10 years ago. Based on early findings, we have been able to describe the continental shelf as a series of subsystems, including the moderately productive Gulf of Maine, which is characterized by deep water and by inflow of more oceanic water to the system from the continental slope region. There is a definite thermocline structure here during the warmer months of the year. Georges Bank is quite different. It is one of the most productive shelf regions of the world. The region is shallow, with considerable nutrient cycling, and very rarely, a well-defined thermocline. The Mid-Atlantic Bight (MAB) area is an estuarine-dependent system, with much of the nutrient and pollutant load moving into the system from the major estuaries (e.g., Hudson, Delaware, Chesapeake) of the region. We consider the Southern New England shelf as somewhat of a transition between the MAB estaurine-type system to the southwest and an offshore system such as Georges Bank to the northeast. Primary production in the MAB is driven by nutrient enrichment from the small estuaries nearshore and the shelf break offshore. We have been studying the northeast continental shelf as four ecological subsystems, examining the changes in population levels of plankton, fish, and benthos, and in hydrography in relation to primary and secondary productivity cycles, seasonal changes in circulation and its influence on production, and the effects of environmental changes on the growth and survival of fish larvae and their subsequent recruitment into the fisheries.

The entire region has been subjected to heavy fishing and marked changes in abundance of fishery resources. During the period 1968 through 1975, significant changes were observed in the fish stocks. The total finfish biomass decreased by some 50 percent over that period (Figure 1). The decrease was largely attributed to the very heavy exploitation of large Soviet, German, and Polish fleets fishing for mackerel and herring. But in the fishing process, their incidental catch exceeded our domestic catch for such prime species as cod, haddock, and flounder. The removal of 50 percent of the predatory biomass of fish through overexploitation has produced stress on the shelf ecosystem. It is very likely that there were some environmental effects contributing to the decline as well, but they have been overshadowed by the high level of fishing mortality, resulting in a stressed ecosystem.

We have posed a series of ecological questions about the effects on an ecosystem of this magnitude of population change. Most of the decline is attributed to heavy fishing mortality, but we recognize that local hydrography and perhaps even climatic changes may have had some influence as well. Our questions were based on a close examination of findings from a recent case-history study of long-term changes in the North Sea. There has been a trend in the North Sea to the increasing abundance of short-lived, fast growing, smaller and less desirable species, as several pelagic species, particularly herring, have declined (Figure 2). We are looking for evidence of the same sort of response to decline in predator pressure on this side of the Atlantic.

Traditional Approach to Sampling

To study the northeast continental shelf ecosystems, a series of stations on the continental shelf is sampled a minimum of six times per year for ichthyoplankton. We use both a systematic series of sampling on transect lines over time, and a somewhat random bottom trawl survey pattern where random numbered stations are occupied in autumn, spring, and summer of the year during bottom trawl surveys. In general, the station pattern represents a 20-km network over the continental shelf (Figure 3). The sampling effort is considerable, requiring large blocks of ship time, and producing an enormous amount of population and environmental data. Last year (1979) the survey area was covered 11 times for a total of 2,200,000 square miles, with scientists, technicians, and ships at sea virtually every month of the year.

Unlike most of the previous descriptions of applications of underway sampling techniques, we are an anachronism at the moment: we are still doing point sampling with Niskin bottles, dropping XBT's for observations of salinity, dissolved oxygen, primary productivity measurements, and nutrients, including nitrite, phosphate, silicate,

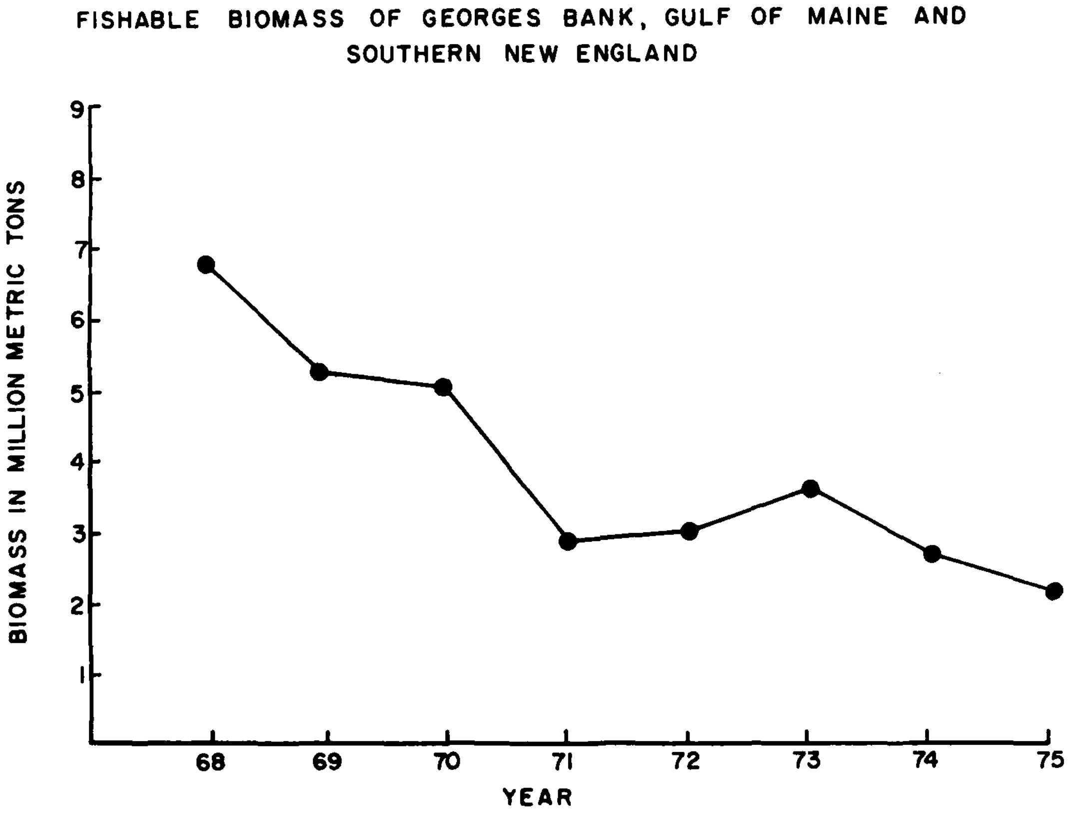


Figure 1 Decline in the fishable biomass of Georges Bank, Gulf of Maine, and Southern New England 1968-1975. Adapted from Clark and Brown (1977).

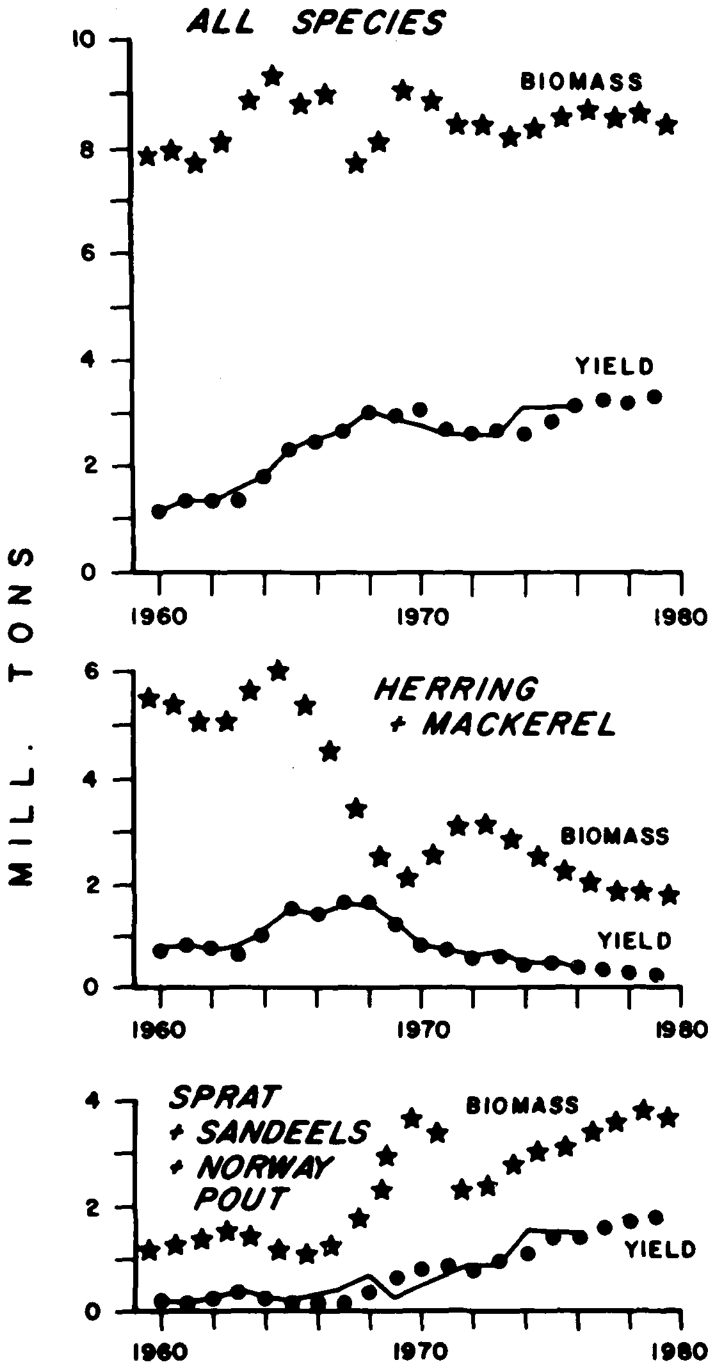


Figure 2 Estimated changes in the biomass of fishes in the North Sea 1960-1976 with model-simulated projections to 1980. From Ursin (1977).

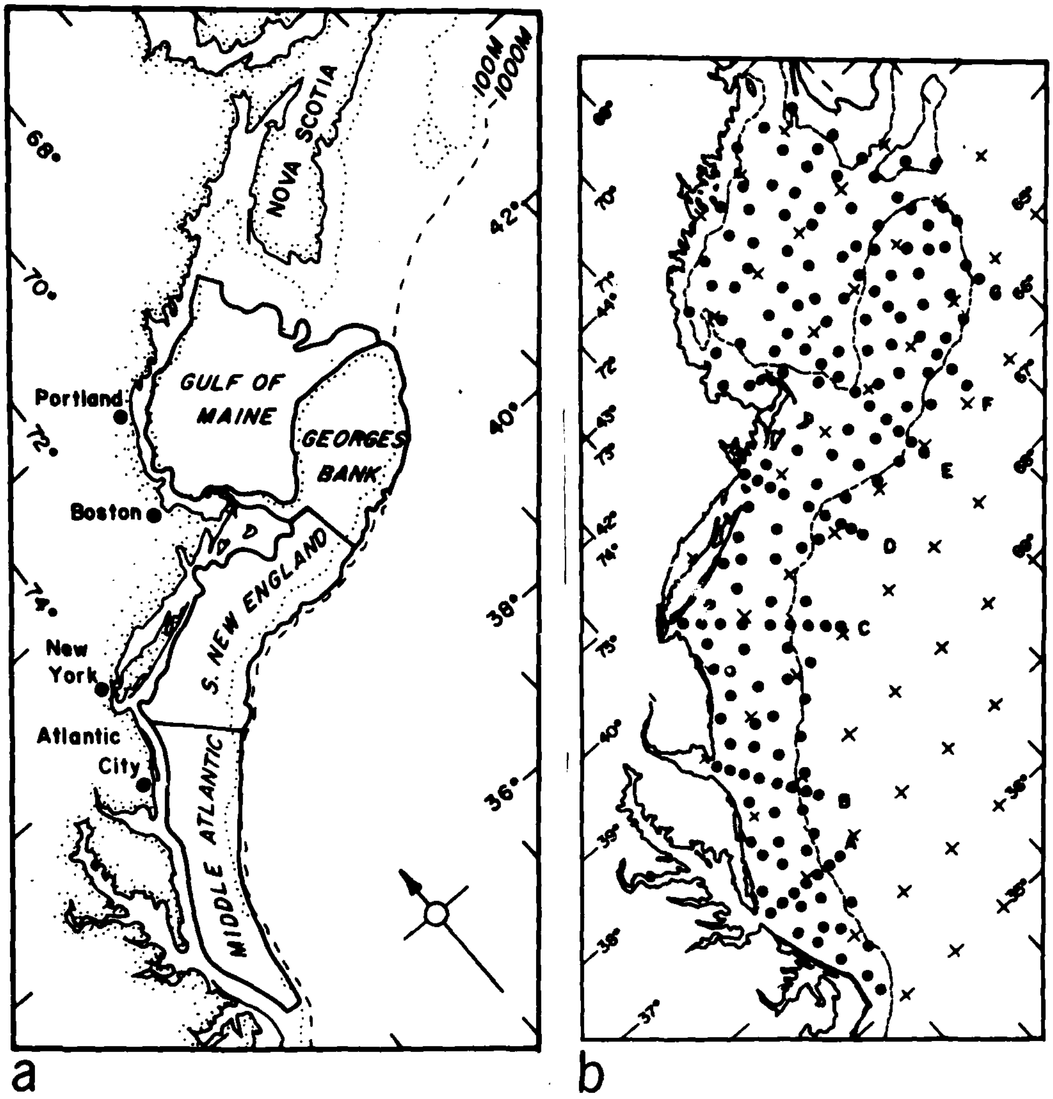


Figure 3 (a) The four geographic areas of the Northwest Atlantic surveyed from 1971 through 1977 during MARMAP operations of the Northeast Fisheries Center, Woods Hole, Massachusetts; (b) MARMAP station locations on the 6x/yr ichthyoplankton hydrographic surveys. From Sherman (1979).

and ammonium. A variety of nets is used to sample fish and plankton, including a neuston net at the air-sea interface that has been standard for the past 10 years. Bongo nets--paired net samplers--are used for collecting larval fish and zooplankton from just above the bottom to the surface, in an oblique and continuous towing configuration. In addition to this suite of biological, physical, and chemical water column observations, we sample fish by occupying trawling stations on the shelf at least three times a year. Unfortunately, we simply do not have enough space on our ships to accommodate the number and kinds of technicians that are required to do both the fish work and the water column and plankton work. So we are constrained at the moment with our 180-foot ships to a very limited capacity to operate complex kinds of towed pumping systems. This is a very real constraint that needs to be considered in the design of underway pumping systems requiring a minimum of personnel support.

Scientists at the Sandy Hook and Narragansett laboratories of NEFC have the prime responsibility for collecting and analyzing the most comprehensive data sets of chlorophyll measurements made over the entire shelf area off the northeast coast of the United States. They have prepared chlorophyll distribution charts for 11 surveys based on chlorophyll measurements taken through the water column at point locations from the Gulf of Maine to Cape Hatteras. It is very dramatic information. In the late summer, high chlorophyll densities on Georges Bank are clearly defined. The high biomass is sustained by the nutrient flux flowing up from the slope/shelf break on the continental slope side, and the coastal break on the Gulf of Maine boundary. Chlorophyll is retained on the bank for most of the year, with essentially a closed circulation system, except for the late autumn and winter. In contrast, evidence points to a dominant estuarine influence on chlorophyll production in the Mid-Atlantic area and a transition zone on the southern New England shelf. The phytoplankton species in the chlorophyll biomass can undergo regeneration within 24 hours, thereby altering spatial patterns of abundance. However, circulation features on the shelf are much more conservative and contribute to the maintenance of general patterns of abundance of chlorophyll, as depicted in the summer and autumn projections of chlorophyll distribution (Figure 4). The presence of eddy systems on Georges Bank contributes to the build up of chlorophyll biomass, whereas in the Mid-Atlantic Bight (MAB), much of the nutrient load associated with the estuaries of the region sustains moderate to high levels of chlorophyll. Besides the nutrient load contributed by the estuaries, there is very likely a high pollutant flux in the MAB that is extremely important to the continental shelf ecosystem. The same hydrographic features concentrating chlorophyll also tend to maintain concentrations in fish eggs and larvae, thereby constituting important spawning and nursery areas.

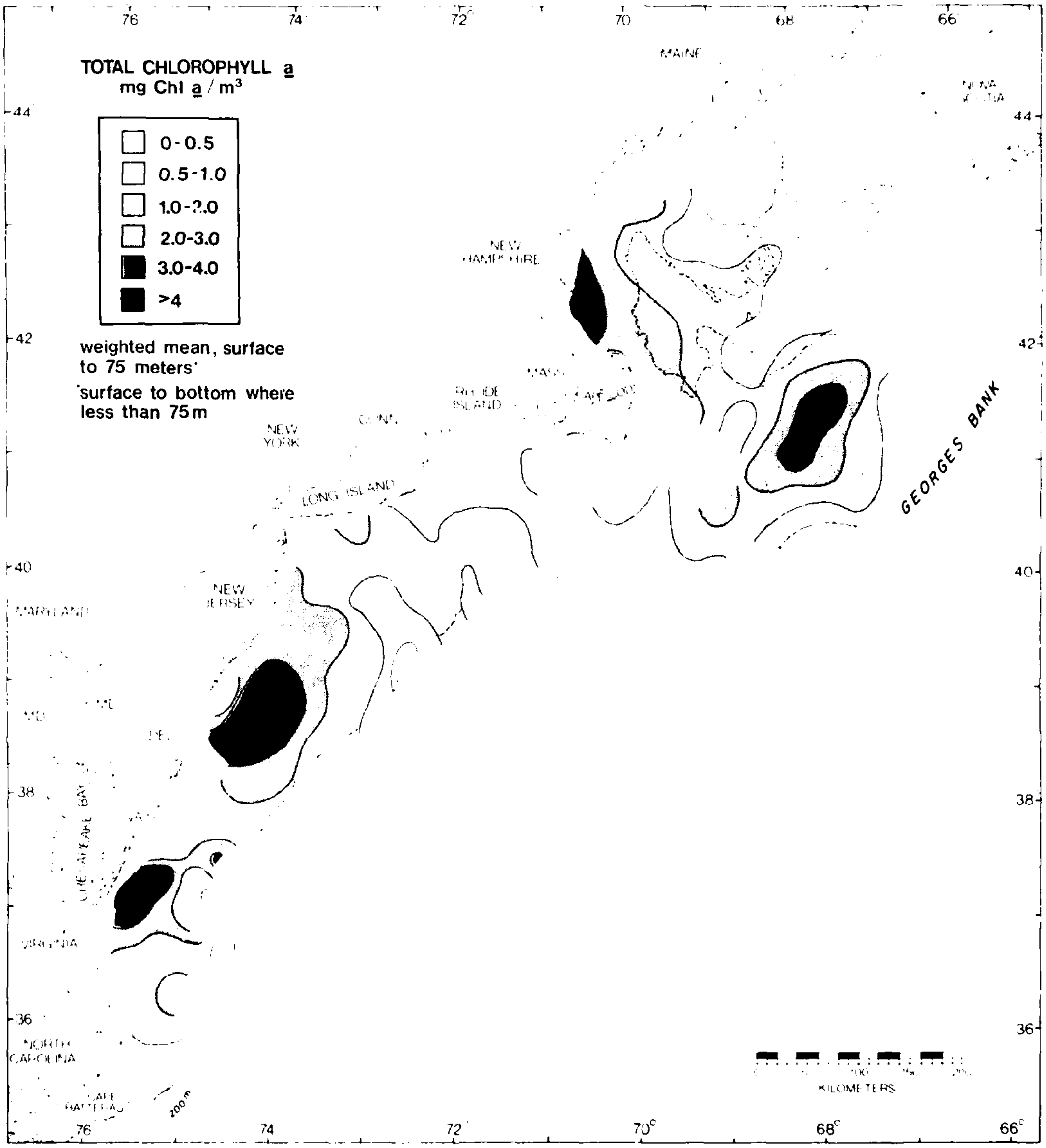


Figure 4a The high chlorophyll concentrations shown on Georges Bank reflect the presence of a clockwise eddy system of currents around the periphery of the bank. In contrast, the high levels of chlorophyll in the region of the shelf from New Jersey to the North Carolina coast result from high nutrient load onto the shelf from the Hudson, Delaware, and Chesapeake Bay estuaries. Associated with the nutrient load from the estuaries is a pollution flux onto the shelf that is under investigation. (Summer distribution.)

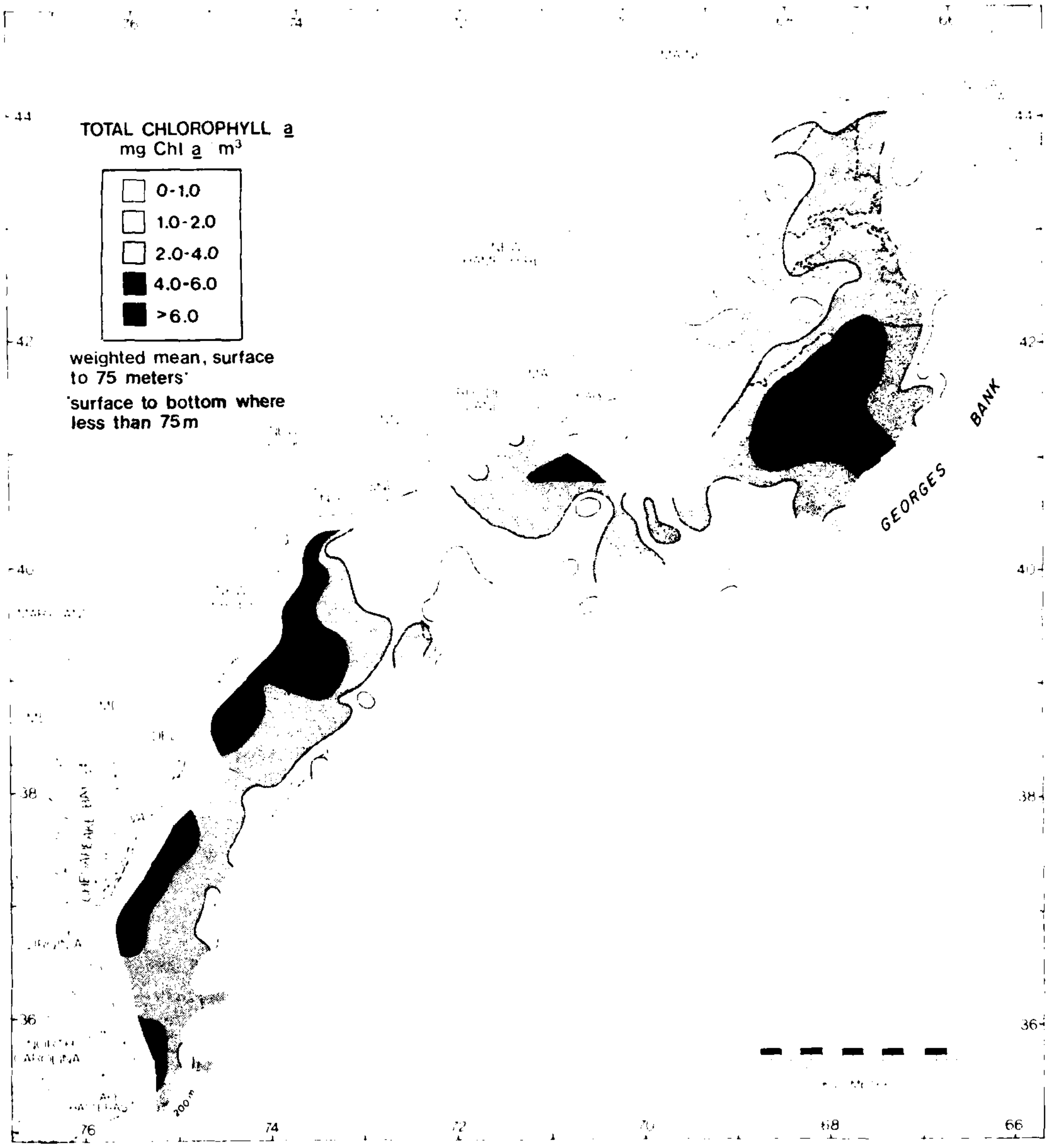


Figure 4b   Chlorophyll concentrations on Georges Bank, autumn. Figures 4a and 4b from Evans, et al. (1979).

Innovative Sampling

Recognizing that aerial remote sensing would provide a means for obtaining a synoptic monitoring of changes in chlorophyll abundance and hot-spots for fish eggs and larvae, a series of joint studies have been planned with NASA Langley and the Brookhaven National Laboratory, to conduct overflights with a U-2 fitted with multispectral scanners. We hope to be able to characterize the productivity flux of the region by examining the relationships between aerial spectral-band reflectance of ocean properties and simultaneous measurements of chlorophyll made at sea. It takes us approximately 30 days to sample biota from one end of that area to the other, using conventional ship operations. This approach introduces a significant bias into our data, since synopticity cannot be achieved. It seems to us the only way that we might look at this area synoptically would be through aerial remote sensing from a satellite or aircraft. Underway flow-through sampling of chlorophyll and primary production would represent an advantage, all allowing for quasi-synoptic measurements of production, and significantly reducing the ship-time required to cover the survey area.

Integrational Problems of Sampling Scale

We are also investigating fisheries recruitment problems over wide time and space scales. The projection of mackerel abundance in Figure 5 depicts typical among-year changes in the abundance of one-year-old fish for a number of species. From 1960 through 1974, the fluctuations in abundance of the one-year-old mackerel recruits ranged from 0.5×10^9 to 7.8×10^9 fish. The percent of mortality reflected in this change attributed to natural environmental changes, fishing effects, and pollution effects has not yet been determined: to sort out the controlling factors requires an approach that integrates both broad-scale (10 km to 1000 km) and fine-scale (1 meter to 10 km) measurements of ocean processes. It means going to a place that is a known spawning area to make observations, and collecting samples on the kilometer/day scale, and in some cases even meter scales, with respect to vertical distribution within the water column, to study larval mackerel predator-prey relationships, and the influence of local hydrography on growth and survival of mackerel larvae. We need to make greater use of plankton particle counters in fine-scale studies. To obtain statistically reliable samples, it will be necessary to filter large amounts of water in the collection of larval fish and their prey (e.g., 500 m^3/station). Calibrated plankton samplers fitted with different mesh sizes are now used to obtain simultaneous samples of the size components in the plankton ranging from 5 microns.

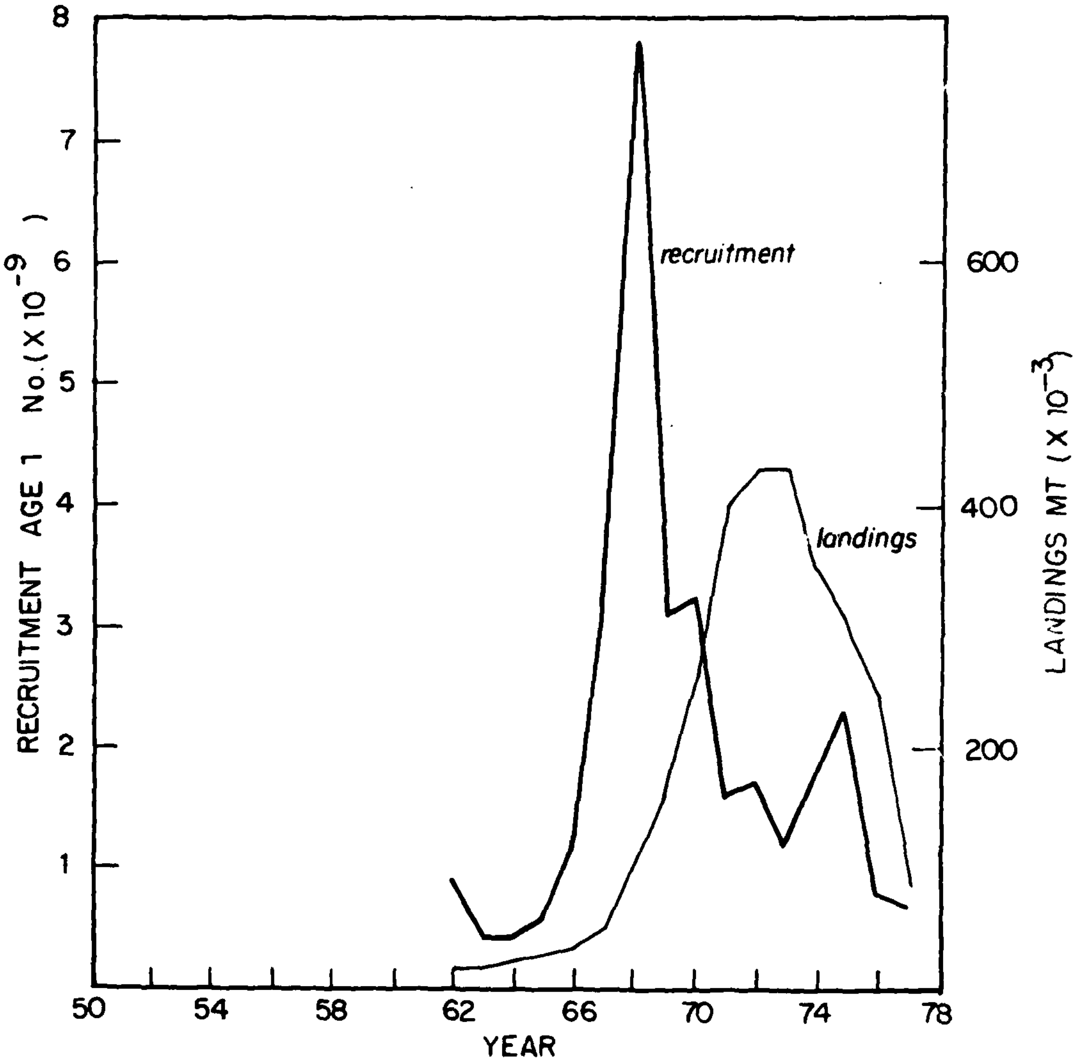


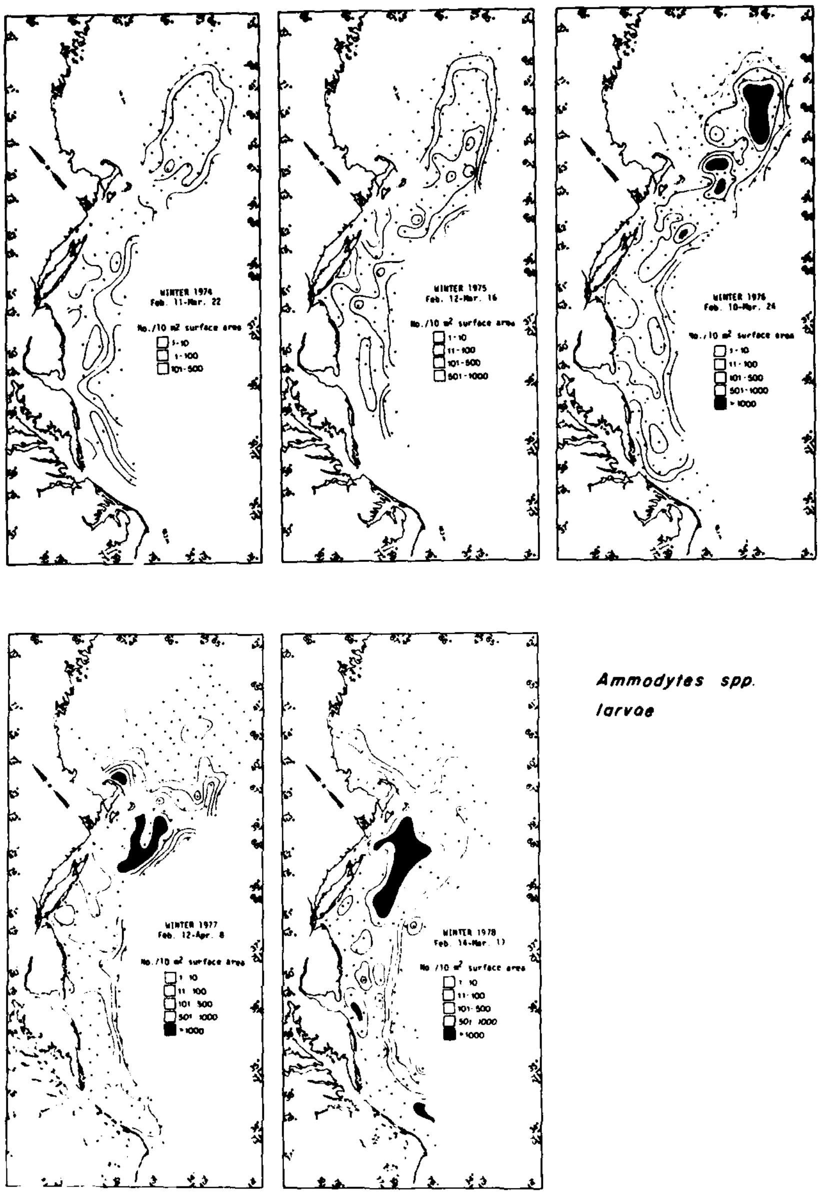
Figure 5 Nominal catch and recruitment for northwest Atlantic mackerel from 1962 to 1977. From Hennemuth, et al. (1979).

The Batfish described by Dr. Herman is an improvement increasing the efficiency of sampling small organisms, but it is necessary for us to collect fairly large numbers of fish larvae to make useful quantitative inferences about changes in the distribution and abundance of the relatively rare fish larvae.

Using conventional sampling methods, the MARMAP program has provided, with very little manipulation of the data, the opportunity to demonstrate the existence for the first time of large-scale changes over space and time of the entire larval fish community. For example, in 1974 and 1975, we observed the onset of a rather significant explosion of a small, fast-growing fish, the sand lance. There has been a persistent pattern of increasing sand lance abundance from 1974 through 1978 (Figure 6). Underway sampling systems for zooplankton and ichthyoplankton are necessary if we are to continue effective bio-environmental monitoring of large areas of the continental shelves, considering rising fuel prices and vessel operating costs.

Trawling is conducted on the broad mesoscale level at some 300 locations over the shelf from the Gulf of Maine to Cape Hatteras to monitor changes in finfish populations. Through these fisheries-independent bottom-trawl assessments, we have been able to provide fisheries managers with a relatively unbiased picture of fish distribution on a systematic basis since 1965. In addition to monitoring changes in the plankton, the hydrography, and the fish of the continental shelf, we have also been surveying the macrobenthos for the past 20 years, and now have a good index of abundance of the principal species groups.

Within the MARMAP monitoring matrix, studies are conducted on biological and hydrographic processes influencing fish distribution and abundance. Temperature and salinity measurements are made on all MARMAP surveys. Current meters have been implanted in the northeast part of Georges Bank which have provided the first direct measurements of the inflow of slope water into the Gulf of Maine. Another series of current meters has been in place now for about a year in the southern part of that system just west of Nantucket Shoals, as part of a joint study of cross-shelf circulation with the Woods Hole Oceanographic Institution (WHOI), the U.S. Geological Survey, and the University of New Hampshire. As we learn more about environmental factors that shape changes in abundances of fish populations, we can move closer to integration of our sampling strategies. It is necessary to continue implementing trade-offs between monitoring events and understanding the cause and effect of a particular event. The closing of the scale gap is an iterative process in which we are continuously evaluating allocations of personnel, ship, equipment, and time resources to maintain a balanced and productive fisheries ecosystem monitoring and research investigation.



Ammodytes spp.
larvae

Figure 6 Population explosion of sand lance (Ammodytes sp.) larvae in early spring from 1974 through 1978. The increase in abundance in sand lance, a fast-growing short-lived, less-desirable food species, may represent an ecological response to the marked reduction in abundance of the biomass of its predators, including cod, hake, pollack, and others. Adapted from Smith, et al. (1978).

Underway Sampling

The only experience with underway sampling that we have had in MARMAP has been a joint project with the Institute for Marine Environmental Research in the United Kingdom. The institute has a continuous plankton recorder that is deployed from commercial vessels as a self-contained plankton sampler. A simple, mechanical, but rather straightforward instrument, it has worked very well, having provided the longest continuous data record of plankton in the North Sea and across the entire North Atlantic. The original plankton recorder was developed by Alister Hardy when the British were investigating the decline in whale stocks in Antarctica. They simply towed the plankton recorder behind the ship at a constant depth. The system used now is similar to Hardy's sampler, consisting principally of a drive shaft, rotated by an external propeller driven as the recorder is towed by the vessel, providing all the energy this system needs. As the plankton enters the sampler, it passes between two rollers of netting and is compressed into a single continuous plankton sample. The gear ratio of the rollers is set to collect plankton continuously over 500 miles of ocean per net-roll, which is stored when expended in a Formalin chamber (Figure 7).

Using the plankton recorder system, British scientists have obtained a very valuable data base. From these data, British scientists reported a significant change in the North Sea plankton for the years 1949 through 1969, with a very marked decline in the abundance of copepod species that serve as important predator-prey components in marine ecosystems. This change in abundance level was first described for copepods about seven years ago. Several investigators have speculated that the changes are associated with increasing pollution of the North Sea. The suggestion was recently advanced that climatic changes may have been generated by an inflow of highly saline subtropical water in and around the British Isles, leading to the suppression of boreal copepod populations. There is no proved explanation for this change yet. The lack of concurrent plankton and environmental data initiated some hard thinking in the United Kingdom. The staff at the Institute of Marine Science in Plymouth has now developed a modified plankton recorder that will collect hydrographic information, including temperature, salinity, depth, and chlorophyll at the same time plankton is collected. The new prototype is an undulating oceanographic recorder (UOR). It was built to be self-contained, following the initial philosophy of having a self-contained unit towed from ships of opportunity, principally commercial vessels (Figure 8). The UOR will undulate in the upper 70 meters of the water column over adjustable horizontal distances of 0.3 nautical mile to 10 nautical miles per undulation, at speeds of 3.6 to 10.0 m/sec (7-20 kts), or more if desired. In recent discussions with researchers in the United Kingdom, they seemed very optimistic about fitting the UOR with a UV sensor that will detect petrogenic hydrocarbons in the ocean. A modified high-speed version of the 10 m fixed-depth plankton recorder has

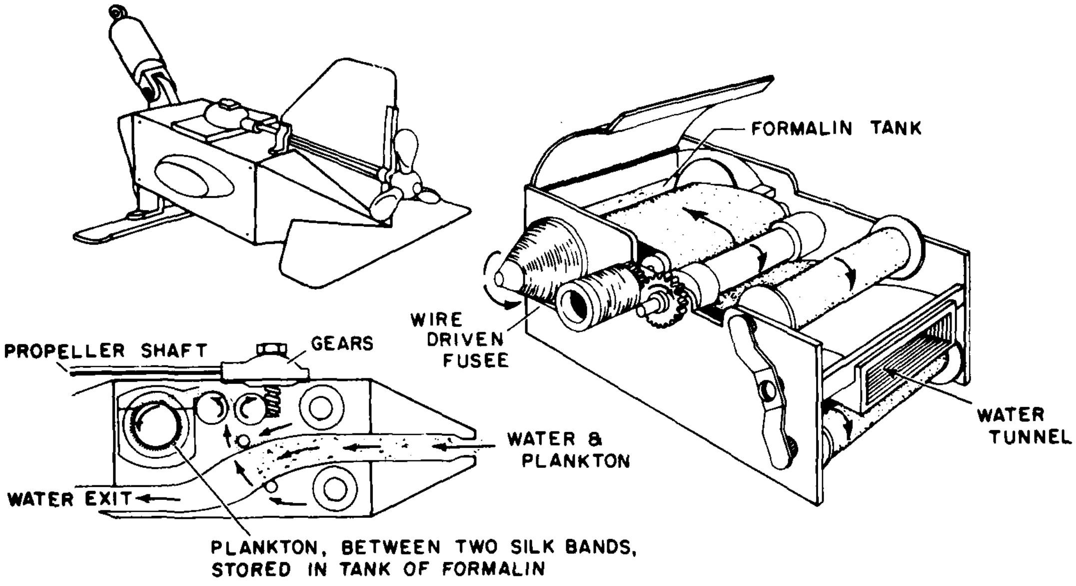


Figure 7 Simplified diagrams of Hardy Continuous Plankton Recorder. Top left: seen from the right rear. Bottom left: a section showing the paths of the two bands of bolting silk. Right: the inside mechanism seen from the right front. From Jossi and Marak (1980).

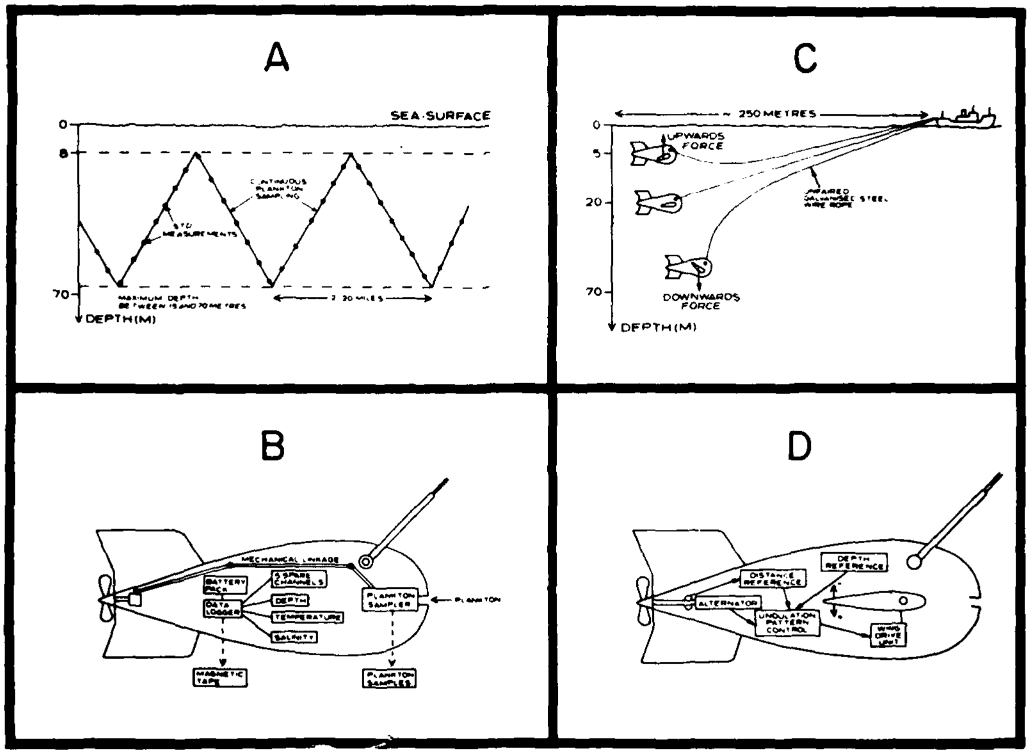


Figure 8 (a) Diagram showing nominal undulation profile of UOR Mark I. The UOR can be programmed to perform regular "saw-tooth" undulations between 15 and 7 m; it samples plankton continuously and measures salinity, temperature, and depth (STD) at predetermined time intervals. (b) Block diagram showing instrumental payload of UOR Mark I. (c) Cable profile (not to scale) and positions of wings during undulation cycle. (d) System for servo-control of wings. The chlorophyll sensor is located above the depth sensor occupying one of the five spare channels depicted in (b). Adapted from Bruce and Aiken (1975).

recently been introduced, recognizing that the original recorder developed in the 1930's was to be towed from ships at a maximum speed of 12 knots. By modifying the posterior portion of the towed body, it can now be towed at speeds up to 27 knots, in keeping with the performance of modern ships. It is still designed to be towed at 10 meters, and is fitted with a temperature sensor.

Marine Resources and Contaminants: Ocean Pulse Approach

In addition to looking at the effects of natural events on the productivity of an ecosystem, we are now faced with increasing offshore development of resources on the continental shelves. Georges Bank and the Mid-Atlantic Bight area are now being explored for gas and oil development. NOAA/NMFS has become more closely involved in studies of the effects of pollution on the productivity of marine ecosystems. We initially became involved on the East Coast during the grounding of the ARGO MERCHANT. The ARGO MERCHANT grounded not too far from Georges Bank, in the adjacent Nantucket Shoals area, releasing seven million gallons of Number 6 oil into waters of the shelf. A sizable contingent of New England marine scientists was unexpectedly mobilized shortly before Christmas 1976 to go out to Nantucket Shoals and try to make an assessment of the effects of the spilled oil on the shelf ecosystem. Since the ARGO MERCHANT spill, we have become rather heavily involved in pollution effects studies. We find that it is absolutely imperative to deal with this problem in the long term, rather than dealing with spill incidents. The chronic introduction of petroleum hydrocarbons into the sea is the real problem. Some evidence is now available indicating that petroleum hydrocarbons can adversely affect fish eggs and fish larvae, and cause severe mortalities when the petroleum hydrocarbon level is maintained at high concentrations in fish spawning areas for extended periods. Pollock eggs that were collected from the region around the ARGO MERCHANT oil spill are shown in Figure 9. Oil droplets were found adhering to the chorion, reducing osmotic exchange. We found in some stations that 90 percent of the eggs affected this way showed serious cytogenetic damage and were non-viable.

John Farrington in his remarks at this workshop mentioned that petrogenic hydrocarbons can find their way into the food web. Well, indeed they do. Oiled fecal pellets were present in copepods collected from the immediate vicinity of the ARGO MERCHANT oil spill (Figure 10). Copepods can produce oil-contaminated fecal pellets without any immediate adverse effects on the copepods themselves at moderate levels of hydrocarbon concentrations in the water. However, copepods serve as prey for most species of young fish; they can be ingested and in this way, petrogenic hydrocarbons are introduced into the marine food web. In addition, all the fecal pellets produced by these copepods transfer the petrogenic hydrocarbon into the bottom sediments or to

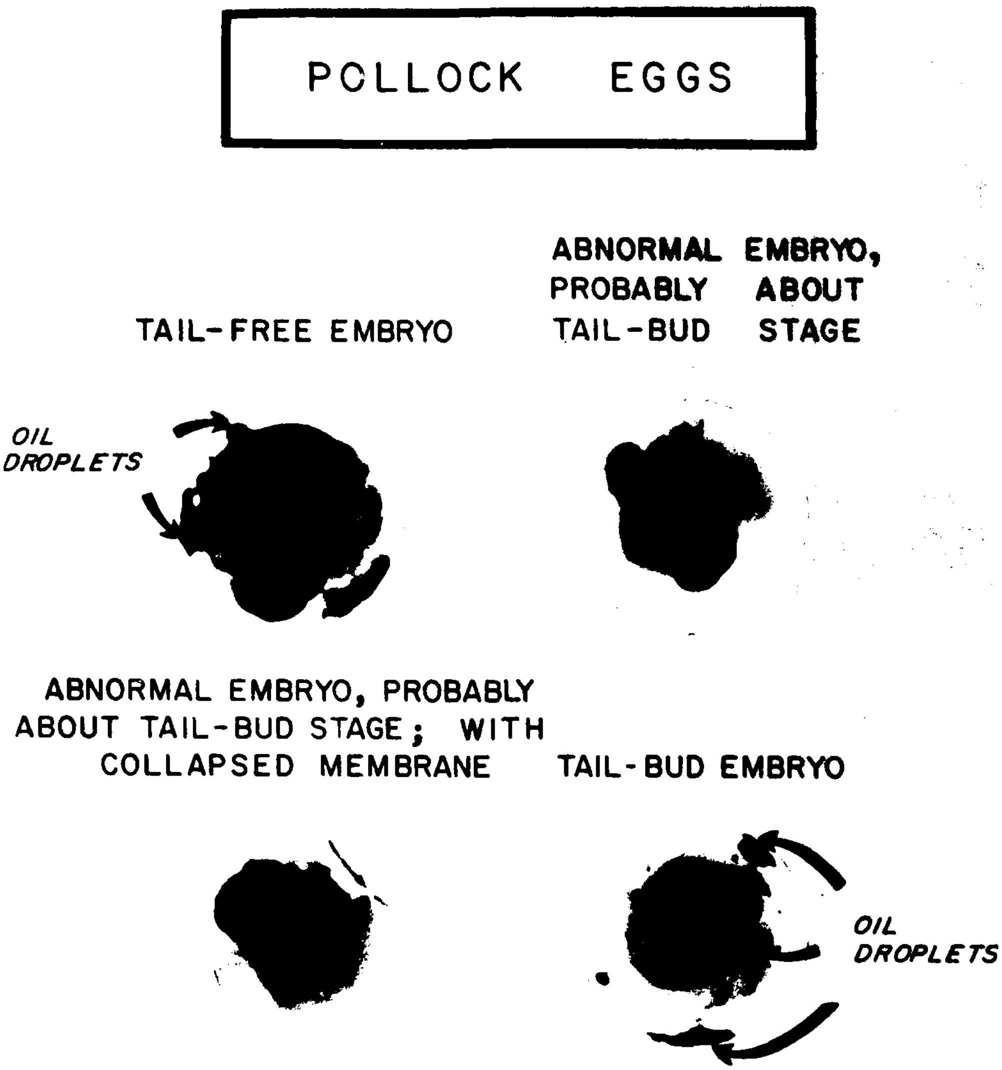


Figure 9 ARGO MERCHANT oil shown adhering to the surface of pollock eggs collected from the vicinity of the ARGO MERCHANT oil spill, and damaged embryos typical of 90 percent of the embryos in pollock eggs collected from a spill site. From Sherman (1977).

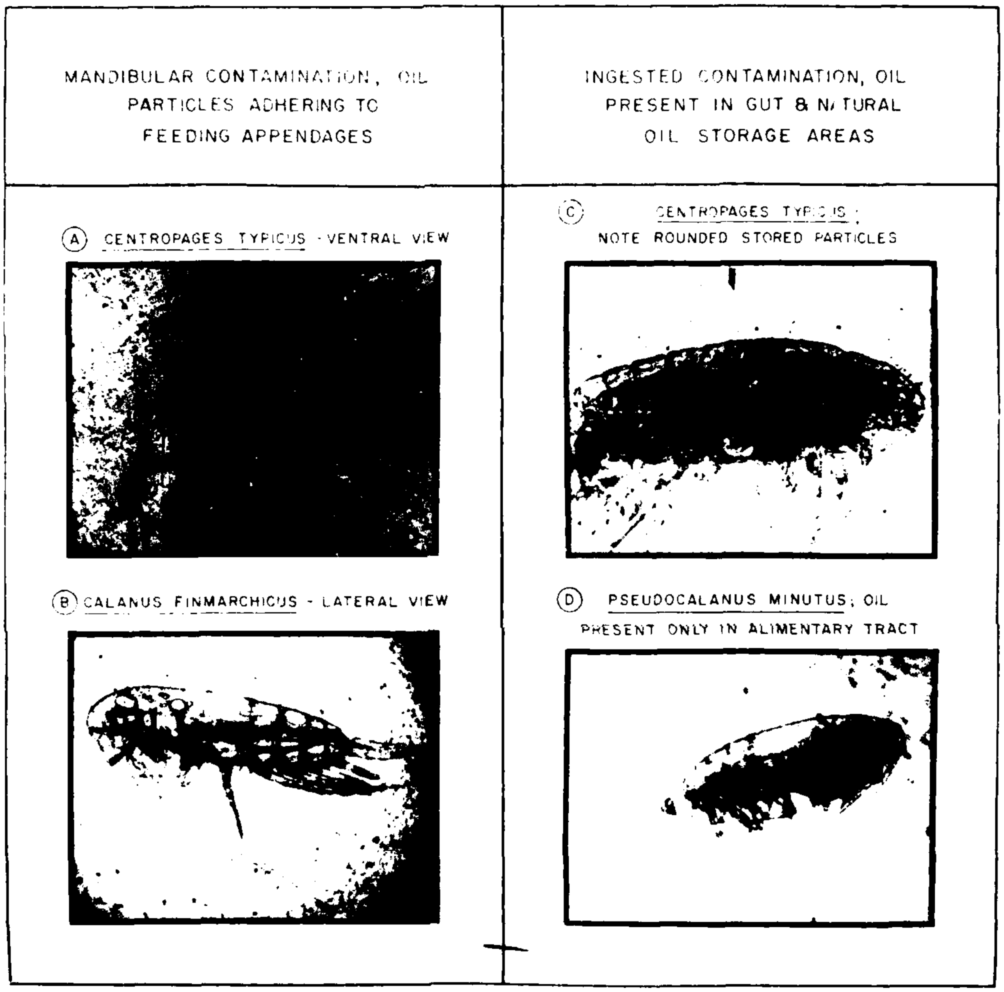


Figure 10 Presence of oil in the alimentary tracts of common copepods collected from the ARGO MERCHANT spill area. Oil fecal pellets are produced by the copepods and introduced into the ecosystem as "fecal rain," part of which is ingested by filter-feeding bottom molluscs (e.g., clams, scallops). From Sherman (1977).

filter feeders in a given area in a persistent "fecal rain," representing another rather important food web pathway. However, in the ARGO MERCHANT case, the residence of oil on the shelf was brief. Nearly all the oil was layered at or near the surface, and was carried offshore into the open Atlantic by the prevailing northwest winds of the season. Damage to the fishery resources was negligible.

To provide a systematic long-term means for monitoring the effects of contaminants of fish stocks, NMFS has initiated the Ocean Pulse Program. This effort looks not only at the changes in the numbers of principal ecosystem components--that is, the population levels, as we do in MARMAP--but also provides the means for measuring changes in the physiology, biochemistry, pathology, genetics, and behavior of selected subsamples from marine populations. As part of Pulse, a series of diagnostic experiments will be done aboard the vessels covering the continental shelf off the northeast coast at least six times a year, and this is an area of research and monitoring in which the development and implementation of flow-through sampling systems, as have been described in this symposium, would be most useful.

Summary: Application and Requirements of Underway Towed Sampling System for Northeast Fisheries Ecosystem Studies

The National Marine Fisheries Service is conducting extensive monitoring surveys of pelagic and shelf ecosystems within the recently established 200-mile Fisheries Management Zone. Abundance levels of plankton, fish, and benthos are measured on spatial scales of hundreds of kilometers and temporal scales ranging from 30 to 60 days per survey. Studies of biological productivity and energy-transfer efficiencies are also conducted within the broad-scale survey matrix, requiring observations on the microscale of meters to tens of meters both horizontally and vertically. During both the mesoscale monitoring surveys and the mesoscale process-oriented studies, measurements are made of the horizontal and vertical structure of the water column, flow fields, nutrient flux, and contaminant flux. All biological, physical, and chemical measurements are made at point sampling locations. Application of an underway towed sampling system in the monitoring operation would reduce operational costs significantly, and provide new insights into biogenic energy-transfer processes.

The general requirements of an underway towed sampling system should include the capacity for measuring:

Microplankton fields (phytoplankton, zooplankton)--measurement of density, biomass composition, and sizes of organism ranging from 0.01 to 10.0 mm, in densities of 1 organism per ml.

Chlorophyll field--measurement of concentrations from surface to 75 m, including the 100 percent to 1 percent light-intensity levels. Net plankton chlorophyll *a* (>20 microns) and nanoplankton chlorophyll *a* (<20 microns) should be separated by size fraction, and measurements made of phaeophytin and acidification ratios at depths of 1, 5, 10, 15, 20, 25, 30, 35, 50, and 75 meters. Light measurements are also desirable.

Nutrient field--sampling from the water column to a depth of 200 m. Measurements should include concentrations of orthophosphorus (PO_4), reactive dissolved silicon (Si), nitrite (NO_2), nitrate (NO_3), and ammonium nitrogen (NH_4).

Macroplankton field--needed measurements require an instrumented towed vehicle that can be programmed to undulate between the surface and 70 m, with an undulating length between 2.5 and 30 km, at speeds between 7 and 20 kts (3.6-10.7 m/sec). Plankton collection should be continuous over the range of undulation depths. The fish should contain sensors for conductivity, temperature, pressure, and chlorophyll *a*. Data need to be recorded at depth *in situ* at rates between 30/min. to 30/hour and stored on digital magnetic tape. Salinity, temperature, depth, and chlorophyll *a* values should be accurate to ±0.1 (0/00), ±0.1°C, and ±0.5 mg/m^3, respectively. The sampler should be automatic and self-contained, with self-generated power supply.

Additional sensors for environmental assessment are desirable for measuring concentrations of: petrogenic hydrocarbons, biogenic hydrocarbons, organochlorines, and trace metals. An underway towed system would be particularly useful for obtaining continuous profiles of prey-densities and water quality over important spawning grounds of fish.

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WORKSHOPS

WORKSHOP SESSION I

Statements of Research Objectives and Required Technology for Present and Future Underway Water Sampling

The participants were asked to write a brief statement of present and future research in their fields requiring underway water sampling, the specifications and characteristics they would find most useful in such systems, and to estimate the time in the future when the specifications and characteristics necessary to long-term research would be needed, if they are not now available.

These statements laid the base for the following day's workshop: two simultaneous sessions dealing with present and future requirements of sampling and analysis, and the present state and prospective development of technology to meet those requirements.

The statements of research objectives and required technology follow.

RESEARCH FOR UNDERSTANDING PROCESSES THAT CAUSE CHEMICAL VARIATIONS AND CYCLING IN SEAWATER

Dana R. Kester

Our application for an underway towed pumping system is to define chemical gradients in the ocean with higher resolution than can be achieved by discrete sampling, in order to better understand the processes responsible for chemical variations and cycling in the sea. The primary interest is in chemical parameters affected by biological and physical processes. These include nutrients, dissolved oxygen, and trace metals (Fe, Cu, Cd, Hg). The types of oceanic systems to be investigated include frontal zones where large horizontal gradients and enhanced biological activity lead to increased chemical fluxes and cycling within the ocean. In the North Atlantic, these conditions are found at the continental shelf edge, along the Gulf Stream, at the boundaries of Gulf Stream rings and at major water-mass boundaries such as occur near Iceland. Continuous sampling and analysis would also be useful in studies of the chemical processes occurring where river plumes extend into the ocean.

The initial interest is in the upper region of the ocean. One may identify three major depth ranges in the ocean basins where chemical gradients are of particular interest. Investigations in the upper 200 m include those processes occurring in the euphotic zone, the seasonally mixed layer of the ocean, and in the upper portion of the main thermocline. Studies down to 1000-1500 m cover the main thermocline, the oxygen minimum, and the nutrient maxima. Studies within 500 m of the seafloor provide information on benthic exchange processes. The upper 200 m represents the most accessible region of the ocean with present pumping technology. Pumping to depths of 1000-1500 m may be possible, but should be pursued only after obtaining more information about upper-layer chemical variability in the ocean, and more experience. It is unlikely that benthic studies using sampling and pumping to a surface vessel will be feasible in the near future.

The requirements for this application are summarized in Table 1. The values displayed are based on the needs developing within the next several years that may be regarded as next steps to obtaining higher-resolution chemical measurements in the ocean. The projection does not represent the ultimate system, nor one that would be needed for research in the 1990's. Requirements are given quantitative values where possible, but some trade-offs can be considered, depending on engineering considerations. The specifications should be regarded as order-of-magnitude requirements. For example, the vertical scale to be emphasized is 1 m, not 1 cm or 10 m; the horizontal scale is 500 m, not 10 m or 5 km, etc.

It is likely that the sampling needs identified for this application can best be met with a systematically designed and engineered capability to meet a range of needs, rather than with a limited system that would be dedicated to this application.

Table 1: Design Requirements for this Application of an Underway Towed Pump System

Requirement

1. Vertical resolution of about 1 m
2. Horizontal resolution of about 500 m
3. Data rate for individual observations: 1 minute
4. Temporal scale of distribution: 1 hour
5. Volume for analysis: 2 liters
6. Delivery rate and pressure head: 10 liters/min at 25 psi
7. Tow speed: 0-5 knots
8. Tow depth: 0.5 - 200 m with undulating ability
9. Single port pump
10. System materials: Teflon (non-metallic, compatible with chemical cleaning)
11. Supplemental sensors at intake: depth, temperature, salinity, oxygen, chlorophyll fluorescence, and light scattering.

WATER MASS MIXING AND LARGE-SCALE VARIABILITY OF CHEMICAL CONSTITUENTS OF SEAWATER

Robert Lorens

I. Application for Underway Towed Sampling

A. Examination of chemical distributions at ocean front and upwelling areas--small-distance surveys

1. water-mass mixing
2. concentration of parameters at frontal areas.

B. Rapid examination of large horizontal-scale (10's of kilometers) variations in chemical parameters.

II. Requirements:

Applications "A" and "B" require different sampling capabilities, although they are not mutually exclusive capabilities.

A. Vertical resolution:

A: 1-2 meters

B: 10's of meters

B. Horizontal resolution:

A: 20's of meters

B: 100's-1000's of meters

C. Temporal:

A: hrs

B: hrs

D. Volume

E. Delivery rate:

A & B: 5 liters/min (5-10 psi)

F. Tow speed

  A: 6 knots

  B: 12 knots

G. Tow depth

  A: 200 m

  B: 100 m

H. For rapid under-ocean (0-100 m) surveys of the type our office would like to do, a multiport system with a separation of 10 to 20 meters between ports would be an asset.

J. Contamination: minimize for nutrients and trace metals.

III. _In_ _situ_ Sensors:

CTD, fluorescence, O_2.

TRACE-GAS RESEARCH

Denis A. Wiesenberg

1. Applications:

We are trying to determine the mechanisms that control trace-gas distribution in surface waters (0-200 m). These gases may be associated with phytoplankton patchiness and nutrient distribution. Since phytoplankton patches have a length scale of about 1 km, we need measurements on a 300 m scale or less. Rapid sampling and analysis is necessary to obtain enough data within these small-scale features to determine the co-variance of certain parameters. The gases that we measure are methane, hydrogen, carbon monoxide, and oxygen. Nutrient measurements include phosphate, silicate, nitrate, and nitrite. Chlorophyll is measured (by fluorometry) as an estimate of phytoplankton biomass. Our area of interest includes the open ocean as well as coastal areas. However, coastal areas have a greater variability in all the above parameters and lend themselves better to rapid analysis by towed pumping system techniques. A higher flow-rate system would be advantageous for obtaining biological samples (phytoplankton and zooplankton) for examination. Particle-counting techniques will be added later for biomass determinations.

2. Resolution requirements

a. Vertical--one meter
b. Horizontal--300 meters
c. Temporal--hours to days
d. Volume--6-8 liters per minute, depending on the length of the hose. Analysis requires about 2 liters, but higher rates are advantageous to avoid smearing.
e. Delivery rate and pressure--6 liters per minute at a pressure >50 psi to allow sample splitting and transfer to second-level ship labs.
f. Tow speed--10 knots or higher
g. Tow depth--surface to 200 meters (variable!)
h. Fixed or undulating--undulating: assuming the system has slip rings, this should be easy

i. Number of ports--single port. A multiple-port system exceeds the capabilities of most of the analytical systems academic institutions can afford to buy.
j. Hose needs to be nontoxic. Entire system needs to be noncontaminating for metals, hydrocarbons, and hydrogen. Teflon would work well.
k. Backflush capability--needed to keep any system clean.
l. Supplemental sensors--T, P, conductivity, light (in fish), and flow rate (on deck).

FISHERY GROUNDS BIOLOGICAL ASSESSMENT

Kenneth Sherman

1. The National Marine Fisheries Service is conducting extensive monitoring surveys of pelagic and shelf ecosystems within the recently established 200-mile Fisheries Management Zone. Abundance levels of plankton, fish, and benthos are measured on spatial scales of hundreds of kilometers and temporal scales ranging from 30 to 60 days per survey. Studies of biological productivity and energy-transfer efficiencies are also conducted within the broad-scale survey matrix, requiring observations on the microscale of tens of meters both horizontally and vertically. During both the mesoscale monitoring surveys and the microscale process-oriented studies, measurements are made of the horizontal and vertical structure of the water column, flow fields, nutrient flux, and contaminant flux. All biological, physical, and chemical measurements are made at point sampling locations. Application of an underway towed sampling system in monitoring would reduce operational costs significantly and promote new insights into biogenic energy-transfer processes.

2. General requirements of an underway towed sampling system should include capacity for measuring:

   2.1 Microplankton fields - (phytoplankton, zooplankton), measurement of density and biomass composition ranging from the 0.1 mm to 10.0 mm size range in densities of 1 organism per ml.

   2.2 Chlorophyll field - measurement of concentration from surface to 75 m including the 100 percent to 1 percent light-intensity levels. Net plankton chlorophyll a (>20 microns) and nanoplankton chlorophyll a (<20 microns) should be separated by size fraction, and measurements made of phaeophytin and acidification ratios at depths of 1, 5, 10, 15, 20, 25, 30, 35, 50, and 75 meters; light measurements desirable.

   2.3 Nutrient field - sampling from the water column to a depth of 200 m. Measurements should include concentrations of orthophosporus (PO_4), reactive dissolved silicon (Si), nitrite (NO_2), nitrate (NO_3), and ammonium nitrogen (NH_4).

2.4 Macroplankton field--Requirements: instrumented towed vehicle that can be programmed to undulate between the surface and 70 m, with an undulating length of between 2.5 and 30 km, between 7 and 20 kts (3.6 - 10.7 m/sec). Plankton collection should be continuous over the undulation depth-range. The fish should contain sensors for conductivity, temperature, pressure, chlorophyll a. Data to be recorded at depth *in situ* at rates between 30/min to 30/hour and stored on digital magnetic tape.

Salinity, temperature, depth, and chlorophyll a values should be accurate to ± 0.1 (0/00), ± 0.1°C, ± 0.05 mg/m^3, respectively. Sampler should be automatic and self-contained, with self-generated power supply.

3. Additional sensors for environmental assessment are desirable for measuring concentration of petrogenic hydrocarbons, biogenic hydrocarbons, organochlorines, trace metals.

4. An underway towed system would be particularly important in obtaining continuous profiles of prey-densities and water quality over important spawning grounds of fish, in studies of factors controlling the growth and survival of fish eggs and larvae.

PHYTOPLANKTON-ZOOPLANKTON BIOLOGICAL SAMPLING

Alex Herman

Phytoplankton Sample: (Chlorophyll)

Resolution: 1 m vertical, 1 km horizontal

Towing speed: ∿3-5 kts

Maximum depth: 100 m

Volume delivery: 4-5 liters/minute

Construction: Materials choice not critical
Contamination usually not a problem

Pump: Submersible, single port, not damaging to organisms

Additional Sensors: Temperature, pressure, salinity at intake--
in situ measurements

Zooplankton Sampling:

Same as above, except

Volume delivery: ∿100-200 liters/minute

Data Rates and Handling

- Data rate of ∿1 sample/second
- Data storage on mag tape or cassette
- Analog display of data

Applications:

Biological and physical processes operating at frontal systems

Study of zooplankton variability (patchiness)

TRACE GASES AND THE CHEMICAL VARIABILITY OF OCEANIC WATERS

Frank L. Herr
Robert E. Pellenbarg

Applications

The Naval Research Laboratory is interested in studying the effects of ocean processes on the chemical variability of the oceans above and within the permanent pycnocline. Significant ocean processes are biological activity, geochemical influences such as atmospheric gas saturation, inorganic particulate fluxes and generation, and water-mass movement and interaction in a physical oceanographic context. These constant ocean processes (and other factors) affect local levels of reduced gases such as CO_2, H_2, CH_4, N_2O; trace metals and the transport of these materials, and such transient tracers as Freon, during oceanic circulation. Identifiable influences on ocean chemical variability are particularly pronounced at oceanic frontal regions such as river planes in the oceans, boundaries of different water masses at shelf/slope breaks, and within continental boundary currents. Further, NRL is interested in the continuing development and application of advanced chemical analytical technology for shipboard and _in situ_ use. Such techniques as laser fluorescence spectroscopy; gas chromatography or liquid chromatography (or both); mass spectrometry, atomic absorption spectrophotometry, and various electrochemical techniques should be supported by the envisioned pumping system.

Resolution Requirements to Meet the NRL Applications

a. Vertical: The implication is that the water intakes should be stable under tow to ± 1 m in moderate seas. In heavy seas ± 3 m vertical stability under tow should be approached.

b. Horizontal: 10 m; may wish to include pinger on fish to aid in tracking the fish in relation to well-known surface platform position.

c. Temporal: One hour is the scale of temporal variations of phenomena we are interested in studying.

d.	Analysis volume:	One liter of water per discrete dissolved-gas analysis; 0.5 liters per discrete trace-metal analysis. For continuous trace-gas analyses, 20 liters/minutes is needed, for which all trace gases will be analyzed; with proper design, waste from gas analysis would not be contaminated and could be used for other analyses.
e.	Delivery rate and pressure:	Delivery rate has to be high enough to ensure turbulent flow in the sampling line. This criterion can be adjusted according to the internal diameter of the delivery system; we envision a system with a minimum pumping capacity of 30 l/minute. On-deck water pressures of up to 15-20 psig are needed to operate spray-nozzle gas strippers and equilibrators.
f.	Tow speed and depth:	Upper limit 20 kt at 50 m, lower limit 6 kt at 500 m.
g.	Single-port capability:	With capability of following physical oceanographic features such as isophysical contours.

The pumping system we require must have its pump submerged to avoid cavitation (and thus loss of the capability to sample dissolved gases). The sampling line must be all Teflon, although an exception may be this material's effect on dissolved fluorocarbon analyses. The pump itself must be all Teflon (best), nylon, or polyethylene construction, or at least coated where parts contact the sample stream. Centrifugal, or perhaps positive displacement, may be the best pump configuration. A peristalic pump is less desirable because of probable damage to various components, especially biota, of the sample stream. Magnetic drive would be useful, but not as powerful as shaft drive. *In situ* CTD and fluorescence capabilities are required.

HYDROCARBON GAS DETECTION

H. Reitsema

Applications

Detection and analysis of hydrocarbon gases for application to oil and gas exploration

Sampling needs

Controlled depth off bottom

100's of meters horizontal resolution

Low hold-up--turbulent flow

Flow rate--to 20 gal. per min.

No hydrocarbon contamination--no gas leaks

CTD analyzer in fish

Analytical capabilities--already exist, as well as adequate gas chromatograph with flame and conductivity detectors.

Data handling used now
--raw data on cassette for processing on shore.

SATELLITE AND SYNOPTIC STUDIES OF UPWELLING-FRONTAL SYSTEMS IN THE CALIFORNIA CURRENT

Eugene D. Traganza

The objective of this research is the development of synoptic models of upwelling systems which are detected entering the California Current by satellite infrared imagery. These systems are fed by upwelling coastal water and can spin up into mesoscale (tens to hundreds of km) features with time scales of days to weeks. Sharp thermal and chemical gradients and associated biomass distribution are characteristic components of these features which persist far offshore (>300 km). These systems change as the water advects and diffuses, thermal and salt fluxes diverge, and with differential uptake and release of nutrients. While a single satellite image is an almost instantaneous view with good spatial and temporal resolution, in situ observations are constrained by the extant capabilities of underway sampling systems towed from surface vessels. Notwithstanding the complexity of the analytical problem, it is possible that the combination of optimal underway sampling technology and satellite imagery will make it possible to detect and better understand upwelling frontal systems entering the California Current.

Sampling System Requirements

Resolution:

a.	Vertical	meters
b.	Horizontal	meters
	i. Measurement resolution	tens of meters
	ii. Synoptic resolution	hundreds of meters
c.	Temporal	
	i. Measurement resolution	minutes
	ii. Synoptic resolution	hours to days
d.	Volume	1 liter/minute
e.	Delivery rate and pressure	25 liters/minute, 1 inch diameter

f.	Tow speed	10-15 knots
g.	Tow depth	0-100 meters
h.	Fixed or undulating	fixed (with servo-constant depth control)
i.	Single or multiport	single (at depths below 1 meter)
j.	System requirements	
i.	Toxicity	nontoxic (to plankton and bacteria)
ii.	Contamination	noncontaminating (for N, P, Si nutrients)
iii.	Gases	"non-gaseous"
iv.	Organism damage	neither damaging nor stressful
k.	Backflush capability	yes, with acid/base wash
l.	Supplemental sensors	
i.	*In situ*	temperature pressure salinity light fluorescence
ii.	Deck	fluorescence flow rate

CONTINUOUS SAMPLING WITHIN THE CONTEXT OF THE CALIFORNIA COASTAL FRONTS PROGRAM

James J. Simpson

Our interest is to determine the chemical and biological response of oceanic systems to physical forcing. Forcing functions of interest include 1) lateral transport due to eddy fluxes, 2) frontogenesis, 3) the impulse response of the integrated oceanic system to storms, and 4) mixing due to internal waves. Hence, the effort is directed largely toward small and mesoscale processes. A combination of laboratory experiments, numerical simulations, and oceanographic field work is used.

Scales associated with horizontal mode of sampling fall in the range of ~ 50 m $< x \leq 500$ km and ~ 1 min. $\leq t \leq 10$ days. A towing rate of 10 to 15 knots is desirable. High flow rates (~ 200 - 500 l/min.), minimum side-wall friction, and a chemically clean system are essential. However, our requirements for cleanliness are less stringent than those associated with the chemistry of trace metals.

Repeated vertical profiling (~ 10 to 15 min.) to the depth of the pycnocline is another mode of sampling of interest to us. Vertical resolution on the order of 1 m is clearly desirable.

Since the gradients of quantities frequently are of more dynamical interest than the magnitude of the quantity itself, a multiport system is of considerable value to our research. The ability to follow isopycnal surfaces, and eventually, to do an integrated set of physical, chemical, and biological measurements in the Lagrangian sense is a long-term goal.

Various signal types (i.e., outputs from analytical devices) and large data rates require an onboard acquisition and processing capability of considerable flexibility.

SUMMARIES OF WORKSHOP SESSION II

- Sampling and Analysis Workshop
- Technology Workshop

SUMMARY

Sampling and Analysis Workshop

Dana R. Kester

In discussing the various applications for underway towed pumping systems for studies of the ocean, members of the group identified the requirements for such a system. We then addressed the analytical capabilities and the improvements that are likely to be needed within the next several years to take advantage of an underway continuous sampling system. Near the end of our session, we began to talk about the data-handling requirements.

In bringing together information about the applications people have in mind for such a system, interest was expressed in looking at the chemical and the biological response to physical variability in the ocean. This variability is associated with eddy exchange processes, with transfer in frontal regions, with storms passing across the ocean, and with internal waves.

The statements of applications and requirements indicate there is a fairly strong universal interest in these oceanic systems. It is evident that the systems are being examined from slightly different perspectives, but it would appear that there is agreement about many of the sampling requirements and about some of the scientific objectives.

Scientific Demands

Sampling Requirements

It became evident in the course of the workshop that there is a fairly wide range of chemical problems in the ocean to be investigated and that the sampling requirements of the entire range are surprisingly compatible.

A fairly large number of problems can be addressed with a sampling system that has a vertical resolution on the order of a meter, as opposed to tens of meters, or tens of centimeters; and horizontal resolution on the order of perhaps half a kilometer, as opposed to five kilometers or tens of meters, and so on.

A significant point of departure was identified as we considered the requirements for chemical analysis, and the sampling of particles and biological distributions. Larger volumes are needed for useful measurements of biological distributions and those of some particles.

There was discussion of single-port versus multiport sampling. Based on the current problems that were identified, and the present understanding of distributions, it was felt that a single port was suitable for many near-term problems, although arguments can be advanced for multiport sampling in the future, as more information and experience with these systems is acquired. It was felt that some of the limitations of a single-port sampling system could be offset by readily controlled vertical sampling, such as an undulating pumping system.

Analysis Requirements

Techniques of analysis for the measurement and characterization of constituents were considered. A number of nutrient analysis systems are available, based mainly on continuous-flow techniques. Some improvements to these could be made in the future to enhance their sensitivity, and to extend analysis to other constituents. This latter point, and the analytical requirements and techniques for organic substances, were discussed only briefly. The state of the art of analytical techniques for particular organic substances, however, is probably not as advanced as that of techniques for other constituents. This is an area that should receive more attention.

Gases in the ocean are receiving a great deal of attention. Gas chromatography is the most commonly used method for detecting and analyzing gases such as methane and carbon monoxide. Other possibilities can be considered; for example, infrared gas absorption for carbon dioxide, and gas chromatography or chemical analysis for hydrogen.

Trace metals are a third class of constituents. While there are laboratory methods for analyzing trace metals in discrete samples, there is no operational method for taking measurements at oceanic concentrations at sea. This would require development of an analytical system to be used with a continuous sampling system. A number of ideas were advanced about how development might proceed: following the pattern of autoanalyzer techniques to automate present analytical methods, for example, or perfecting techniques based on the fluorescence of metal-organic compounds, or perhaps instrumental techniques.

Some consideration was given to the analysis of particulate material--characterizing the amount in suspension, its relationship to ocean color, and its chemical composition.

It was generally agreed that a towed pumping system should be supplemented with sensors at the intake to document the position in the water column that is being sampled, and this can most readily be achieved by using a CTD system with the pump.

Data-Handling Requirements

Data handling presents problems comparable in magnitude to those of sampling and analysis. We addressed it briefly, but data-handling requirements merit in-depth examination.

Although it is clear that the data should be in digital form for efficient handling, it is important to have graphical presentations of the time phase of the different parameters measured, and to be able to relate these to ship position through navigational information.

To use the system interactively, graphic display and at least some moderate computation capability should be onboard ship that can make information available in close to real time. Whether this should be done with a central data-processing minicomputer or with a separate system was discussed, but consensus was not reached. This is a point that should be examined for future systems.

SUMMARY

Technology Workshop

Reece Folb, Marshall Tulin, and Shelton Gay

FOLB: Our workshop group approached the technological needs of underway water sampling by looking at the problems of sampling at 100 meters and 1000 meters, and at means for achieving the objectives described for sampling systems. This approach led us to consider the hydromechanics of the system, to develop the capability of the system itself--the smear, tubes, and pumping. We examined aspects of control, and briefly, the approximate costs of these systems, and finally, some areas for further development, and made a preliminary estimate of the costs of these systems (Tables 1 and 2, attached).

Shelton Gay will discuss concerns about developing the 100 meter systems and the 1000 meter systems, Marshall Tulin will address concerns with the smear, the tube size, and the pumping problem, and I will conclude with a brief summary.

GAY: As I commented yesterday, towing is an open-ended problem unless some bounds are established. We decided the proper place to start was limiting the tension at the towing ship. We established an upper limit of 15,000 pounds. We then calculated the length and characteristics of the towline for depths of 100 meters and the speeds we could achieve as a function of the diameter of a faired cable, and of a bare cable with an internal hose. These are attached ("Limited Towing Speeds at Given Depths"). Taking very conservative estimates of the various parameters that limit the physical possibilities within the system, and hoping they bound the region of real systems that could be produced, then, presumably, the other inputs--pumping rates, sample integrity, etc.--will give us some limits for which we can specify minimum sizes for the hoses and tubes, which will then establish the limiting factors on the sizes of the systems we could produce.

TULIN: We asked ourselves the question whether present pumping technology will allow pumping systems at depths to 1000 meters, and what the parameters are that determine the hydrodynamic longitudinal diffusion and smear.

In one effort, calculations were made of the pumping requirements based on the stipulation that the flow be turbulent, assuming rather low flow rates ("An Overview of the Relations Between Pumping Capacity and Towing Design," attached). Those calculations, based on a smearing estimate for longitudinal diffusion in the tube alone, indicate that the pressure requirements are really not very severe to go to depths of the order of 1000 meters. However, those flow rates are on the order of tens of liters per minute, not hundreds, which I understand from the sampling and analysis group is desirable for some cases. In another effort, we have quantified specific relations for the diffusion lengths--based both on the tube effect and storage effect ("Pumping and Hydrodynamic Smearing," attached).

I might point out that hydrodynamic smearing determines the resolution of the spatial scales that can be obtained in the sampling system. This is why we put some emphasis on them: two sources are the tube effect and storage effect. The storage effect will occur in a pump casing, for example. It will depend on how the pump is operating, but also on any dead storage region. We derived the best relations we could--some instant hydrodynamics for those effects.

Our conclusions are that for the practical cases we considered (that is, we put in some numbers for a range of cases) the storage effect is likely to dominate, or be most important, at depths to 300 meters or so. For example, if you want a vertical resolution length of 10 meters from an undulating sampler, without increasing your pumping head over 100 pounds per square inch, we thought that was possible to achieve.

At a towing speed of six knots and a depth of 300 meters, the storage volume cannot exceed one liter, and this indicates the limitations of storage capacity. The calculations should be made more carefully, of course. The limitation cited is for a flow rate of 20 liters per minute; regardless of accuracy, it points up the storage problem.

At deeper sampling depths, tube smearing becomes more important. My calculations indicate that beyond 1000 meters, tube smearing will be the controlling factor. Nevertheless, the same resolution length--that is, of 10 meters--can be obtained at depths of 1000 meters. To control the storage effect, flow rates will have to be raised to 200 liters per minute, which may be desirable in any case. The increased flow rate can be achieved with pressure on the order of 100 psi, but the tube sizes will have to be expanded, perhaps to 4 centimeters or so, which means that a very careful look should be taken at multiple-tube systems--not for sampling, but for ideas about the specific shape of the tube.

With careful design, paying due attention to storage volume and tube smearing, present technology can be used for sampling at 1000 meters, and if provided with a pump producing 100 psi, will allow resolution lengths of the order of two meters. That is our preliminary conclusion.

FOLB: Taking up the requirements expressed for an undulating body, there appear to be no insuperable difficulties in the hydrodynamics, or in achieving the desired degree of control (see "Controllable Bodies"). Speeds of 5 and 10 knots are feasible, as are dive and climb rates of 2 to 5 meters per second, and these maneuvers could be executed in various steps, if you need a certain sampling time at a particular altitude, or sinusoidally.

Present accuracies can probably be maintained at plus or minus one meter. There is also the possibility of developing bottom-following systems. These have been attempted with collision-avoidance sonar on the front end. They would probably require some additional developmental studies. We need to know from the user what static accuracy is required, the frequency response, overshoot, and damping that need to be designed into the system.

To sum up the discussions of our workshop, for the bare cable systems that do not require fairings for 100 meter depth and 15 knot capability, the costs might run between $75,000 and $150,000. We concentrated on these systems because there seem to be several applications for shallow systems, and they have greater adaptability for use on ships of opportunity.

For faired cable systems, the costs might range from $100,000 to $300,000. Faired cable systems are more complicated.

The group speculated that for multiple sampling purposes, one sampling tube could be located within the strength member--within the cable itself--and other sampling tubes in a fairing of the strength member. This would require some developmental efforts, and a faired system for handling purposes.

One area that warrants technical improvement is the traction engine and storage arrangement for faired wire. The traditional driven-drum winches are massive, require significant deck space and must be near the overboarding and towing ground tackle. It is possible to design a traction engine that would provide the line pull and winch rate that the group considered adequate (15,000 lbs and 200 ft/min). It would also occupy a relatively small area near the overboarding ground tackle. The storage drum (or a faking basket) could be elsewhere (on the 0-2 level or forecastle deck) and a low-tension storage drum could conceivably allow multiple-layer storage of faired wire. No conclusions were drawn, but this is a design area where the potential for initial and operational savings exist. Also, heave compensation is more easily achieved with a traction because the inertial loads are lower.

The hydrodynamic design of the sampling system for 100 meter depths is well within our grasp. Sampling systems for greater depths would probably require fairings.

We talked about designing modular systems that could be put together to meet individual requirements. The principal developmental work for these systems would probably be in the cable connections for transferring the strength member from one cable to another to get longer cables, for carrying the tubing, for transferring the tubing between strength members, and for carrying the electrical leads.

It was generally agreed that metallic pumps and Teflon hoses were a good choice of pumping systems designed to provide sample water for hydrocarbon and dissolved-gas analysis. As with plastic pumps, the reservoir or void volume in volutes and other pump cavities is a critical parameter in minimizing the smear and diffusion of a sample.

Other plastics with good to excellent hydrolytic properties, as well as better mechanical characteristics, should be evaluated to see if they can be adapted to these applications without affecting the quality of the sample or shipboard analytical equipment. Fluoroplastics, polytetrafluoroethylene (PTFE) in particular, exhibit outstanding chemical inertness. They have some very undesirable engineering characteristics that severely limit pump and seal design, and they have a limited service life. This is principally due to the poor mechanical properties and wear resistance of unfilled PTFE. Polysulfone (Udel), polycarbonate (Lexan/Merlon) and phenylen oxide (Noryl) are examples of plastics with mechanical characteristics that would allow the design of pumps with higher output pressures, smaller voids, and longer service life. The costs could also be reduced if a family of such pumps were available to the oceanographic community.

Hoses with other than PTFE liner materials could be more durable, less susceptible to kinking, and potentially less expensive. Nylon hose, particularly Nylon 11, has good properties for handling seawater. Again, the material must not contaminate the sample.

TABLE 1: Approximate Estimated Cost of Underway Water Sampling Systems

Bare Sampling Hose Case

Scope Unit	100 m	1,000 m	10,000 m
Winch +PU	$ 20K	$ 50K	$ 100K
Cable +HF	$ 15K	$ 40K	$ 300K
Towed Body	$ 8K	$ 20K	$ 50K
Launch & Recovery	$ 30K if REQ	$ 40K	$ 60K
	$ 43K $ 73K	$ 150K	$ 410K

TABLE 2: Approximate Estimated Cost of Underway Water Sampling System

Faired Sampling Hose Case

Depth Unit	100 m 15 kts	1,000 m 10 kts	5,000 m 5 kts
Winch	$ 50K	$ 120K	$ 500K Tract
Winch			$ 500K St.
Cable & Fairing	$ 20K	$ 130K	$ 350K
Towed Body	$ 8K	$ 20K	$ 50K
Launch & Recovery	$ 30K If REQ	$ 40K	$ 100K
	$ 78K- $ 108K	$ 310K	$ 1.4M

LIMITED TOWING SPEEDS AT GIVEN DEPTHS

Shelton M. Gay

The limit on towing speed as a function of depth may be computed from the equation:

$$\frac{Ry}{T} = \bar{\eta}/z \qquad (1)$$

$R = C_R qt$ = resistance per unit length of towline

C_R = resistance coefficient

q = dynamic head

t = towline thickness (if faired)

= towline diameter (if round)

y = depth

T = tension at the upper end of the towline

$\bar{\eta}/z$ = value of the cable function for maximum depth per unit tension

Rearranging equation (1),

$$q = 1/2\rho U^2 = \frac{(\bar{\eta}/z)T}{C_R\, ty} . \qquad (2)$$

Assuming $\rho \approx 2$ slugs/ft^3, then $U = \sqrt{q}$,

and therefore, values of U may be computed for specific values of the outer parameters.

To bound the problem, it is assumed that the maximum permissible value of T, T_m, is 15,000 lbs. This selection for T_m is defensible only on the grounds that loads higher than this aggravate the problems of structural attachment of the handling system to the ship, and affect the weight of the winch and outer gear.

Faired Cable

The faired cable is assumed to consist of an electromechanical cable of diameter d mounted in tandem with several hoses (one to three, say) having the same outer diameter, with a trailing fairing member of some sort.

The following values are assumed for the parameters noted:

C_R = 1/2 (this assumes a fairly draggy faired towline arrangement), and
$\bar{\eta}/z$ = 0.8 (a value representative of a variety of fairing arrangements).

Values of U are presented in Table 3 as a function of towline thickness for depths of 100 and 1000 m.

TABLE 3

Y(m)	t(in)	0.5*	0.75	1.0	1.5	2.0
100 m	U (knots)	25	20	17-1/2	14	12-1/2
1000 m	U (knots)	8	6	5-1/2	4-1/2	4

* 1/2 inch towline would be unacceptable, as the assumed volume of T would exceed 50 percent of the breaking strength.

The fact that maximum towing speed is reduced at a towline diameter increase results from the assumption of maximum tension at the upper end of the towline.

The values given in Table 3 are representative of the performance that can be achieved with a fairly crude towline, and are thus considered conservative. Towing speeds at least equal to or higher than these should be readily achievable with an actual system. Also, the tension at the upper end of the towline will vary nearly as the square of the towing speed. Thus, the larger towline can be towed a little faster than shown if some increase in tension is acceptable.

Round (double-armored towline)

Assume an armored tube with the tube I.D. = 60 percent cable O.D. and wall thickness 0.1 x O.D .

The area that can be armored is:

$$\frac{\pi}{4}(t^2 - 0.8\ t^2) = \frac{0.2\ \pi\ t^2}{4}$$

Assuming $C_R = 1.8$,

$R = 1.8\ q\ t$

and the weight of unit length in water is

$$W = (1.456)\ \frac{0.2\ \pi\ t^2}{4},$$

so that

$$W = \frac{W}{R} = 1.52\ t/q\ .$$

The constants used are based on empirical data and typical construction practices.

Also

$$T_m \simeq \frac{0.2\ \pi}{4} \times 10^5\ \frac{\mathrm{lb}}{\mathrm{in}^2} \times (t\ \mathrm{in.})^2 = 15708\ t^2\ (\mathrm{in.}).$$

AN OVERVIEW OF THE RELATIONS BETWEEN PUMPING CAPACITY AND TOWING DESIGN

J. Dexter Bird and D. B. Dillon

The pumping system in an underway towed sampling system is subject to a number of constraints relating to the tow cable. The pump must provide flow at sufficient pressure and volume to provide turbulent flow of the sample within a maximum residence time in the sample delivery tube.

In order for the flow in the tube to be turbulent, the Reynolds number, VD/V, must exceed its critical value, plus an appropriate "safety factor." The critical Reynolds number is of the order of 2500; a value of 5000 is an appropriate design minimum.

The time to steam through a "patch" of water of horizontal extent X is

$$t_{\text{passage}} = X/V_s$$

The residence time of the sample in the pipe is

$$t_{\text{residence}} = \lambda \cdot Y/V,$$

where λ is the ratio of towcable length to towing depth, typically 1.5 to 2.

It has been shown that the ratio of residence time to passage time must not exceed

$$\frac{t_{\text{residence}}}{t_{\text{passage}}} \leq \sqrt{\frac{\lambda Y}{\gamma \cdot D}}$$

where γ is a "safety factor" of the order of 10. This relation ensures that samples of unlike composition are not mixed while in the sampler tube.

The pressure to pump the fluid is derived from the Darcy-Weisbach equation in the form

$$\Delta P = \frac{.45 \cdot f \cdot \lambda Y \cdot V^2}{2 \cdot g \cdot D},$$

where f is a pressure factor.

$$f = .39/R^{.25}, \quad R \geq R_c$$

Finally, the flow rate, Q, is the product of the flow speed and the area of the tube bore.

Table 4 shows the flow rate, residence, time, and pressure for 3/8" and 3/4" bore tubes at towing depths of 100 m and 1000 m. These assume that the pump is designed to supply the flow at R=5000. It is found that the residence times are consistent with the limiting values using this procedure

$$(\nu = 1.5 \times 10^{-5}\ ft^2/sec)$$

TABLE 4

	Tube Bore	
Sample Depth:	.375 inch	.750 inch
100 m	.825	1.65 gpm
	291	residence time 582 (seconds)
	42	5.3 psi
1000 m	.825	1.65 gpm
	2705	residence time 5411 (seconds)
	394	49.3 psi

PUMPING AND HYDRODYNAMIC SMEARING (LONGITUDINAL DIFFUSION)

Marshall P. Tulin

Hydrodynamic smearing determines the resolution of spatial scales that can be obtained in a sampling system.

Two sources of smearing are recognized (tube effect and storage effect). For practical cases considered, the latter is likely to be more important at depths to 300 meters and the former for depths beyond 1000 meters. Formulae follow:

Tube effect $\lambda = \frac{\sqrt{\gamma}\, L}{10} \cdot \sqrt{\frac{\rho U_o^2}{\Delta p}}$; $\beta = 10^{-1} = \frac{\sqrt{\bar{x}^2}}{\lambda^{\frac{1}{2}}}$

Storage effect $\lambda = \frac{10 U_o \mathcal{V}}{F}$ $\qquad \gamma = \frac{\lambda d(\mathcal{V}ol)}{\sqrt{\bar{x}^2}}$

$$\gamma = \frac{U_o \mathcal{V}}{\beta^{\frac{1}{2}} F}$$

for $\beta = 10^{-1}$; $F = 20$ liter/minute; $U_o = 6$ knots; $\gamma = 10$ corresponds to $\mathcal{V} = 1$ liter.

I. A resolution length of 10 m is possible with $\Delta p = 100$ psi; $U_o = 6$ knots; $L = 300$ m; $\mathcal{V} = 1$ liter; $F = 20$ liters/minute (corresponding to $\gamma = 1$).

II. Depths to 1000 m can be achieved with the same resolution length provided that F is maintained at quantities larger than 200 liters/minute (speed maintained at 6 knots and $\mathcal{V}$ at 1 liter; $\gamma = 1$).

Tube diameter in these cases will be about 3-4 cm.

CONTROLLABLE BODIES

J. Dexter Bird

Controllable bodies are feasible, with scope/depth ratios of approximately 2 to 1, at tow speeds of approximately 5 to 10 knots, with climb and dive rates of 2 to 5 meters/second. These could follow step functions or sinusoids. Present static accuracies are approximately ± 1 meter. Bottom-following systems are also feasible with present technology.

The user needs to specify his static accuracy, frequency response, overshoot, and damping requirements.

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