SEDIMENT TRAP TECHNOLOGY
AND SAMPLING

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SEDIMENT TRAP TECHNOLOGY AND SAMPLING

Report of the
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George Knauer and Vernon Asper, Co-Chairs
University of Southern Mississippi
Center for Marine Science

Hydrodynamics Subgroup: Sample Integrity Subgroup:

Wilford D. Gardner, Group Leader Cindy Lee, Group Leader

Robert Anderson
Vernon Asper
Michael P. Bacon
Cheryl Ann Butman
Giselher Gust
Susumu Honjo
Andrew Soutar

Thomas Bailey
Peter R. Betzer
Jack Dymond
Kathleen Fischer
Dierk Hebbeln
David M. Karl
George A. Knauer
Richard S. Lampitt
Rolf Peinert
Cynthia H. Pilskaln
Alan Shanks
Mary W. Silver
Merritt Tuel
Stuart G. Wakeham
Paul Wassmann

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Contents

1 Summary

2 Introduction
   2.1 What We Have Learned from Sediment-Trap Studies?
   2.2 Evidence That Sediment Traps Provide Reasonable Flux Information

3 Hydrodynamics
   3.1 Theoretical Analyses
   3.2 Trap Geometry and Spacing
      3.2.1 Diameter, Aspect Ratio and Reynolds Number
      3.2.2 Particles and Flow Field
      3.2.3 Nature of Particle Trapping Mechanisms
      3.2.4 Brine Solutions
      3.2.5 Baffles
      3.2.6 Screens
      3.2.7 Closure Mechanisms and Obstructions to Flow at the Trap Opening
      3.2.8 Flow Separation Guides (Lips)
      3.2.9 Tilt and Wave Effects
      3.2.10 Gimballed and Vaned Traps
   3.3 Field Calibrations With Independent Flux Estimates
      3.3.1 Radionuclides
      3.3.2 Sediment Accumulation Rates
   3.4 Intercomparison Experiments
      3.4.1 Santa Barbara Basin
      3.4.2 Panama Basin (STIE)
      3.4.3 Data Integrity with Respect to Oceanographic Processes
   3.5 Experimental Design and Mooring Configuration

4 Sample Integrity
   4.1 Passive Sinkers vs. Active Migrators
   4.2 Which Organisms Should Be Removed
   4.3 Swimmer Prevention
   4.4 Use of Poisons and Preservatives
   4.5 Loss/Contribution from Dissolution/Leaching
   4.6 Sample Splitting and Sieving

5 In-situ Investigations of Flux

6 Summary of Recommendations for Sediment Trap Studies
   6.1 Hydrodynamic Recommendations
      6.1.1 Long-Range Recommendations
      6.1.2 Recommendations for Immediate Application to Research Programs
   6.2 Sample Integrity Recommendations
6.2.1 Long-Range Recommendations ............................................. 54
6.2.2 Recommendations for Immediate Application to Research Programs 55

7 References

8 Appendix A: Abstracts

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Authors</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.1</td>
<td>Sediment-trap Measurement of Particle Fluxes: Effects of Bacteria and Zoo-</td>
<td>Cindy Lee, Stuart Wakeham and</td>
</tr>
<tr>
<td></td>
<td>plankton</td>
<td>John Hedges</td>
</tr>
<tr>
<td>8.2</td>
<td>Can the Effects of Swimmer Leaching in Sediment Trap Studies be Corrected?</td>
<td>George Knauer</td>
</tr>
<tr>
<td>8.3</td>
<td>The Measurement of Total C, N and P Flux</td>
<td>David Karl</td>
</tr>
<tr>
<td>8.4</td>
<td>The Use of Screens as a Potential Solution to the Swimmer Problem: Results from a Field Experiment</td>
<td>David Karl and George Knauer</td>
</tr>
<tr>
<td>8.5</td>
<td>Biological Mediation of the Oceanic Carbonate System: A Proposal Asses-</td>
<td>Peter Betzer, Robert Byrne, Gis-</td>
</tr>
<tr>
<td></td>
<td>sement                                          ............................</td>
<td>selher Gust, Kenneth Carder and</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Richard Feely</td>
</tr>
<tr>
<td>8.6</td>
<td>What is a “Swimmer”?</td>
<td>Mary Silver</td>
</tr>
<tr>
<td>8.7</td>
<td>Seasonal Variation in the “Swimmer” Problem at the VERTEX Seasonal Station in the North Pacific</td>
<td>Anthony Michaels, Mary Silver and Marcia Gowing</td>
</tr>
<tr>
<td>8.8</td>
<td>The Fecal Pellet Fraction of Open-Ocean Particle Flux: Is a Major Portion Disintegrating in the Traps?</td>
<td>Cynthia Pilskaln</td>
</tr>
<tr>
<td>8.9</td>
<td>Swimmers in the Northeast Atlantic: A Serious Impediment to Flux Estimates in the Upper Water Column</td>
<td>Richard Lampitt</td>
</tr>
<tr>
<td>8.10</td>
<td>Preliminary Results of Preservative Investigations</td>
<td>Rolf Peinert</td>
</tr>
<tr>
<td>8.11</td>
<td>Particle Sedimentation in Polar Oceans: Preservation Problems</td>
<td>Dierk Hebbeln and Gerold Wefer</td>
</tr>
<tr>
<td>8.12</td>
<td>A Non-disruptive Sieving Technique</td>
<td>Thomas Bailey, Marsh Youngbluth and Peter Davoll</td>
</tr>
<tr>
<td>8.13</td>
<td>Commercial Fishing Operations as Hazards to Sediment Traps</td>
<td>Robert Anderson and Pierre Biscaye</td>
</tr>
<tr>
<td>8.14</td>
<td>A Trap for all Seasons?</td>
<td>Wilford D. Gardner</td>
</tr>
<tr>
<td>8.15</td>
<td>Sedimentation of Particulate Matter by Marine Snow Aggregates</td>
<td>Vernon Asper</td>
</tr>
<tr>
<td>8.16</td>
<td>Settling Particles in the Oceanic Interior; Trapping Efficiency Depends Upon the Reality of the Descent Mechanism</td>
<td>Susumu Honjo</td>
</tr>
<tr>
<td>8.17</td>
<td>Flow Effects on Sediment Trap Efficiency</td>
<td>Keith Stolzenbach and Cheryl Ann Butman</td>
</tr>
<tr>
<td>8.18</td>
<td>Particle Collections in Sediment Traps: A Barometer of Horizontal Processes in the Ocean?</td>
<td>Giselher Gust, Peter Betzer and Robert Byrne</td>
</tr>
<tr>
<td>8.19</td>
<td>Understanding Sediment-Trap Performance: An Evolutionary Process</td>
<td>Giselher Gust</td>
</tr>
<tr>
<td>8.20</td>
<td>Sediment Trap Design and Ground Truth Cycle off Southern California</td>
<td>Andrew Soutar</td>
</tr>
</tbody>
</table>
8.21 Use of Natural Radionuclides to Assess Sediment Trapping Efficiency in the Field - Michael Bacon .......................................................... 84
8.22 The Easily Soluble Fraction of the Settling Particle Flux - Jack Dymond and Robert Collier ................................................................. 84
8.23 JGOFS Expert Group Recommendations - Rolf Peinert .................. 85
8.24 Measurement of Settling Particle Fluxes in the Ocean - Michael P. Bacon . 87

9 Appendix B: Attendees ........................................................................ 92
## List of Figures

1. Trapping efficiency vs. flow velocity, length of experiment, initial particle concentration and orientation of the container to the flow. 7
2. Percent weight loss on ignition of sample vs. inside diameter of cylinder with constant aspect ratio. 13
3. Outline of segregation mechanism in a narrow-mouthed compared with a wide-mouthed cylinder. 13
4. Flow in traps generated by steady flow at various Reynold's numbers. 15
5. Thickness of bottom tranquil layer for traps of various aspect ratios. 16
6. Flux vs. mean R_t measured with cylinders in a one-year experiment in the Vema Channel. 16
7. Mass flux collected during four deployments of the moored Flow Actuated Sediment Trap (FAST). 17
8. Size and density fractionation of the total flux collected by each speed interval of the moored FAST and by simultaneously deployed drifting traps. 21
9. Vertical flux measured with traps vs. horizontal flux measured and estimated from current meter data, moored nephelometer data and hydrographic data in the Vema Channel. 23
10. Effect of baffle length on performance in cylindrical sediment traps. 26
11. Relative particle collection efficiency for baffled cylinders with different aspect ratios (upper) and constant aspect ratio of 3 (lower). 27
12. Normalized flux collected in cylinders vs. tilt. 29
13. Effective tilt angle caused by the passage of internal waves. 30
14. Measured trap fluxes as a function of depth during the Santa Barbara Basin intercomparison/calibration experiment. 36
15. Sources of true and trap-measured flux. 43
16. The "Labyrinth of Doom" device for swimmer effect compensation. 45
17. Dissolved and particulate Zn and Cd collected by sediment traps. 50
18. Phosphate release from four categories of swimmers over time. 50
A.1 Total fluxes in sediment traps FS 1 (1984/1985) and FS 3 (1987/1988) in the Fram Strait. 74
A.2 Total fluxes in the Bransfield Strait, Antarctica, 1983–1985. 75
List of Tables

1 Naturally occurring parent/daughter radionuclide pairs that are potentially useful for validating sediment traps. .................................................. 32
2 Mean total C and N in preserved vs. unpreserved trap material after removal of swimmers, and total C and N values of removed swimmers. .......... 44
3 Common poisons and preservatives — advantages and disadvantages. .... 48
1 Summary

At the request of the National Science Foundation, a group of scientists experienced in sediment trap applications met to discuss the complexities of sediment trap collections. The meeting was hosted by the University of Southern Mississippi Center for Marine Science and took place on November 14–16 at USM's Gulf Coast Research Laboratory. The purpose of the meeting was to pool the considerable experience represented by the group and apply this knowledge to the solution of several difficult problems which continue to plague certain aspects of sediment trap technology. There was broad agreement by the group that sediment traps have provided important insight into many oceanic processes of which we were formerly ignorant or only partially aware, including magnitudes and rates of the downward transport of particulate materials, seasonality of downward fluxes, coupling between vertically stratified ecosystems, and water column regeneration rates. In addition, the group felt that past sediment trap research has clearly demonstrated that sediment traps perform well under a variety of conditions, and produce values which compare favorably to flux estimates derived using independent methodologies. It is therefore expected that these tools will be employed into the foreseeable future and will continue to form an integral part of the Global Ocean Flux Study.

Although the group was optimistic that traps would continue to be used extensively to determine downward particle flux, it was acknowledged that such use is not without some potentially serious problems. The most formidable of these are hydrodynamic biases in trap collections caused by the flow of water relative to the trap mouth and interference from “swimmers” (those organisms that actively swim into the trap and die and which therefore cannot be considered as part of the passively sinking particulate pool). While there is no question as to the potential seriousness of certain hydrodynamic/swimmer problems, it was the consensus of the group that these problems are tractable, at least in the ocean’s interior, and that the usefulness of sediment traps is of sufficient import to justify a continuing research effort into understanding and dealing with the complexities of the technique.

The workshop group was divided into two sub-groups: (1) The Hydrodynamics Group which dealt with the physical problems associated with trap-associated flow and (2) The Sample Integrity Group which dealt with swimmers, preservatives and sample processing. It was agreed that either problem category could dominate, depending on the environment or circumstances. Each group was charged with evaluating past results and developing sets of recommendations for both ongoing research (e.g., the JGOFS North Atlantic Bloom Study) and anticipated future programs.

The findings of each group are discussed within the text and a general set of recommendations is listed in section 6. Highlights of these recommendations are as follows:

Hydrodynamics:

1. Because hydrodynamic biases result from the flow of water relative to the trap mouth, we strongly recommend that flow be monitored and that all possible precautions be effected to minimize this flow. These precautions can include deployment in tranquil regions (where applicable), minimizing drag and/or windage on the mooring line or surface hardware when surface-tethered deployments are
used, choosing surface vs. bottom mooring configuration based on flow likely to be experienced by either configuration, and limiting the number of traps on a single mooring line in cases where that is logistically feasible and where that will reduce flow relative to each trap.

2. Laboratory (e.g., flume) and field studies are needed to further explore the performance of a given trap and/or mooring design and to explore ways of minimizing trapping biases. These studies should examine the interactions between the flow of water and trap configuration, flow within the trap, the responses of natural particles to the flow, and especially the mechanisms by which particles are retained in the trap.

3. Previous experiments indicate that cylinders appear to be the least biased collectors under the conditions in which traps have been tested. Cones, in the configurations tested, appear to experience increased flow within the trap and may also suffer sample loss from particles adhering to the sloping walls. Cylinders should be used wherever possible, but definitive assessment of properly sealed and baffled cones is recommended because they are capable of collecting larger samples.

4. In order to calibrate traps, a primary, unbiased standard is required. Given that this may be impossible, we recommend that independent estimates of vertical flux be used for comparison, including sediment accumulation rates of conservative tracers and the measured flux of appropriate radionuclides. We also suggest that a neutrally buoyant trap be developed for comparison with other mooring configurations. This trap would be expected to experience little or no flow relative to the trap mouth and thus provide an opportunity to collect samples free of hydrodynamic biases.

Sample Integrity:

1. All sediment trap samples should be examined microscopically to determine the presence of swimmers. This approach requires that at least one individual involved with each project be trained in the intricacies of swimmer recognition and moreover that a clear set of criteria be established to direct the identification process. To date, it remains unclear which organisms in the trap samples should be removed as artifactual and which ones should remain as representing true, passive, vertical flux.

2. Once identified, swimmers should be removed if possible and their products accounted for, including leached soluble material.

3. A high priority should be given to establishing means of eliminating swimmers from sediment trap collections so that the tedious process of identifying and removing swimmers can be obviated. This recommendation is of considerable importance, yet experience indicates that complete elimination of the problem might not be possible. It was recommended that scientists with expertise in zooplankton behavior and hydrodynamics engage in studies with experienced sediment trap scientists to explore possibilities in this area.
4. There was no clear consensus with respect to the appropriate use of preservatives/poisons. Because certain preservatives/poisons can interfere with analysis of the soluble pool (e.g., DOC cannot be measured in the presence of formalin), some group members felt that for short deployments (i.e., <1 week) preservatives/poisons may not be necessary. Others disagree. Clearly, the preservative/poison used will be specific to the question asked and there is therefore no universal remedy. Ongoing research is expected to suggest appropriate preservatives/poisons based on specific sampling objectives. Nevertheless, it was recognized that a significant fraction of particle-associated solutes can partition into surrounding trap solutions (e.g., C, N, P, metals). The group felt strongly that surrounding trap solutions should therefore be recovered and analyzed for the relevant solute and a correction to the flux measurement applied.

2 Introduction

Over the past decade, the use of sediment traps to measure coastal and oceanic particle fluxes and composition has proliferated. The sediment trap is currently the only existing tool for the direct measurement of settling particles in the ocean. As with many tools used in scientific research, increased usage of traps has uncovered problems associated with trap use under different conditions. This report addresses many of those problems and recommends specific solutions to some and the need for further study of others. It is clear, however, that research on particle flux using sediment trap technology has shown us that under favorable conditions, traps can be accurate. We have learned much about the importance of particulate matter in global biogeochemical cycles from this research.

Below, we will review some of the findings of past sediment trap research which are independent of problems associated with trap usage and some of the evidence showing that traps can provide accurate information under favorable circumstances. In spite of the considerable methodological problems discussed later in the report, there was universal support from members of the Working Group that sediment traps are a valuable tool in oceanographic research. We would like to emphasize here, however, that for future sediment trap research to advance our knowledge at the same rate as in the past, we need to make major progress in improving the accuracy and precision of trap-derived flux estimates. These improvements must include both trap design and sample treatment. Furthermore, we need to increase our commitment to sample replication to provide a better assessment of precision in flux data and to the investigation of approaches to assess the accuracy of flux data.

2.1 What We Have Learned from Sediment-Trap Studies?

One area where we have significantly increased our knowledge is in the understanding of mechanisms and rates of global material transfer. For example, sediment-trap studies have shown us clearly that the descent of material to the deep-sea floor is directly related to surface production and reflects the seasonality of that production (Deuser et al., 1981; Wassmann, 1984). We have learned much about the particle size distribution, residence times, and sinking speeds of particles, especially from optically monitored traps, although
considerably more work is necessary before we have a complete picture (Carder et al., 1982; Asper, 1987). It is now clear, however, that material collected in traps has settled at rates much faster than expected for individual particles, suggesting that aggregation occurs and is a major mechanism of vertical transport (reviewed in Fowler and Knauer, 1986). We have learned that flux can be episodic in nature (Honjo, 1982). In some regions, such as the polar seas, most of the annual particle flux occurs within a very short period (Bodungen et al., 1981; Wefer et al., 1988). Sediment traps have verified that substantial lateral transport of materials occurs (Honjo et al., 1982; Martin and Knauer, 1985; Walsh et al., 1988). We have a much clearer picture of the importance of atmospheric input to particle flux in the oceans (Jickells et al., 1987). The speed of dispersal processes is shown from studies showing the rapid appearance of radionuclides from the Chernobyl nuclear accident in deep water (Fowler et al., 1987; Buessler et al., 1987).

A major area of progress is in the description of water-column processes. We now know that fresh, labile materials, both organic and inorganic, are present at mid-ocean depths (Coale and Bruland, 1985; Wakeham and Canuel, 1988). For example coccoliths are present at depths below the zone of dissolution, suggesting rapid transport (Honjo, 1976). We also have evidence of mid-depth diagenesis, dissolution and decomposition, as well as production (Lee and Cronin, 1982; Karl et al., 1984; Lee and Wakeham, 1987). Mid-depth maxima in organic compound concentrations, biological activity, and fecal pellet production all point to a more dynamic deep water column than previously realized (Urerre and Knauer, 1981; Karl and Knauer, 1984; Wakeham and Canuel, 1988). Not all of these findings are unique to sediment-trap technology, but in each case, our knowledge has been considerably enhanced by their use.

One of the unique contributions of sediment trap studies has been our increased knowledge of large particle composition and morphology. We have become aware of the wide spectrum of material in transit towards the sea floor and the great biological complexity, particularly on a latitudinal basis (see Peinert et al., 1989). Our knowledge of the interaction between living organisms and detrital material has been considerably enhanced, as well as our understanding of the interactions between small and large particles (reviewed in Alldredge and Silver, 1988). We are just beginning to learn about the potentially great significance of transfer between particulate and dissolved phases (Coale and Bruland, 1985; Lee and Wakeham, 1987; Karl et al., 1988). We have learned much about biological processes in the sea. As well as examples given above, we have learned more about life histories of many organisms (Smetacek, 1985; Noji et al., 1986; Bernstein et al., 1987; Reid, 1987). The export of material from specific upper water column food chains is clearly seen from sediment-trap studies, as is the episodic nature of individual species growth and removal (Honjo, 1982; Bodungen, 1987).

2.2 Evidence That Sediment Traps Provide Reasonable Flux Information

Various studies of the vertical transport of material using sediment traps have provided results which agree with data obtained using different scientific approaches. This suggests that fluxes derived from traps are "reasonable" for specific particles, chemical compounds, time periods or ecosystems. Below we present a sampling of studies which support the use
of traps for collecting the passive downward flux of particulate materials; the list is not intended to be exhaustive.

- Estimates of radionuclide production and distribution in the ocean agree well with the nuclide fluxes measured by traps (Knauer et al., 1979; Lorenzen et al., 1981; Coale and Bruland, 1985; Bacon et al., 1985; Biscaye et al., 1988).

- Calculations of new production based on swimmer-picked sediment trap N collections agree reasonably well with new production estimates using N-15 (Knauer and Martin, 1981; Knauer et al., 1988; Knauer et al., submitted). Recently, Small (et al., pers. comm.) working in Santa Monica Basin, CA, have also obtained excellent agreement between estimates based on sediment trap N collections and those based on rates of nitrate assimilation.

- Comparisons between the measured rain rate of refractory elements (Al, Th, Ti) and the accumulation rates of these elements in sediments are generally in good agreement (Dymond et al., 1981; Dymond, 1984; Dymond and Lyle, 1985; Fischer et al., 1986).

- Sediment trap Mn fluxes obtained by Martin and Knauer (1984) are sufficient to account for the excess Mn accumulating on the sea floor calculated from other independent studies (e.g., Bender et al., 1970).

- Using water column Mn standing crop and sediment trap Mn data, Martin and Knauer (1980) calculated a water column Mn residence time of 60 y. This agrees well with residence times of 53 y (Bewers and Yeats, 1977) and 51 y (Weiss, 1977) measured by independent methods.

- Correlations between alkalinity fluxes and dissolution of calcareous tests are found in the Pacific and Atlantic Ocean (Betzer et al., 1984b; Almogi-Labin et al., 1988).

- Oceanic dissolved inorganic carbon profiles are correlated with the attrition of particulate carbon flux versus depth (Viecelli, 1984).

- The supply of mineral aerosol particles like dust and sand to the sea surface of the Pacific matches well with the flux measurements from mid-water sediment trap collections (Betzer et al., 1988).

- Combined long-term estimates of benthic mineralization and carbon accumulation fit well to carbon fluxes in shallow, coastal areas (Hargrave, 1978; Wassmann, 1984) and in the deep sea (Emerson et al., 1985).

- An obvious relationship exists between estimates of total primary production and POC sedimentation out of the euphotic zone, both spatially and seasonally (Suess, 1980; Deuser et al., 1981; Ittekkot et al., 1984 a, b; Betzer et al., 1984b; Lee and Cronin, 1984; Deuser, 1986b; Pace et al., 1987; Wassmann, 1988).

The examples mentioned above indicate that sediment traps have provided both quantitative and qualitative data about particles and are suitable for more quantitative measurements (e.g., the vertical flux of particulate matter in the sea), in spite of the problems
associated with their use. No other suitable alternative to sediment traps exists, although pumping systems have been suggested. However, the relationship between the sizes and settling rates of the large particles important for the vertical flux (e.g., marine snow) contains considerable scatter, and measurements of the distribution of particulates and their size classes cannot be reliably converted into sedimentation rates. Results from filtration of large volumes of water at various depth intervals must therefore be used with extreme caution when used to estimate vertical flux.

The following discussion is focused on some of the problems which have been encountered in the use of sediment-trap technology currently. The text is divided into two sections, hydrodynamics and sample integrity, followed by a listing of recommendations for further study and current research.

3 Hydrodynamics

Proper use of sediment traps and correct interpretation of results require that potential collection biases be recognized, understood, minimized, and, where possible, eliminated. Two basic questions about the use of traps are:

1. Can traps yield an unbiased, quantitative measure of the total gravitational flux of particles through a given horizontal plane if suitably designed for a given oceanic environment?

2. Do traps yield samples that are quantitatively unbiased with respect to chemical, mineralogical and biological composition of settling material?

Traps in any current obstruct and alter the flow field. Under most conditions observed in the laboratory and field, this results in the generation of eddies at the top of the trap. The size and frequency of eddy formation and the flow structure within a trap varies with trap geometry. These complex flow patterns generate vertical velocities much greater than the typical fall velocities of most marine particles, making it difficult to predict the behavior of particles in the vicinity of a trap. Theoretical analyses of biased trapping mechanisms and conditions can suggest hypotheses to be tested, but quantification of trap biases can be achieved only through experiments under controlled or measured flow and particle conditions.

Two early reviews of sediment trap methodology (Bloesch and Burns, 1980; Blomqvist and Håkanson, 1981) and an annotated bibliography of papers using sediment traps prior to 1980 (Reynolds et al., 1980) have suggested criteria for selecting and deploying an unbiased collector, but these recommendations were based on very few quantitative studies specifically of hydrodynamical trap biases. At that time, for example, there were only two published studies (Hargrave and Burns, 1979; Gardner, 1980a) of traps collecting natural sediments under controlled conditions in a laboratory flume (e.g., see Fig. 1). Recent work on the dynamics of sediment trapping has been consistent with the earlier findings, but has also provided a more complete theoretical framework for studying trap biases (Butman et al., 1986), as well as quantitative studies of specific biased trapping effects both in the laboratory (Butman, 1986; Hawley, 1988) and in the field (e.g., Gardner, 1985; Farmenter et al., 1983; Baker et al., 1988).
SEDIMENT TRAPPING EFFICIENCY

- 4.0 - 4.5 cm/sec
- 9.0 - 9.5 cm/sec
- STILL WATER IN FISH TANK
- 4.3 cm/sec WITH TRAPS ROTATED DURING EXPERIMENT

Figure 1: Trapping efficiency for a variety of traps tested under conditions differing in flow velocity, length of experiment, initial particle concentration and orientation of the container to the flow (Gardner, 1980a).
In this section, we review some of the major findings of previous theoretical and empirical (laboratory and field) studies of particle trapping in flows. A complete listing and detailed discussion of the implications of these studies are beyond the scope of this workshop report. We will instead discuss what we feel are the most significant parameters of interest, give examples of studies relating these parameters to trapping efficiency and discuss the limitations to these studies. We will also provide recommendations for trap use in the near future, in light of known (or highly suspected) hydrodynamic biases, and recommendations for future research in this area. The results are discussed by topic (e.g., biases associated with trap geometry, diameter, baffling, etc.), rather than by method (e.g., laboratory versus field studies). Calibrations are most easily made in the laboratory because of the difficulty in obtaining an independent, unbiased estimate of particulate flux in the field on the same time scale as trap deployments. In the field, time scales for calibrations of traps range from thousands of years for comparisons in areas with low sedimentation rates based on radionuclide dating (e.g., Gardner et al., 1985) to tens of years in areas with high sedimentation rates based on radionuclide dating (Soutar et al., 1977; Bruland et al., 1981; Dymond et al., 1981) or marker horizons (Pennington, 1974), to annual rates based on varves in anoxic basins (Soutar et al., 1977; Brunskill et al., 1984; Naes et al., 1988) or production rates of radionuclides in the water column (Brewer et al., 1980; Lorenzen et al., 1981; Anderson et al., 1983; Bacon et al., 1985; Fisher et al., 1988). Confidence increases in these sorts of calibrations as the time scales of methods converge, but all of the methods have limitations (see section 3.3.2). The bulk of information on hydrodynamic biases comes from field studies where comparisons are made between traps of different geometries, but where the true flux of particulates is not known to better than a factor of two and sometimes not at all. An advantage to field studies is that no scaling assumptions need to be made about trap or particle dynamics, whereas in the laboratory, these are sometimes necessary.

It is important to recognize from the outset the strengths and weaknesses of laboratory versus field studies of particle trapping, and to view them as complementary, rather than competitive or alternative, techniques. Laboratory studies in a moving fluid (e.g., in a flume or wind tunnel) have the advantage of providing a controlled flow and particle environment for evaluating specific hydrodynamic effects, and they also allow for direct and accurate evaluation of results. Flume studies are also free from most biological effects (i.e., swimmers, fouling, etc.) which can complicate in situ hydrodynamic measurements. They are limited, however, by the range of field conditions that can be reasonably mimicked in the laboratory, and are constrained by boundary layer dynamics. To date, all laboratory studies except one (Hawley, 1988) have been done only in unidirectional, steady flow, and while effects of bidirectional, oscillatory flow can be studied (in a wave tank, for example), it is unlikely that laboratory conditions will ever mimic the complex, multidirectional, and unsteady (at many time and space scales) flow, turbulence, and mixing characteristics of many ocean environments where traps have been and are likely to be deployed. Furthermore, it is difficult (and in some cases, likely impossible) to simulate certain kinds of natural particles, using physical mimics, in the laboratory. This is particularly true for aggregates. The advantage of field studies is that traps can be tested within the natural flow and particle regimes, but in most cases, the true particulate flux cannot be defined on similar time scales. Even the flow and particle environment in the water approaching a trap may be difficult (or exorbitantly expensive) to monitor at the proper time and space scales to evaluate
3.1 Theoretical Analyses

Theoretical discussions of sediment-trap biases have appeared in several papers throughout the years with formal treatments given in Hargrave and Burns (1979), Bloesch and Burns (1980) and Butman et al. (1986). The latter provided the most encompassing dimensional analysis of the physical variables that affect particle trapping, a control-volume analysis of the mass flux into and out of the traps, and a description of particle behavior within the trap flow field. Following a critical review of the laboratory studies previous to Butman (1986) and Hawley (1988), Butman et al. (1986) also presented several physical models to account for hydrodynamic biases observed in the reviewed trap calibration studies.

The dimensional analysis of Butman et al. (1986) identified six dimensionless parameters which may be used as guidelines to estimate collection efficiency. Of these, only three were shown by dimensional analysis to be important under typical trapping conditions in the ocean: (1) the trap Reynolds number, \( R_t = uD/\nu \), where \( u \) is the flow at the height of the trap mouth (the average speed measured by a current meter in the field), \( D \) is the outside diameter at the trap mouth and \( \nu \) is the kinematic viscosity (ratio of fluid viscosity to fluid density), (2) trap aspect ratio, \( A = H/D \), where \( H \) is the trap height and \( D \) is the inside diameter at the trap mouth, and (3) the ratio of flow speed to particle fall velocity, \( u/W \), where \( W \) is the gravitational sinking speed of the particles. For noncylindrical collectors, trap geometry, which was not parameterized by Butman et al. (1986), is also expected to be an important determinant of collection efficiency. The control-volume analysis and results of empirical flume studies guided predictions regarding the dependence between the dimensionless parameters and collection efficiency. For fixed values of the other two parameters, the collection efficiency of cylinders (for \( A>1 \)) was expected to:

1. decrease over some range of increasing \( R_t \),
2. decrease over some range of increasing \( u/W \), and
3. increase over some range of increasing \( A \). For fixed values of \( R_t \), \( u/W \) and \( A \) (where applicable), and relative to cylinders with the same mouth opening,
4. small-mouth, wide-bodied traps were expected to be overcollectors, and
5. funnel-type traps (hereafter called "cones") were expected to be undercollectors.

Results of the flume calibration studies of Hargrave and Burns (1979), Gardner (1980a) and Butman (1986) support all of these predictions except (2), which has not been systematically tested in the laboratory. The conditions tested in the flume studies were relatively narrow, however, encompassing \( R_t \) of 500–20,000, \( A \) of 1–3.7, and using only natural (fine) sediments or glass beads, but not, for example, particles simulating natural aggregates. The biases demonstrated cannot be generalized beyond the parameter range tested. The flow-visualization studies of Gardner (1980a) and Hawley (1988) provide observations of flow behavior in traps for \( R_t \) up to 30,000 and \( A \) up to 8. Dimensional analysis has not been used to quantify the geometry of cones. One could simply use the dimensionless parameter...
of slope or use a ratio of the cone mouth diameter to cone height to obtain a dimensionless parameter of cone aspect ratio, $A_c$. No empirical experiments have been made of the trapping efficiency of cones as a function of $A_c$ or $R_t$. However, numerous field studies provide direct or ad hoc evidence supporting or refuting the theoretical and laboratory results. The evidence for and against specific biased trapping effects (i.e., as a function of the dimensionless parameter that was varied) is summarized in the sections that follow.

3.2 Trap Geometry and Spacing

In the field, flow can approach a trap from any direction, so symmetry of the trap is required to maintain uniform flow dynamics in the trap. Furthermore, the spacing of replicate traps both parallel and perpendicular to the mean flow determines the extent to which they may be influenced by the disturbed flow field of a neighboring trap, and thus, be collecting under different conditions than the other so-called “replicates”. It has been shown empirically and suggested by potential flow theory that a minimum of three trap diameters cross-stream and ten diameters downstream are required to eliminate trap-trap flow interactions (Butman, 1984).

Flow visualization studies under controlled conditions have resulted in the following qualitative observations. Traps obstruct flow, causing water to accelerate around traps to conserve net water movement. Acceleration of the flow over the top of an open trap results in decreased pressure in that region, which draws water out of the trap at its leading (upstream) edge. In addition, the drag produced by the trap edge slows down the flow near the trap, producing a shear zone. If the pressure gradient and shear over the trap are sufficiently large, eddies develop. Depending on the geometry and $R_t$, the eddies can either spin off into the downstream flow, plunge completely into the downstream end of the trap opening, or break on the downstream edge of the trap, with only a portion of the water entering the trap. The areas where fluid enters and leaves the trap are not always equal and change with $R_t$. Within a trap the fluid develops internal flow fields which depend on the geometry of the trap. Flow structure at the top of cylinders and cones is similar in that near the upper trap a primary circulation cell develops with depth of penetration being a function of $D$ and $R_t$ and the degree of turbulence being much greater than in the approaching fluid. Beneath the primary cell a complete or partial counter-rotating secondary cell may develop (depending on $R_t$, from which fluid parcels break off intermittently and move deeper into the trap. Beneath this regime a tranquil layer of fluid may be found depending on $A$ and $R_t$ as will be discussed later.

The structure, strength and flushing rates below the primary cell are generally much larger in cones than in cylinders, though this needs to be examined as a function of $R_t$. The secondary cell in a cone also appears to have higher turbulence and shear than in a cylinder. Details of the internal flow and turbulence levels and their effect on particle behavior are being investigated by G. Gust at the University of South Florida (see appendix A). Soutar et al. (1977) reported that the insertion of deep baffles within a trap eliminated the large-scale secondary flow within a trap, but this has not been reproduced by later observations of flow past baffled traps (Gardner, 1980a; Gust, unpublished data).

At least six studies have shown that small-mouth, wide-body traps were overcollectors relative to cylinders (Pennington, 1974; Hargrave and Burns, 1979; Gardner, 1980a, b;
3.2 Trap Geometry and Spacing

Butman, 1986; Butman et al., 1986). In flume experiments unbaffled cones were relative undercollectors, as predicted, but the baffled cones tested by Gardner (1980a) in a very low-\(R_t\) environment (2,000–6,000) had collection efficiencies similar to cylinders with the same mouth diameter.

Cylinders and cones fulfill the requirements of axial symmetry. However, some flume and field experiments (e.g., Gardner, 1980b and Butman, 1986) indicate that baffled cones with \(A_c \approx 1\) undertrap particles, especially fines, but tests have not been made on cones that are scaled to the geometry of large cones with \(A_c \approx 2\) (Honjo and Doherty, 1988; Bruland et al., 1981; Staresinic et al., 1982) now used in the field. There is also independent evidence from field studies that large baffled cones (\(A_c \approx 2\)) collect particles at the rate at which they settle in low-energy environments (Soutar et al., 1977; Honjo, 1982; Dymond et al., 1981; Bruland et al., 1981; Bacon et al., 1985; Brewer et al., 1980, see sections 3.3 and 3.4).

Even though there is evidence that cones with \(A_c \approx 1\) may be undercollectors under certain environmental conditions, they are widely used because they have the advantage of a large surface area that can concentrate a large sample into a small collection cup where it can be preserved and processed more easily. Furthermore, they are generally deployed in low-energy environments (i.e., the deep ocean) where there is evidence that they are unbiased collectors. We emphasize, however, that only a very limited number of cone geometries have been calibrated in the laboratory and they do not include the traps proposed for use in GOFS and JGOFS. The ability of cones to concentrate samples has led many investigators to attach cones to the bottom of cylinders, or put cones inside of cylinders, further complicating attempts to compare trapping characteristics of a particular trap design compared with calibrated geometries.

**RECOMMENDATION:** Only axially symmetric traps should be used and when replicates are deployed together, they should be adequately separated from one another to avoid trap-trap interactions. Small-mouth, wide-body traps should not be used to obtain estimates of particulate flux, since they have been shown to be relative overcollectors in all calibration studies to date. Likewise, unbaffled cones have been shown to be relative undercollectors and should not be used. There is insufficient evidence to evaluate the potential biased sampling characteristics of baffled cones in high-energy environments, but results from tests in low-energy environments indicate that certain cone and baffle configurations may be unbiased collectors and, thus, may be used with caution in these environments. Because of the advantages of cones for long-term deployments (i.e., that they concentrate samples), further laboratory calibration and field studies are needed on scaled versions of the cones used in the field collecting under all conditions.

### 3.2.1 Diameter, Aspect Ratio and Reynolds Number

As discussed earlier, two important dimensionless parameters in trap analysis are the Reynolds number (\(uD/\nu\)) and aspect ratio (\(A\)). Because changing trap mouth diameter (\(D\)) changes both the Reynolds number and the aspect ratio, calibration studies which simply test varying trap diameters have varied two dimensionless parameters simultaneously (\(R_t\) and \(A\)). Only one dimensionless parameter should be varied while holding the remaining constant in order to systematically test for the dependence between each parameter and
trapping efficiency. Most experiments have failed to do this, so it is difficult to determine whether observed changes in efficiency are related to $R_t$ or $A$. Because $R_t$ and $A$ are so closely linked in most experiments, their effect will be discussed together in this section.

The one laboratory calibration study (Butman, 1986) where trapping efficiency as a function of aspect ratio was tested with $R_t$ held constant, involved cylinders with $A$ up to 3.7. This study showed an increase in efficiency as a function of $A$, with mean efficiencies leveling off between $A$ of 2.7 and 3.7 ($R_t = 10,000$). The coefficient of variation, however, also increased with increasing $A$. Field studies of trapping efficiency as a function of $A$ up to 6 (Gardner, 1980b) and 10 (Blomqvist and Kofoed, 1981) with $R_t$ being equal (but not necessarily constant since current was not measured throughout the experiments) show an increase in efficiency until the aspect ratio exceeds 3–5, with the upper value corresponding to larger $R_t$. The mechanism by which particles are retained inside of traps allows increased particle retention until $A$ is sufficiently large, after which the dynamics of particle retention are constant.

Butman (1986) also conducted trapping efficiency experiments in a flume as a function of $R_t$ and changed $R_t$ by varying trap diameter, while holding $A$ constant. Dimensionally this is the same as varying $R_t$ by varying $u$. However, in predicting trap efficiency one is predicting the behavior of particles within a turbulent flow, so the above hypothesis should be verified by empirical tests before it is universally applied especially since $u/W$ will also change when $u$ is changed. This study showed that collection efficiency decreased by a factor of 2 when $R_t$ was increased from 2,000 to 5,000 and then leveled off for $R_t$ up to 20,000. One caveat is that the diameter of the smallest trap tested was 1.8 cm, and this was the only trap with a collection efficiency significantly different from the others.

In the field study of Blomqvist and Kofoed (1981) cylinders less than 3–4 cm in diameter were biased collectors relative to the larger diameter cylinders ($A = 8$, $D = 1–31$ cm) tested on a given deployment. The small cylinders overcollected organic-rich particles (Fig. 2) and undertrapped mineral matter (i.e., high density material), contrary to hypothesis (2) of Butman et al., (1986) listed above, suggesting that some trapping mechanism may be peculiar to cylinders with very small diameters. Blomqvist and Kofoed suggested that higher-density particles were being centrifugally spun out of eddies at the top of narrow traps rather than being carried into the trap with the low-density organic matter (Fig. 3). No other biasing was noted for cylinders up to 31 cm in diameter. The true flux of particulates is not known in Blomqvist and Kofoed’s field study so whether or not the small-diameter cylinders are absolute overcollectors is not known. They did not measure velocity during the deployments, but have numerous current measurements from other times, so while $R_t$ is unknown, the measurements at other times provide constraining values, as will be discussed later.

A recent study of the structure of flow within cylinders as a function of Reynolds number (Hawley, 1988) tested cylinders with diameters of 1.3 to 10.2 cm, aspect ratios of 1 to 8, and Reynolds numbers of 500–20,000 (Fig. 4). Hawley noted the depth of penetration of the eddies (from 1 trap diameter at low $R_t$ to a maximum of 2.5 trap diameters at $R_t = 20,000$), and plotted the thickness of a bottom tranquil layer as a function of $R_t$ for $A$ of 3, 5, and 8 (Fig. 5). The tranquil layer ceased to exist at $R_t = 6,000$ for $A = 3$ and at 8,000 for $A = 5$, but for $A = 8$ the tranquil layer was still one trap diameter from the bottom of the trap at $R_t = 20,000$. It has been pointed out that this tranquil layer is important
3.2 Trap Geometry and Spacing

Percent Wt. Loss on Ignition

![Graph showing percent weight loss on ignition vs. cylinder diameter with data points labeled I, II, III, IV, V.](image)

Figure 2: Percent weight loss on ignition of sample vs. inside diameter of cylinder with constant $A = 8$ (data from Blomqvist and Kofoed, 1981).

![Diagram comparing segregation mechanism in narrow-mouthed and wide-mouthed cylinders. Compact particles are hurled beyond the narrow-mouthed trap, while light, voluminous matter moves with the eddy into the trap.](image)

Figure 3: Outline of segregation mechanism in a narrow-mouthed compared with a wide-mouthed cylinder. Compact particles (mineral matter) are hurled beyond the narrow-mouthed trap, whereas light, voluminous matter moves with the eddy into the trap (from Blomqvist and Kofoed, 1981).
in the particle trapping process (Gardner, 1980a, 1985; Butman et al., 1986). Hawley's observations were made 10–15 minutes after the start of each experiment — an interval comparable to that used by Lau (1979) and Butman (1986), but in a 3 hour experiment he noted that the tranquil layer thickness continued to decrease through the first hour, after which it remained constant, so the thickness of bottom tranquil layers at equilibrium may be even less than stated.

In an attempt to utilize a very large natural flume and to get outside of boundary-layer flow, traps were deployed for one year in the Vema Channel of the South Atlantic where currents were expected to be fairly steady, but not uniform across the channel (Gardner et al., 1981). Identical traps were exposed to different regions in the channel where mean velocities ranged from 1.7 to 21.9 cm/sec. The traps were cylinders \((A = 3, D = 30 \text{ cm})\), with baffles whose cells were 1 cm wide \(\times 5 \text{ cm deep}\), but in the bottom one diameter height of the cylinder was a cone that emptied into a poisoned sample jar. The mean \(R_t\) during the experiment ranged from 2,500 to 33,000, but the fluxes measured in the traps did not exhibit the decrease in efficiency shown over that range by the laboratory experiments of Butman (1986); in fact there was a slight increase over the upper range, but lack of replicates prohibits statistical verification (Fig. 6). Whether the difference between the laboratory and field experiments reflects a difference between laboratory and field conditions (glass beads vs. natural particles, boundary-layer vs. free-stream flow), the use of baffles in the field traps, or the use of small-diameter cylinders in the laboratory experiments cannot be determined from the data.

A novel field study by Baker et al. (1988), however, does agree with Butman et al.'s (1986) hypothesis and Butman's (1986) laboratory results that trapping efficiency decreases over some range of increasing \(R_t\). Baker et al. used traps of identical geometry on a mooring and on a drifting buoy in a channel experiencing significant tidal flow. Particle concentrations were homogeneous on the tidal excursion length-scale. The traps were equipped with rotating sample collectors which, for the moored trap, was interfaced with a current meter so that samples could be fractionated according to intervals of current speed \((<12, 12-30, 30-50, \text{ and } >50 \text{ cm/s})\). The floating traps integrated over fixed time intervals. The material collected in these “speed-fractioning traps” was normalized to the material collected in the drifting traps for closely overlapping times. The measured flux in the moored trap was observed to decrease as current speed, and thus \(R_t\) increased, and the estimated average settling velocity of trapped particles increased as speed (and \(R_t\)) increased. In contrast to the moored traps, the drifting traps showed neither of these trends. Despite the strong biases demonstrated at the higher current speeds, it was shown that the agreement between drifting and moored traps was within 10% when mean channel speed was <15 cm/s and the accumulated duration of speeds <12 cm/s was >60% of the deployment period. These are important and encouraging results for ocean trapping since currents in deep water are generally <15 cm/s.

In contrast to Butman's (1986) study, Baker et al. (1988) found that efficiency decreased between a mean \(R_t\) of 5,000 and 30,000, leveling off for \(R_t\) up to 100,000 (Fig. 7). Because of the trap mouth diameter (20 cm) and speed range for the slowest flow interval (<12 cm/s), Baker et al. could not resolve efficiency changes for \(R_t\) of <20,000. They considered collections under these relatively low \(R_t\) conditions to be “unbiased” because they agreed well with efficiencies obtained from their free-drifting traps. It is possible, however, that at the
Figure 4: Flow in traps generated by steady flow at various Reynold's numbers. For a–c, A = 5; for d, A = 3. $R_f = 4,300$ for a, 8,000 for b, 10,000 for c, and 6,000 for d (from Hawley, 1988).
Figure 5: Thickness of bottom tranquil layer from observations in Hawley (1988). Squares are for A = 8, triangles for A = 5 and circles for A = 3 in steady flow.

Figure 6: Flux (mg/m²/day) vs. mean $R_t$ measured with cylinders ($A = 3$, with a cone and sample jar in the bottom 1D) in a one-year experiment in the Vema Channel (Gardner et al., 1981). No decrease in flux is observed over the $R_t$ range where Butman (1986) observed a decrease in flume experiments, but $R_t$ was not constant in the Vema Channel.
3.2 Trap Geometry and Spacing

Figure 7: Mass flux collected during four deployments of the moored Flow Actuated Sediment Trap (FAST) suffered a sharp decrease with increasing current speed (open symbols), whereas the mean flux collected by the drifting trap over the same current speed was relatively uniform (closed symbols). (From Baker et al., 1988.)

lowest $R_t$ ($2,000$) tested by Butman (1986) (corresponding to the smallest cylinders tested by Blomqvist and Kofoed (1981)), collection efficiency is again biased. In this case, the relative over-collection might be due to a physical trapping mechanism other than the one operating at higher $R_t$ ($>30,000$), where Baker et al. (1988) showed traps to be relative undercollectors. This would indicate a fairly narrow range of $R_t$ ($2,000 < R_t < 30,000$) for which traps would be unbiased collectors. Severely complicating a comparison of the results of Butman, Blomqvist and Kofoed, Gardner et al., and Baker et al., however, is the fact that cylinders were used in the first two studies, a cone was at the bottom of the cylinder in the third study, and a steep-walled (minimum slope = $73^\circ$) asymmetric cone ($A_e = 3.9$), placed inside a cylinder was used by Baker et al. This underscores the need for systematic studies of $A$ and $R_t$ effects using the specific trap designs that are intended for use in the field.

Other studies (e.g., Blomqvist and Kofoed (1981), Bothner et al. reported in Parmenter et al. (1983), Staresinic et al. (1982), Eadie (1988), and many others) have contributed useful information. Each of these studies, however, was compromised by an incomplete data collection plan; in each case either the currents were not known or several parameters were varied simultaneously. These studies will not be discussed here except to underscore the requirement for systematic studies of $A$ and $R_t$ effects using the specific trap designs that are intended for use in the field.

In summary, a general theory for particle collection by traps has been successful in predicting trap biases as a function of certain dimensionless parameters that can be tested under controlled laboratory conditions. Results of the flume calibration studies have been...
successfully extended to a wider parameter space by field experiments specifically designed to test theoretical predictions and empirical laboratory results, but are limited thus far by the vast differences in the trap designs tested between the laboratory and field. Furthermore, the flume calibration studies and subsequent field tests are few and cover a relatively narrow range of environmental conditions ($R_t$ and particle types) and trap designs. Further studies obviously are needed to define the types of traps and range of conditions ($R_t$, $A$, $u/W$) for which unbiased collections would be expected.

**RECOMMENDATION:** When using cylinders, the Reynolds number of the environment should be used to select an aspect ratio sufficiently large to maintain a tranquil layer of fluid at the trap bottom. Hawley's (1988) studies of fluid motion in traps indicate that $A = 3$ would suffice up to $R_t = 6,000$ (about 6 cm/s for $D = 10$ cm), $A = 5$ up to $R_t = 8,000$ and $A = 8$ is sufficient for at least $R_t = 20,000$ (about 20 cm/s for $D = 10$ cm), but quantitative laboratory studies with particles and follow-up field studies are required to test the fluid observations.

Cylindrical traps have been calibrated over only a narrow range of Reynolds numbers (2,000 to 20,000), so more experiments are needed to increase the range over which we can predict the effects of flow on trapping efficiency of cylinders. This is particularly important since large diameter traps have a relatively high $R_t$ even collecting in low velocity fluid. Oceanic conditions with relatively high $R_t$ ($>10^5$), a wide range of particle types and size classes, and traps with high $A$ ($>3$), remain to be studied quantitatively. The results of Blomqvist and Kofoed (1981) suggest that cylinders less than 3–4 cm in diameter are biased collectors and should not be used in making quantitative flux estimates, particularly with respect to composition.

The range of Reynolds numbers and $A_c$ over which cones have been tested is also small. More laboratory and field experiments need to be made with conical traps to determine their trapping efficiencies as a function of flow processes since this trap geometry is advantageous for collecting and concentrating large samples. For the short term, rather than making hydrodynamic tests on a complete range of cone geometries, it may be easier to simultaneously compare collection rates in calibrated cylinders with collection rates in conical traps, especially existing conical traps.

### 3.2.2 Particles and Flow Field

Laboratory and theoretical studies (Murray, 1970; Jobson and Sayer, 1970; Lande and Wood, 1987) have shown that the gravitational settling velocity of particles may be affected by turbulence. Turbulence and mixing are most frequently encountered in surface and bottom boundary mixed layers where significant turbulent energy is introduced or dissipated. No studies have been performed to determine whether the intensity of oceanic turbulence away from boundaries is sufficient to significantly alter the gravitational settling velocity of particles, especially the particles and aggregates with settling velocities of 10's–100's m/day which are responsible for the flux of particles. Until turbulence in the oncoming flow is measured over the applicable time and space scales, we will assume that it is reasonable to ignore the effect of turbulence on settling particles in most environments. Instead, we expect that the advective (horizontal or streamwise) flow approaching the trap mouth
3.2 Trap Geometry and Spacing

controls the trap-internal recirculation patterns which in turn govern the accumulation of particles inside traps.

The trap-induced flow overwhelms turbulence in the environment unless the scale of natural eddies have vertical structure on the order of the size of the trap (i.e., if a passing eddy would impose large positive and negative vertical velocities on the flow field). In nearly all cases the average current speed in the flow approaching the mouth of the trap is the important flow variable to use in dimensional analysis to predict the flow structure and particle trapping characteristics of a particular trap.

It has been well established that individual, fine particles settle too slowly in the oceanic water column to contribute substantially to the vertical flux. Only when incorporated in some kind of aggregate (fecal pellets or marine snow) do they begin to settle at significant rates. In accordance to Stokes’ law, these aggregations serve to increase the sinking speed by: 1) increasing the effective radius of the particles (and therefore decreasing total drag), and 2) by increasing the bulk density of the particles by excluding interstitial water.

Although direct, in situ observations of these phenomena are rare (Asper, 1988), indirect evidence to support this inferred acceleration of sinking speeds includes the covariance of surface productivity events (Deuser and Ross, 1980), observations of the phase-lagged arrival of small particles at shallow and deep time-series sediment traps in the PARFLUX program (e.g., Honjo, 1982), delivery of undecomposed algal material to deep (4,000 m) sediment traps (Billett et al., 1983), and short time lags between phytoplankton blooms and the arrival of ‘phytodetritus’ on the sea floor (Lampitt, 1985). While fecal pellets may be quite important in some areas and seasons, they are generally responsible for less than 10–20% of the mass flux.

Marine snow recently has been shown to provide an alternative mechanism of rapid vertical transport of fine material under a variety of conditions. These aggregates are extremely delicate, however, so that most sediment trap and water bottle samples bear no morphological resemblance to the aggregates which existed prior to the sampling operation. The consequence of this alteration is that it is impossible to calculate the speed at which the aggregates were sinking from the size distribution of the partially disaggregated constituent particles.

The extreme friability of these marine snow aggregates prevents the application of standard oceanographic sampling methods to their study. Most successful techniques employ either hand collection via SCUBA techniques (limited to the surface waters) or non-contact photographic techniques. Recent applications of these techniques to measure sinking speeds (Asper 1987; Asper, 1988; Shanks, unpublished; Alldredge and Gotschalk, 1988) have shown that considerable scatter exists in a plot of aggregate size versus sinking speed, and that only when the dry weight of the aggregate is measured can a good relationship to sinking speed be shown.

For sediment trapping operations, the importance of these observations is the following:

1. Turbulence associated with interactions between the flow and the trap structure may be sufficient to destroy aggregates and alter their sinking characteristics within the trap.
2. Therefore, actual sinking speeds of particles approaching sediment traps will likely be significantly different than those predicted from the size distributions of the trap particles determined after recovery.

Although determination of the in situ size spectra from sediment trap material is unlikely, it is nevertheless worthwhile to wet-sieve samples in an attempt to determine relative biases in particle size or density under a variety of flow conditions and trap configurations. For example, Baker et al., (1988) used a Flow Actuated Sediment Trap (FAST) to test whether changes in the current speed, and thus $R_t$, would affect the total mass collected and the particle size and density distributions. Results from three deployments are summarized in Fig. 8. The relative flux of particles with density $>1.65$ g/cm$^3$ showed a pronounced shift from fine-grained particles at speeds $<12$ cm/s to particles with diameters $>125$ μm at speeds $>50$ cm/s. The relative flux of all size classes of particles with density $<1.65$ g/cm$^3$ decreased as current speed increased. The similarity of the size/density distributions from the $<12$ cm/s moored FAST sample and the drifting traps reinforces the conclusion that the efficiency of the moored trap at low speeds is close to 100% (Baker et al., 1988).

Furthermore, Baker et al. (1988) computed the fall velocity for each of five particle size classes from $<38$ μm to $>250$ μm and then for three moored FAST deployments compared the change in absolute flux between the $<12$ cm/s speed class and each of the other three speed classes. Each deployment found a consistent trend of decreasing efficiency with decreasing fall velocity. For particles with $W < \sim 3$ cm/s (2,600 m/day), most of the efficiency decrease occurred between $<12$ and the 12–30 cm/s samples, with additional flux decreases at higher speeds accounting for $<10\%$ of the total. These are the first results to test and confirm the hypothesis of Butman et al. (1986) that collection efficiency decreases with decreasing particle fall velocity.

We briefly note some particle size/density biases from other field experiments. Gardner (1980b) found large differences in the percentage of particles collected that were $>63$ μm, most notably more than 90% of the particles collected in an unbaffled cone ($A_c \approx 1$) were $>63$ μm, whereas in baffled cones and cylinders the percentage was closer to 70%. Blomqvist and Kofoed (1981) found that cylinders less than 4 cm in diameter overcollected low-density particles, and Noriki and Tsunogai (1986) also found that narrow cylinders ($D = 7$ cm, $A = 8.6$) collected more organic matter than large baffled cylinder/cones ($D = 25–80$ cm, $A_c = 1.5–2.4$). Baffled cylinders ($A = 5.2$) collected more particles $<63μm$ when tilted either upstream or downstream than vertical cylinders both in flows $<15$ cm/s and 15–62 cm/s (Gardner, 1985).

RECOMMENDATION: The mean flow speed should be monitored at the height of the trap mouths in all field studies where traps are deployed for quantitative flux estimates. Because it has been shown that biases can occur as a function of $u/W$, it is important that more experiments be made to understand the nature of the particle trapping mechanism. Because particles frequently do not settle as individuals, it is necessary to consider aggregation state, in situ sinking speed and potential trap-induced disaggregation effects in addition to measured particle size distributions in sediment trap samples. Photographic, holographic, or other non-interfering techniques to measure the size distribution of aggregates at the entrance and inside of sediment traps in the field would be extremely useful. Make laboratory or field measurements
Figure 8: Size and density fractionation of the total flux collected by each speed interval of the moored FAST and by simultaneously deployed drifting traps (DT) from Baker et al. (1988). Within each density category particles of larger size make up an increasingly larger fraction of the total flux as current speed increases. The size/density distribution of the trapped particles from the drifting traps closely matches the distribution in the lowest speed interval of the moored FAST.
on the shear strength of aggregates to determine the conditions under which they are likely to be destroyed. Flume and other calibration studies should use particles which are representative of those likely to be encountered in nature.

### 3.2.3 Nature of Particle Trapping Mechanisms

The ultimate goal in designing a sediment trap is to collect an unbiased sample of particles settling through the water column. We have been able to empirically relate a trapping efficiency to several dimensionless parameters, but have not fully identified the mechanism by which particles are collected and retained in a trap. We can predict when some traps will be inefficient collectors, but not exactly why. From studies of flow structure within traps, three regions require in-depth study:

1. **At the trap mouth where eddies are generated:** Are particles of particular sizes and densities preferentially selected for or against, and under what flow conditions? For the fine-grained, slow settling particles (large \( u/W \)) dominating the mass of particulate matter in the ocean, particle inertia relative to the mean or turbulent flow is negligible, so particles will follow streamlines very closely and no particle discrimination should occur. In the limiting case, particles would follow the flow exactly and be swept into and out of the trap with no collection at all.

   As particle size and settling velocity increase, particle paths begin to deviate from streamlines. Evidence is mounting that the average fall velocity of particles collected in traps is on the order of 100 m/d (Deuser and Ross, 1980; Honjo, 1982; Deuser, 1986a, b) and is likely to be in the form of large aggregates (1 mm or greater; Asper, 1987), in which case further theoretical and empirical evaluation is needed to determine the size and density of particles that no longer follow streamlines and might experience sorting (see Soo, 1967; Tooby et al., 1977; Butman et al., 1986). This may present a complication for flume calibrations which do not use full-sized traps, because although it is possible to scale the shape of traps to be hydrodynamically similar to full size traps in the field, it may not be possible to simultaneously scale the particles with the dimensionless parameter \( u/W \) and have the particles behave similarly in the lab and field. For example, simulations of the \( R_t \) experienced by a trap in the field must use a larger \( u \) in a flume to compensate for a scaled-down trap. Particles with the same \( W \) are more likely to be sorted at a higher velocity and maintaining \( u/W \) constant requires particles with an increased \( W \), and these particles may not behave similarly in the turbulence and flow encountered.

2. **In the central region of the trap below the depth of regular eddy penetration:** What combination of parameters result in a particle's transfer from this transition zone to the lower tranquil region? Is the retention of particles here based on their \( W \), the vertical velocity of water, residence time in the trap, and size (especially height) of the trap? It is clear that only a small percentage of the particles entering the trap remain in the trap. Otherwise all traps would overcollect and, rather than measure the vertical flux, would respond to changes in particle concentrations. Gardner et al. (1981) showed that this is not the case by simultaneously measuring both the vertical flux (using sediment traps) and
3.2 Trap Geometry and Spacing

horizontal flux (product of measured currents and particle concentrations). They found that the vertical flux, which varied by less than a factor of 3, was only 0.01 to 0.1% of the horizontal flux past the traps (Fig. 9). The horizontal flux at the trap locations varied by more than a factor of 50, with no obvious correlation between vertical and horizontal flux (Fig. 9).

3. In the bottom tranquil region of the trap (when it is present) or the viscous sublayer across which particles must settle: What parameters control particle retention in this zone? Particles can be resuspended from this zone if A is small enough to let strong eddies reach the bottom or if upwelling at high $R_t$ lifts particles up from the bottom. Deep collection tubes and brines can protect particles from resuspension (Knauer et al., 1979). Baker et al. (1988) noted a decrease in trap efficiency despite the use of brines and deep collection tubes, which argues for biases at high $R_t$ occurring in the eddies (centrifugal separation) or central region of the trap (low residence time for low W particles to settle).

RECOMMENDATION: Laboratory and field studies are needed to study the behavior of particles within different regimes inside of traps. Calibration tests need to use particles that are appropriately scaled to those found in the ocean. It is not enough to understand flow in traps; we must understand the behavior of particles within the flow. Empirically derived relationships between environmental parameters and trapping efficiencies are useful, but these should not displace studies aimed at unravelling the physics of the particle trapping mechanisms.
3.2.4 Brine Solutions

Brines with densities greater than seawater are often used to isolate samples in traps, retain poisons and preservatives, and retain dissolved or leached components of the sample (Knauer et al., 1979, 1984). The addition of a brine presumably has two hydrodynamic consequences. First, it changes the effective aspect ratio of a trap, since the higher density region acts as a false bottom. At the same time, it prevents resuspension of particles settled within the brine. Second, only particles with a density greater than the brine can settle into the brine. Aggregates with a density < brine density (regardless of their fall velocity) will settle onto the interface until they are: 1) resuspended, 2) exchange pore water with the brine and settle, or 3) roll around and break up or collapse to the point that their density exceeds the brine density. The quantitative effects of brines on collection efficiency have never been studied in laboratory calibrations and have been only cursorily addressed in field studies. If a brine is added to a trap one must still be certain that the aspect ratio of the trap is large enough to maintain a tranquil layer of the bottom of the trap.

RECOMMENDATION: In calculating the aspect ratio of a cylinder, H must be measured from the trap mouth to the top of the brine. All traps should start with brine the same distance below the top of the trap with A above the brine appropriate for the environment so that aspect ratio does not vary during the experiment. In order to maximize H one would want to minimize brine depth, but the height of the brine layer should always exceed the level of particles collected. In most cases one trap diameter should be sufficient, but further evaluation is needed.

3.2.5 Baffles

The use of baffles at the top of traps is intended to diminish turbulence within a trap and to exclude very large organisms. Flow visualization studies have demonstrated that turbulence is decreased in both vertically walled traps (Soutar et al., 1977) and in cones (Gardner, 1980a). The use of baffles also increased the efficiency of cones in both laboratory and field experiments (Gardner, 1980a, b) especially in retaining particles <63μm, but we emphasize that the few cones tested have had a smaller A than the large cones now used in open ocean experiments. Further testing with cones is strongly recommended.

Field experiments with cylinders 9-cm wide, A = 2–6 (Gardner, 1980b) and for cylinders 25-cm wide, A = 2.5–3.5, and a cone at the base (Gardner, unpublished data) showed that trap efficiency also increased with the insertion of baffles into cylinders, especially for particles <63μm. Flume calibrations (Butman, 1986) showed both increases and decreases in efficiencies with the insertion of baffles into cylinders, but the A of traps was not constant in these experiments.

In a field experiment using VERTEX MULTITRAPS, Martin et al. (unpublished data) found that baffles may be effective in reducing swimmer effects but may also result in decreased trapping efficiency. In this experiment, identical cylindrical traps (7.6 cm diameter × 60 cm tall) were deployed with baffles of varying lengths (0–15 cm) at 150 m for 14 days. The results (Fig. 10) indicate a slight reduction in collection of both total mass and carbon. Flushing of the trap solution was investigated by initially filling the traps completely with a brine solution (40 °/oo NaCl) and after recovery measuring the amount of this solution
remaining. This result (Fig. 10d) indicates that the deeper baffles resulted in enhanced flushing rates, although the flow environment and possible losses during deployment and/or recovery are not known.

Unfortunately, none of these experiments can be adequately compared because of absolute and time-varying differences in $A$, differences in $R_t$, and differences in baffle geometry. Does the addition of baffles change the $R_t$ at which you still get a bottom tranquil layer in cylinders? How does this change with baffle geometry?

**RECOMMENDATION:** Quantitative studies of the effects of baffles on trapping efficiencies as a function of $A$, $R_t$ and baffle geometry (diameter and height) are needed for both cylinders and cones.

### 3.2.6 Screens

The addition of screens flush with the trap mouth offered the hope of decreasing turbulence within a trap, but whether or not that occurs is unknown. Screens also have been used to exclude swimmers from trap samples (e.g., Karl and Knauer, 1989). Such screens have been added at the top of the trap mouth, below the baffles, and down in the brine — above the sample. The concern about screens is that in excluding swimmers, one might also exclude large aggregates. Aggregates could be broken up (with or without screens), but could also clog the screens and prevent other particles from entering.

Only two laboratory experiments have added screens on top of cylinders; in one using a 1 mm mesh screen there was a significant increase in trapping efficiency (Gardner 1980a), but in the other, which used a 4 mm mesh screen, there was not (Butman 1986). Neither experiment used particles the size of marine aggregates. The laboratory study of Butman (1986) indicated that anything which obstructs flow through the trap mouth (e.g., screens or baffles) increases the replicate variability (Fig. 11) suggesting that more replicates would be needed to adequately estimate the mean flux in screened traps.

**RECOMMENDATION:** The use of screens may exclude some swimmers, but since they may also affect the collection rate of particles, experiments (especially field experiments with natural particles) are needed to quantify the effect of screens on particle trapping.

### 3.2.7 Closure Mechanisms and Obstructions to Flow at the Trap Opening

The use of closure mechanisms ensures sample integrity during recovery, though there is ample experience suggesting that open traps recovered vertically can retain their samples intact, especially if brines are used (Knauer et al., 1979). Closures are preferred to prevent contamination of samples with particles from shallower depths as well as loss of sample. Closures must not, however, disturb the flow around the mouth or in the interior of the trap. This could change the hydrodynamics of the trap and while it may or may not alter the trapping efficiency of the trap, the effect will not be known without further testing. Flow visualization studies show that fluid and associated particles entering vertically-walled traps comes from below the rim of the trap and accelerates upward and over the trap mouth (Gardner, 1980a). The presence of an obstruction will interfere with this flow and will be especially problematic if the trap deviates from a vertical orientation. Trap efficiency...
Figure 10: Effect of baffle length on trap performance from Martin et al. (unpublished) experiment. The traps were deployed for 14 days at 150 m from a surface-tethered drifting array. a) Total particle weight caught by traps using various baffle lengths, b) carbon weight, c) zooplankton 'swimmers' picked from the traps, d) volume of saline solution remaining after recovery of the traps.
Figure 11: Relative particle collection efficiency for baffled cylinders with different aspect ratios (upper) and constant aspect ratio of 3 (lower), showing effects of obstruction to flow through the mouth opening. Traps are drawn to scale below the figure. Vertical bars connect replicate values.
measurements in the Gardner (1980a) study suggested that cylinders overtrap slightly when there are irregularities around the trap mouth (such as the threads on a glass jar). Butman (1986) also concluded from her flume studies that irregularities at the top of cylinders increase the variability in flux measurements.

**RECOMMENDATION:** Further studies are needed to fully assess the impact of irregularities at the top of traps.

### 3.2.8 Flow Separation Guides (Lips)

In order to reduce the acceleration of flow over the top of traps, Soutar et al. (1977) suggested the use of a flat lip (flow separation guide) around the top of a trap. This lip is intended to eliminate vertical fluid velocities in the vicinity of the trap mouth and thus reduce turbulence. Lips are used in conjunction with deep baffles which are intended to further reduce the flow within the trap.

While this seems advantageous, there are at least two disadvantages associated with the use of lips: 1) when currents are low, particles could settle on the lip and later be swept into the trap when current speeds increase and 2) the lips must be maintained absolutely parallel to the oncoming flow; any deviation of the trap from vertical will cause the uplifted lip to shed eddies over the trap opening. Present trap configurations utilizing vertical flow suppression (lips) have not been thoroughly tested.

**RECOMMENDATION:** Laboratory and field experiments at appropriate scales are needed to define the effects of lips on the collection characteristics of specific trap configurations.

### 3.2.9 Tilt and Wave Effects

The collection rate of cylinder traps increases when tilted either into or away from the current (Gardner, 1985). Increases to 125% were noted at 5° tilt and reached 250–300% at 45° (Fig. 12). The proportion of particles <63 μm was greater in tilted traps than in vertical traps. No similar tests have been made on cones.

Moorings may be designed to minimize tilt, but traps held vertically in the upper water column still can experience an effective tilt due to the passage of internal waves. The presence of internal waves causes vertical motion past moored or drifting traps because the traps stay at nearly constant depth. The vertical component of flow causes the oncoming water to approach the trap at an angle, thus creating an effective tilt (Fig. 13; Gardner, 1985). The effective tilt increases with wave amplitude and frequency and decreases with higher currents past the trap. During the Sediment Trap Intercomparison Experiment (STIE) in the Panama Basin, internal waves with periods of about 40 min. caused an effective tilt of up to 40° for floating traps in the thermocline.

Hawley (1988) tested the flow dynamics of cylinders (A = 5) subjected to wave action in a laboratory tank. Over the same range of $R_t$, the overall flow pattern was similar whether flow was steady or wave induced, but mixing was much more intense and eddies penetrated more deeply during vertical wave motions. Similar tests need to be made using particles.

**RECOMMENDATION:** Laboratory and field experiments are needed to test the effect of internal and surface waves and tilt on the collection efficiency of traps, especially
Figure 12: Normalized flux collected in cylinders with baffles (A = 5.2) tilted upstream and downstream. Flux in each trap is normalized to the average flux in two vertical cylinders during each experiment. Numbers refer to experiments; dots indicate single trap value; bars indicate range of two replicate traps; dashed bars are when velocity was 0–15 cm/s and solid bars are when velocity was 15–62 cm/s. (From Gardner, 1985.)
Figure 13: Passing internal waves (dotted line highly exaggerated) cause an "effective" tilt angle (t) because of the vertical velocity vector (B) caused by orbital motion of water in an internal wave superimposed on a mean flow past a trap (A). The effect is likely to be significant only when wave amplitude is >20 m, period is <4 hr., and mean velocities are <20 cm/s. The most likely location for such conditions is the pycnocline. Since t increases as A increases, floating traps experience larger effective tilts than moored traps. (From Gardner, 1985).
cones. Moorings should be instrumented with current, tilt and temperature sensors to monitor the passage of internal waves.

### 3.2.10 Gimballed and Vaned Traps

One approach to maintaining traps in the vertical is to gimbal them. This can be accomplished by freely hanging a trap away from the mooring line or by attaching the trap to a vane with two degrees of rotational freedom. The first method may function well in low-velocity flows, but high-velocity flows might cause erratic oscillations due to vortex shedding from the trap or suspending line. Attachment points for a gimballed trap must be symmetric so that drag forces are equal above and below the pivot point. If the center of mass of a trap is also at the pivot point, however, the trap will oscillate up and down stream because the open end of the trap changes the symmetry of drag forces (Gardner, 1985). The oscillation can be reduced to a few degrees by putting the center of gravity well below the pivot point, but any oscillation could impact trapping efficiency due to increased turbulence within the trap.

A second objective of the vaned trap is to ensure an unobstructed approach of the flow toward the trap, but the design of the vane must be well-engineered and the vane must be large enough to ensure that the trap is oriented with the flow even at low-velocity. This is especially true for large traps that may be paired or multiple traps that are vaned to provide replicates at a single depth (example in Bloesch and Burns, 1980). Without instrumental verification there is uncertainty of whether the traps always faced the flow. Flow obstruction may account for large variability reported in some early trap experiments with paired traps (Honjo, 1978; Izeki, 1976).

**RECOMMENDATION:** Proper engineering and monitoring are required to use these methods successfully without incurring unknown and unwanted side effects. In most cases the use of symmetric traps on taut moorings will produce the most consistent and reliable results.

### 3.3 Field Calibrations With Independent Flux Estimates

#### 3.3.1 Radionuclides

A number of naturally occurring radionuclides have been proposed as tracers for calibrating sediment traps in the field (Knauer et al., 1979; Lorenzen et al., 1981; Bacon et al., 1985; Coale and Bruland, 1985). Their important characteristics are that they (1) are chemically reactive in the sense that they are strongly adsorbed by marine particulate matter and (2) are supplied to the oceanic water column at exactly known rates by decay of their parent nuclides in the decay series. The most useful parent/daughter radionuclide pairs are listed in Table 1. In practice a calibration is based on a determination of the degree of radioactive disequilibrium (deficiency of daughter nuclide relative to parent nuclide) in the water column above the trap to be calibrated. From this the expected flux of tracer (i.e., the daughter nuclide) at the depth of the trap is easily calculated. Comparison of measured tracer flux with expected flux gives a measure of trapping efficiency. For sediment traps deployed near the seafloor, inventories of excess daughter nuclide in the sediment column
Table 1: Naturally occurring parent/daughter radionuclide pairs (half-lives in parentheses) that are potentially useful for validating sediment traps.

<table>
<thead>
<tr>
<th>Parent</th>
<th>Daughter</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{238}\text{U}$ ($4.47 \times 10^9$ y)</td>
<td>$^{234}\text{Th}$ (24.1 d)</td>
</tr>
<tr>
<td>$^{234}\text{U}$ ($2.48 \times 10^5$ y)</td>
<td>$^{230}\text{Th}$ ($7.52 \times 10^4$ y)</td>
</tr>
<tr>
<td>$^{226}\text{Ra}$ ($1.62 \times 10^3$ y)</td>
<td>$^{210}\text{Pb}$ (22.3 y)$^a$</td>
</tr>
<tr>
<td>$^{210}\text{Pb}$ (22.3 y)</td>
<td>$^{210}\text{Po}$ (138 d)$^a$</td>
</tr>
<tr>
<td>$^{228}\text{Ra}$ (5.75 y)</td>
<td>$^{228}\text{Th}$ (1.91 y)$^a$</td>
</tr>
<tr>
<td>$^{235}\text{U}$ ($7.07 \times 10^8$ y)</td>
<td>$^{231}\text{Pa}$ ($3.25 \times 10^4$ y)$^a$</td>
</tr>
</tbody>
</table>

$^a$Produced via one or more intermediates.

below the trap can be used as an alternate and independent measure of expected nuclide flux.

Measurements of natural decay-series radionuclides in trap samples can place useful limits on the degree of hydrodynamic bias that may have occurred. However, there are important conditions and limitations that should be kept in mind. First, the balance between supply and removal can only be assumed for times that are long compared to the residence time (in the water column) of the reactive nuclide. Large seasonal variations in the fluxes of several radionuclides, correlated with variations in mass flux, have been observed with traps deployed in the deep sea (Bacon et al., 1985). This suggests that accurate calibration requires integration of the flux over a period of at least one year. Somewhat better temporal resolution may be achievable in the upper ocean, where short-lived (half life of 24 days) Th-234 is an appropriate tracer to use. Here, integration times of a few months may be sufficient.

Another important limitation that should be kept in mind is that lateral advection and diffusion can redistribute the tracers, in either dissolved or particulate form, thus upsetting the vertical flux balance that is assumed. These effects are minimized in the case of Th isotopes (Anderson et al., 1983), making them the preferred tracers to use (Th-230 in the deep ocean, Th-234 or Th-228 in the upper ocean). Even for Th, however, lateral effects cannot be ignored entirely. Under some conditions, measurement of additional tracers (Pb-210 or Pa-231) can be used to derive approximate corrections for lateral effects (Bacon et al., 1985).
In practice the use of natural radionuclides to estimate trapping efficiency requires measurements not only of the trapped material but also of nuclides in the water column (to establish the integrated deficit) or the sediment column (to establish the integrated excess). The number of samples required and their vertical distribution depend on the particular tracer that is being used.

If a good agreement is found between measured and expected tracer fluxes when the two are compared for appropriate and comparable time scales, as discussed above, then it can be taken as evidence that hydrodynamic bias is small for particles with which the isotope is associated. However, it should not be concluded from this that the sample is free of bias from the effects of swimmers or poor preservation or that these results apply to all particles. Most marine organisms have low concentrations of natural radionuclides in comparison to the concentration in particles making up the passive flux. Thus a significant population of swimmers could be present in a sample without contributing significantly to the tracer content of the sample. Because of the high affinity of the reactive nuclides for particle surfaces, a significant fraction of the trapped sediment could be lost by dissolution or decomposition without causing a significant net loss of tracer. Any tracer lost from destruction of particles could be quickly adsorbed by the particles that remain. Measurements of Th isotopes in trap supernatant solutions show little net release (<5%), even over times of several months (A.P. Fleer and M.P. Bacon, unpublished data).

The workshop raised the question of whether the reactive radionuclides do indeed act as unbiased tracers of the whole spectrum of particles that make up the passive settling flux. It is conceivable, for example, that the tracers preferentially tag a certain fraction of the settling particles that are trapped efficiently and that an inefficiently trapped fraction is relatively free of tracer. Thus the trap might accurately record the flux of tracer but not the flux of all sediment components. Such a scenario may be unlikely, but there is a need to examine it further, perhaps by measuring radionuclide concentrations in trapped particles that have been separated according to size, type (e.g., fecal pellets vs. marine snow), or settling velocity.

The present data base of radionuclide measurements in trap samples appropriate for estimating trapping efficiency is very small (Brewer et al., 1980). The existing collections of sediment-trap samples should be systematically analyzed for reactive radionuclides to assess the possibility of bias. This effort should be limited, however, to those traps deployed continuously in the deep sea for at least one year. The appropriate nuclides to measure are Th-230, Pa-231, and Pb-210. For time-series collections it is sufficient to analyze composite samples to give a one-year integrated flux measurement. Thus the effort required would be just one analysis per trap-year.

Future sediment-trap deployments should be designed, when possible, to allow for radionuclide analysis as a test for bias. This means that the annual cycle of particle flux must be adequately sampled, preferably by continuous collection for one year or longer. The most reliable tests are provided by the Th isotopes, the choice of isotope depending on the depth of the trap below the sea surface: Th-234 for <200 m, Th-228 for 200–1,000 m and Th-230 for >1,000 m. Other nuclides (Table 1) can also give valuable information. When Th-234 is used to calibrate shallow traps, integration times of a few months may be sufficient.

In conclusion, radionuclide measurements can provide important information for judging how well a sediment trap has performed over a long period of time. It is perhaps best to
think of "calibration" by radionuclides as a test for hydrodynamic bias, except for traps near a boundary layer. A positive test (poor agreement between measured and expected tracer flux) is strong evidence of trapping bias. A negative test (good agreement) gives confidence that the trap performed well, though it does not prove that bias was absent at all times.

**RECOMMENDATIONS:**

1. Existing collections of sediment-trap samples should be systematically analyzed for natural radionuclides to test for hydrodynamic bias.

2. Future deployments of sediment traps should be designed (e.g., consider deployment length and sample handling), whenever possible, so that radionuclide measurements can be used to test for hydrodynamic bias.

3. Measurements of the radionuclide composition of fractionated sediment-trap samples should be undertaken to determine whether there are particular components of the sediment that are preferentially tagged.

### 3.3.2 Sediment Accumulation Rates

As discussed above, trap fluxes can be compared with sedimentation rates measured in sediments beneath the traps. The problem is that the time scales of the trap and sediment accumulation measurements are usually very different. Such comparisons can best be made for refractory components of the sediment. However, if losses due to dissolution and degradation can be determined, then such comparisons can be extended to non-conservative components. The reliability of this sort of calibration decreases as the disparity between time scales increases. Beginning with the highly disparate time scales, Gardner et al. (1985) found that fluxes measured during 10-30 day trap deployments (99 g/m²/yr) agreed fairly well with sediment accumulation rates in the Holocene (60-70 g/m²/yr). In areas with higher sedimentation rates Pb-210 has been used to measure sedimentation rates over periods of 10's of years. Trap fluxes measured in the lower head of the Quinault Canyon were 67-97% of the Pb-210 based accumulation rates and 146% of the accumulation rates measured on the adjacent slope (Baker and Hickey 1986).

Some of the California basins (Santa Barbara, Santa Monica) and other regions such as the Black Sea, Saanich Inlet, and Norwegian fjords are anoxic, allowing preservation of distinct and identifiable annual layers (varves). Such basins are ideal for comparing trap fluxes with sediment accumulation rates because of reduced dissolution, degradation, bioturbation and swimmer problems. In the borderland basins off southern California the trap fluxes measured have been 22-190% (Soutar et al., 1977), 77-121% (Bruland et al., 1981), and 40-84% (Dymond et al., 1981) of the Pb-210 measured accumulation rates, with differences resulting from combinations of height above bottom at which measurements were made, time of year, trap geometry, and degree of lateral transport contributing to sedimentation below the traps. In a Norwegian fjord Naes et al. (1988) measured trap fluxes of 50% the Pb-210 accumulation rate, the difference attributed to transport below the trap.

Pennington (1974) found that for cylinders (A = 3.7) trap fluxes in an oligotrophic lake (0.26 cm/yr) agreed well with sedimentation rates based on Pb-210 dating (0.27 cm/yr) and
3.4 Intercomparison Experiments

Many other similar comparisons have been made. Because of the difference in time scales such comparisons must be evaluated carefully, but they do show that trap fluxes are not off by an order of magnitude, and are probably within less than a factor of two of the real flux in most low-velocity environments.

3.4 Intercomparison Experiments

Many field tests have been made to compare the collection rates of traps of different designs without knowing the absolute sedimentation rate. Some of those have been discussed earlier in this report and others from before 1980 were reviewed in Bloesch and Burns (1980) and Blomqvist and Håkanson (1981). We briefly discuss here two intercomparison experiments because the experiments were made in the natural environment and the traps used were large ones, some of which are still being used for open ocean measurements.

3.4.1 Santa Barbara Basin

The intercomparison experiment in Santa Barbara Basin offered the advantage of being an anoxic basin with good preservation of material settling to the seafloor and a well-known varve and Pb-210 accumulation rates for calibration as well as intercomparison of different traps.

Four traps of radically different design were tested; two unbaffled cylinders (A = 2.5), a baffled cone (A_c = 2.1) and two different boxes with different types of baffling (A ≈ 0.5) (Dymond et al., 1981). Currents at 160 m were 1–17.5 cm/s with a mean of 5.2 cm/s, yielding R_t's of 1,700–12,000. The traps were deployed on two moorings and were located between 150 and 400 m (all above the anoxic layer) in the 600 m deep basin. Measured fluxes ranged from 370 to 774 g/m²/yr, with differences potentially due to use of different preservatives, baffles, and position in the water column as well as different designs (Fig. 14). There is no significant trend for flux as a function of R_t. The measured fluxes were lower than the 25-year record of sedimentation in the basin (890–920 g/m²/yr), which probably results from a significant input into the basin by near-bottom transport.

3.4.2 Panama Basin (STIE)

Results from the STIE in the Panama Basin have yet to be fully analyzed or published, but some information is available in a technical report (Spencer, 1981). The traps tested ranged from cylinders between 7 and 30 cm in diameter to cones 56–138 cm in diameter to boxes 100 cm square. There are too many details and caveats to describe here which relate to ascertaining which traps did or did not function properly. For example, some traps lost sample when tangled during recovery. Traps were deployed on five separate moorings at depths ranging from 665 m to 3,791 m for four months in a small, nearly enclosed sub-basin at the margin of the Panama slope. Two sizes of cylinders were deployed on surface-tethered moorings for short (1–2 day) deployments. Particle concentrations increased with depth at the trap sites (Gardner et al., 1984), so it is not surprising that trap fluxes also increased with depth for traps of the same design as a result of sediment resuspension and lateral advection from the walls surrounding the basin.
Figure 14: Measured trap fluxes as a function of depth during the Santa Barbara Basin intercomparison/calibration experiment (Dymond et al., 1981). Profiles are of particle concentration based on nephelometer profiles made at time of deployment (single heavy solid line) and recovery (all other lines).
A group of traps which included cylinders (Gardner, D = 25 cm; A = 2.5), cones (Honjo, 12–15 cm × 25 cm baffles, D = 146, A_c = 1.2; Soutar, 1 cm × 5 cm baffles, D = 56, A_c = 2.1) and moored cylinders (Knauer MULTITRAP, D = 7, A = 8 filled with brine at deployment and about half full at recovery; Farrington, D = 25, A = 3 with bottom two D containing a funnel and rotating sample cups; Gardner, 1 cm × 5 cm baffles, D = 30, A = 3 with bottom one D containing a funnel and sample cup) show a tendency for the total flux to decrease from about 140 mg/m²/d in the surface to about 110 mg/m²/d at about 1,000 m and then to increase to 180 mg/m²/d in the near-bottom depths (Spencer, 1981). Fluxes measured with the moored traps were within about 20% of each other for similar depths. The Th-230 measured in this group of traps was greater than or equal to the rate of production in the water column indicating that this group of traps with very different geometries not only yielded very similar fluxes (see section 3.3.1), but that the absolute fluxes were also reasonable. The results of these field experiments are encouraging for future efforts at determining true oceanic fluxes in low to moderate energy environments, and should be analyzed further in the theoretical framework outlined by Butman et al. (1986) and in this report.

3.4.3 Data Integrity with Respect to Oceanographic Processes

During time-series sediment trap experiments in the open ocean, the annual variability of particle fluxes has been observed to covary with the sequence of upper layer productivity events (Deuser and Ross, 1980; Honjo, 1982; Deuser, 1986a, b). The studies cited used baffled, steep-walled cones on rigid moorings (i.e., no measurable tilt with currents under 10 cm/s) in the deep, relatively energy-depleted ocean interiors. These and other data sets have been consistent with oceanographic processes and coherent each year, indicating that time-series trap experiments in the deep ocean provide quantitative as well as qualitative information on the biogenic and lithogenic fluxes to the ocean interior. If there is a hydrodynamic bias affecting these traps, the effect appears overwhelmed by seasonal variations which vary fluxes by a factor of 2–5 times due to changes in particle production in surface waters. Not only do these pulses of high sedimentation follow periods of high surface productivity, but the pulses can be followed down through the water column with the use of time series sediment traps at multiple depths (Honjo, 1982).

3.5 Experimental Design and Mooring Configuration

Designing a sediment trapping experiment requires more than simply using appropriate technology to construct a mooring. Oceanic processes vary over many temporal and spatial scales. Experiments must be designed to incorporate measurements over the time and space scales that are appropriate to answer the questions being asked. This is at least as true for sediment trapping as for other types of measurements. Appropriate design of sediment trapping strategy needs to take into account both the range and time scale of variability. Time scales must be sufficient to provide representative mean values, and spatial scales over which the mean values and variability can be extrapolated need to be determined. It is desirable that replicate samples be routinely acquired in order to determine the statistical confidence in the results and to investigate the ranges over which flux can vary.
In situations of negligible fluid motion relative to sediment traps, any trap design should provide an accurate measurement of the gravitational settling flux of particles free of hydrodynamic bias. Mooring configurations and trapping experiments should be designed with the ultimate goal of no flow relative to the trap. For practical reasons this may not be possible. For example, there will be some depth limit, depending on location, below which current velocity relative to traps is best minimized by using bottom-moored traps rather than surface-tethered floating traps. Shallow surface-tethered traps may be subject to considerable windage and therefore experience enhanced flows. Other considerations, such as the need for long time-series data or collections in inaccessible regions such as high latitudes may also require the use of fixed moorings. Where flow past traps is expected, every attempt should be made to: a) show that the flow did not introduce serious bias into the measured fluxes, based on independent experimental (lab and field) results, or b) provide some means to evaluate and correct for the bias, either based on hydrodynamic theory or empirical relationships derived from experimental results.

Ideally, neutrally-buoyant traps, similar in principle to SOFAR floats, would be used to minimize fluid flow relative to traps. Unfortunately, such traps are still at the experimental stage and require further testing before they will be ready for routine use. Furthermore, even "perfect" neutrally-buoyant free-floating traps which remain on a predetermined constant isopycnal surface will experience some fluid motion relative to the traps caused by small-scale shear and turbulence and by inertial movement of the traps in internal waves or other nonlinear-flow situations. Field and laboratory studies must be carried out to determine the conditions under which these residual motions will introduce significant bias into measured fluxes. Free-floating traps must then be instrumented with flow sensors to determine if, and when, these flow conditions are exceeded. This approach is also very expensive and complex, especially for routine use. There is also the caveat that separate traps will not collect from the same water mass and biological community, so space scales of patchiness must then be evaluated.

Given that ideal free-floating sediment traps are not yet available, we must, for the present, rely on surface-tethered floating traps and bottom-moored traps to collect particle fluxes. Each approach has its advantages under certain situations. Mooring design is a complicated engineering problem. The optimum mooring configuration will change from one situation to another, but certain considerations such as minimizing flow relative to traps and maintaining a vertical orientation of the traps should guide all mooring designs.

Surface-tethered floating trap arrays are presently used as an alternative to the ideal neutrally-buoyant free-floating trap for trapping in the upper water column of the open ocean where surface currents and other factors make it impractical or impossible to deploy sediment traps from bottom-anchored moorings (Knauer et al., 1979; Betzer et al., 1984). However, defining the optimum strategy for floating sediment traps is extremely difficult (there clearly was not a consensus among participants at the meeting). Some common guidelines can be stated, however. Foremost among these is the desire to minimize flow relative to the trap. For traps deployed close to the sea surface, where current shear is the greatest, it may be desirable to maximize drag on the trap itself (i.e., design the trap as a drogue) and minimize drag imparted on the mooring at the sea surface. Current shear in the upper water column makes it impossible to design a multiple-depth floating trap array in which traps at each depth are floating with the current. Most certainly one or more traps
will occasionally experience significant net flows, perhaps as great as several 10's of cm/sec as was measured by current meters deployed on VERTEX floating MULTITRAP arrays. therefore, one approach to minimize flow relative to floating traps in shallow waters is to design floating arrays with a single trap or with multiple traps at a single depth.

For floating arrays reaching to depths greater than a few hundred meters (the exact depth depending on the nature of the traps and the mooring cable), most of the overall drag will be imparted on the mooring cable and not on the trap itself. Current flow relative to some of the traps will be unavoidable. Under these conditions, there may be little benefit to designing arrays with traps at a single depth, and multiple-depth trap arrays will be preferred if for no other reason than because it is logistically much easier to track one floating array than multiple arrays.

The group consensus was that further engineering studies are needed to improve the ability of floating traps to move with the currents coinciding with hydrodynamic studies of trapping biases caused by fluid motion relative to traps. Meanwhile, it is essential that floating traps be instrumented with current meters or other flow sensors so that potential hydrodynamically-induced trapping biases can be identified. Floating traps deployed to the depth of the bottom of the thermocline should also be equipped with thermistors as a means of assessing vertical excursions of water relative to the traps due to internal waves. Internal wave activity coupled with horizontal currents define an effective tilt of sediment traps which, in turn, affects trapping efficiency. Knowledge of internal wave activity and horizontal current speed are both needed to compare results from different trap deployments. Tilt recorders and/or depth sensors should be considered as standard instrumentation for floating trap arrays deployed in regions of high current shear to provide an accurate knowledge of the actual position of each trap. Further testing of physical parameters which influence trapping efficiency (see section 3.2 above) may eventually permit identification and quantification of trapping biases and possibly even a means of correcting for these biases; however, this can only be done if traps are properly instrumented with appropriate sensors.

Other considerations must also be incorporated into the design and deployment of floating sediment trap arrays. For example, the tether line to surface floatation must not be so taut that vertical pumping action is transferred to the traps by wave-induced movement of surface floats. The arrangement of floats and use of a segment of very stretchy mooring line (bungee cord or surgical tubing) can isolate traps from surface wave motion. Deployment and recovery procedures must be designed around the fact that we must work off of relatively small ships under conditions (e.g., weather) that are sometimes unfavorable. Samples must be protected under these conditions. Mooring recoveries must be designed to keep traps in a vertical orientation to prevent loss of samples if open collection tubes are used as traps. Given that it may not always be possible to recover traps in an upright orientation, closing mechanisms should be incorporated into trap designs to prevent loss of samples during recovery.

Limited testing of the trapping efficiency of traps deployed on fixed moorings in the relatively quiescent deep sea suggests that these traps have performed well (see sections 3.3 and 3.4). However, “past performance is no guarantee of future return”, since we cannot always predict currents at a particular location. A continued effort must be made to anticipate and minimize hydrodynamic biases for traps deployed on fixed moorings in the deep sea as well as for traps deployed in more energetic surface waters. A well-designed
neutral buoyant drifting trap (NBDT) could be used to test for hydrodynamic biases of both free-floating and moored traps over short time scales in a manner similar to Staresinich et al. (1982) and Baker et al. (1988). In an area of stable and uniform flow and uniform particle flux a series of different trap designs could be moored at equal depths simultaneously with an NBDT. In order to test biases over a range of $R_t$, one must use either several environments with stable flow at different velocities or divide samples into separate bins based on velocity. Baker et al. used a channel that experienced wide variations in the tidal flow. It was impossible to obtain complete agreement between samples binned according to velocity on the mooring and time-binned samples on the floating traps. The same sample changes should be used with the moored and floating traps to direct samples into different bins based on the velocity experienced by the moored trap and telemetered to the floating trap. Samples from each trap could then be compared for quantity, composition and size distribution to test for hydrodynamic biases of different trap designs. Size distributions will be only relative since even during gentle wet sieving there is a breakdown of particles.

**RECOMMENDATION:** All possible precautions should be taken to minimize flow relative to each sediment trap and current meters should be deployed routinely in association with all sediment traps. The addition of tilt, temperature and depth sensors should also be encouraged. The development of a neutrally buoyant drifting trap is encouraged for field calibration of traps. Replicate samples are necessary to show that samples are representative of the vertical flux; single samples could be influenced by a rare but overwhelming event.

### 4 Sample Integrity

A pervasive problem with our current use of sediment traps is the collection of organisms, the "swimmers", which clearly are not passively sinking particles (Knauer et al., 1979; Lee et al., 1988). Activities of these organisms in traps alter particles in the traps and thus poisons or preservatives are required to deter such potential alteration. Furthermore, organisms affect sample splitting and sieving accuracy, and contribute dissolved products through dissolution and leaching into the trap solution. Quantifying the contribution of swimmers to the dissolved pool is difficult because solution rates appear to differ for various elements and components of the particulate flux. Also, some preservatives interfere with measurements of the soluble fraction of certain elements. Below, we discuss rationale for deciding which swimmers are appropriately considered part of the net vertical flux. We then discuss how these organisms and other factors can affect sample integrity.

#### 4.1 Passive Sinkers vs. Active Migrators

The vertical exchange of particulate material in the sea occurs via two closely related processes: (1) the passive sinking of non-living particles, with their associated organisms both living and dead, and (2) the active vertical movements of living organisms. Sediment traps are devices designed to assess quantitatively the first process. No equivalent, standardized samplers are yet available to assess the second process, which may quantitatively rival or exceed the first over some depth ranges (Angel, 1984; Longhurst and Harrison,
4.1 Passive Sinkers vs. Active Migrators

1988). A serious concern of many ocean scientists who have measured the passive particulate flux using sediment traps, is the role that active larger organisms, or “swimmers” as they are often called, may contribute to trap collections. Here we discuss the nature of the living organisms that are collected in addition to the non-living material in traps and the rationale for the removal or inclusion of these organisms as part of item (1) above.

The most numerically abundant living organisms in sediment traps are bacteria and microscopic photosynthetic organisms (at least in traps moored through the upper 2,000 m of the water column). The former are regarded as decomposers of the non-living organic matter they accompany and thus appropriately included in the passive flux. Photosynthetic organisms, including cells ranging from bacteria-sized photoautotrophs to mm or larger algae, are occasionally dominant contributors in near-surface traps. These photosynthetic organisms are considered appropriate contributors to the flux since their descent is largely unidirectional and the populations mostly die or are lost as recruits for future generations.

A variety of additional micro-organisms occur on particles. These include small protozoa, such as flagellates and ciliates, and larger protozoa, such as the sarcodine radiolaria and foraminifera. In many cases, these appear to be members of the decomposer community, consuming bacteria, photoautotrophs, and other protozoans housed on the particles. When these are members of the particulate decomposer community, and thus obtain their substrate requirements from particles, they are appropriately included with the mass flux of “non-living particulates”. Some of these living organisms can be many hundreds of μm, or even mm in size, such as the large phaeodarian radiolaria (Gowing, 1986). It is also possible that some metazoans, such as some of the harpacticoid copepods known to accompany marine snow (Alldredge and Silver, 1988) are truly members of the decomposer food chains and thus appropriately included in the particulate flux.

The largest group of conspicuous organisms in sediment traps are likely trap intruders and thus not appropriately included in the particulate flux. These would include diel vertical migrators, such as common crustaceans and jellyfish, and organisms at the depth stratum of the trap that are attracted from the surrounding area and swim into the trap. Others are organisms that move over the trap and, because of behavioral response to the trap presence, may enter the trap collectors (Harbison, 1987). For example, pteropods can abandon their feeding structures and sink rapidly when alarmed.

Other organisms and organism-related products are more difficult to assess as “appropriate” contributors to the flux. Traps occasionally collect eggs, for example, that normally settle during their development. If the eggs were to hatch, their more advanced stage would be designated as a swimmer or trap intruder. Larvaceans pose particularly severe problems because they are likely to enter traps with their detritus-rich, fecal-pellet encumbered mucus houses. The houses, in regions where larvaceans are common, may constitute a substantial amount of the non-living particulate material. The houses and their larvacean inhabitants, should thus be removed from trap samples as swimmers. Other organisms, such as pteropods and foraminifera, likewise may be accompanied by mucus and both the organisms and their products should be removed as swimmers. However, this is technically not possible.
4.2 Which Organisms Should Be Removed

It is now well documented that organisms occur in sediment traps for a variety of reasons. We now define "swimmers" as organisms (or their products), either metazoan or protozoan, that are alive at the time of trap entry and which are not members of the decomposer community of sinking particles. Such organisms should be removed or otherwise excluded as a contribution to the particulate flux. The challenge is to identify these organisms in trap samples and attempt to remove them or correct for their direct and indirect influences. From a practical standpoint, the food source of the conspicuous organisms entering traps is unknown and thus the designation of most organisms as swimmers is usually tentative. Metazoans are mostly assumed not to be part of the decomposer webs of sinking particles, but future research in this area is clearly warranted. Evidence from direct observations in surface waters indicates that aggregates possess a metazoan fauna in some cases. Small protozoans, such as the flagellates and ciliates, are presumed to be part of the decomposer webs, contribute relatively small amounts of material (Silver et al., 1984; Taylor et al., 1986), and are technically impossible to remove. The small protozoans are thus included in the flux. The large protozoans, however, are more difficult to assign. Some, such as foraminifera, may be stressed or moribund individuals, whereas others may be performing ontogenetic migrations. Others, such as the intact phaeodarian radiolaria, appear to be consuming materials commonly abundant on sinking detritus, and thus are appropriately considered as members of the decomposer community. Since the sarcodine radiolaria are important contributors to trap flux to depths of at least 2,000 m, their food web relationships require further investigation.

We suggest that the downward flux of material is mediated by several discrete processes, as shown in Fig. 15. Fig. 15a shows the true flux, which represents the major routes by which materials are transferred from the surface of the sea to depth. The true flux includes a "passive" or sinking part and an "active" or swimming part. The passively sinking fraction includes non-living particles (a), and live algae and microbes that decompose the non-living particles (b). Dissolved material leaches from (a) and (b) as they settle and this contribution is represented in (e). Material is also actively carried to depth by living, actively migrating organisms which is shown in (f) although the quantitative significance of this mechanism to downward flux is not well understood.

Traps actually measure the components represented in Fig. 15b. This includes the non-living passive flux (a) and the living algae and decomposer microbial communities (b). They also include a group of "cryptic" swimmers that are difficult to see or to remove (c), organisms such as the transparent siphonophores, smaller larvaceans, and possibly a large number of the living foraminifera, radiolaria, mucus products of these, and fragments of the organisms. Some of the items in (c) could be removed, under the most favorable conditions, whereas others are technically too difficult to separate from the trap contents. The obvious metazoa (d), including the crustacea and larger, pigmented or opaque organisms are usually removed and these organisms are the ones usually called "swimmers." Dissolved material leaches from (a), (b), (c), and (d) and contributes to the soluble pool shown in (e). In Fig. 15b, the cryptic swimmers (c) and obvious swimmers (d) probably include some vertical migrants but also represent non-migratory organisms that live at the trap depths and are attracted into the collectors.
4.3 *Swimmer Prevention*

The goal of trap users is to recover the fraction of dissolved material associated with the passively sinking particles to remove the live organisms not associated with the non-living particles. Since the live organisms are most abundant at shallower depths, the “contamination” by swimmers is most serious near the surface.

**4.3 Swimmer Prevention**

Developing a method to exclude swimmers from sediment traps is one of the most vitally important tasks facing those interested in using traps in a quantitative fashion. The following methods are some of the most common ones being discussed and all require further investigation.

**Screens** — At the present time, one measure being taken to reduce contamination by macrozooplankton is to place a screen in the trap, normally directly beneath the baffle. Screens with dimensions of 0.3–2 mm have been employed with varying degrees of success (Karl et al., 1989). This procedure, while excluding large swimmers, will also exclude passively-sinking particles that are greater than the dimensions of the screen. However, in coastal and oceanic habitats where the presence of swimmers is substantial (i.e., where swimmer carbon is equal to or greater than non-swimmer carbon (Table 2)), this procedure may represent an acceptable alternative in some cases. The physical barrier approach currently appears to be the only way to assure a swimmer-free collection for the measurement of elements and compounds that might otherwise be compromised by the presence of macrozooplankton swimmers. Recently Coale (submitted to Limnol. Oceanogr.) has described a device called the “Labyrinth of Doom” (Fig. 16) which consists of a series of
Table 2: Mean total C and N in preserved vs. unpreserved trap material after removal of swimmers, and total C and N values of removed swimmers (from Knauer et al., 1984).

<table>
<thead>
<tr>
<th>Trap Material with Swimmers</th>
<th>Total Swimmers Removed (μg)</th>
<th>Swimmer C and N as % of Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>N</td>
<td>C</td>
</tr>
<tr>
<td>-----------------------------</td>
<td>-----------------------------</td>
<td>-------------------------------</td>
</tr>
<tr>
<td>Unpreserved</td>
<td>1970</td>
<td>276</td>
</tr>
<tr>
<td>Formalin</td>
<td>2910</td>
<td>380</td>
</tr>
<tr>
<td>Azide</td>
<td>1260</td>
<td>175</td>
</tr>
</tbody>
</table>

*Control

funnels which concentrate passively sinking material into a central collection tube while swimmers are distributed randomly between the inner collection tube and the outer one. Analyses of both the inner and outer samples allows determination of the input of swimmer material and correction for it in the inner sample.

**Hydrodynamics** — Introduction of swimmers into the body of the traps by active convective flow may contribute to retention of swimmers within the trap. The swimmers may be acting as passive particles, with convective flow into the trap being faster than their swimming speed. We recommend *in situ* studies to evaluate the responses of swimmer organisms within the trap flow and support precautions which can reduce the over-trapping of any passively sinking particles, including swimmers.

**Other, Novel Techniques** — It is likely that the majority of swimmer organisms could be dissuaded from entering the trap by exploiting their natural responses to various chemical or physical stimuli. The following ideas are largely speculative, but provide suggestions for further investigations:

- **Sonication** — It is likely that certain species of swimmer are deterred by certain sound frequencies. This can be addressed experimentally in the laboratory and in the field without too much difficulty. This method might not be effective against soft-body “jellies” or protozoan swimmers.

- **Electric charge** — As for sonication, low electric charges at the trap mouth may prove to be a deterrent. Considerations of this method include power requirements, corrosion
Figure 16: The "Labyrinth of Doom" from K.H. Coale (submitted to Limnol. Oceanogr.). Passively sinking particles fall into the inner cylinder while swimmers are collected in both inner and outer chambers. The contribution of swimmers to the sinking flux sample is evaluated by analyzing both collections and normalizing to relative areas (see text).
problems, and the possible alteration of the surface properties of particles in such a way as to change their sinking characteristics.

Chemicals — There is already a body of unpublished data on the repulsive effects of various chemicals. No substances have been identified as being particularly effective, and some likely candidates appear to be attractive. Many swimmers for instance readily swim into 2% formalin solutions which are toxic. It is possible that alarm pheromones will be discovered and can be used for specific organisms. However, even in the most favorable setting, one would be required to use multiple "alarms" to address the swimmer population in all its diversity.

Distraction — An alternative to a repulsive chemical is an attractant which could be placed within a trap but in a chamber removed from the sample. Ideally, this attractant would have a limited range, attracting swimmers within but not outside of the trap. Once attracted away from the sedimenting material, swimmers could then be poisoned or removed. This has considerable potential as far as crustacean swimmers are concerned.

RECOMMENDATION: The above suggestions should be critically examined in the light of existing wisdom and experiments should be carried out as soon as possible to further examine any likely candidates. The whole study of particle flux would take a quantum leap forward if swimmers could be prevented from entering traps without affecting the settling particles.

4.4 Use of Poisons and Preservatives

To be most useful, sediment trap collections must yield materials which retain their original character and integrity, despite long periods in the traps. Additives (commonly referred to as "poisons" and "preservatives") are used to insure that samples obtained in sediment trap collections are retrieved with a minimum of physical or chemical disturbance, disruption, or degradation (Knauer et al., 1984; Wassmann and Heiskaren, 1988). Poisons, such as sodium azide and mercuric chloride, prevent deterioration of samples by retarding bacterial decomposition but without significantly binding to the material in the sample, while preservatives, like formaldehyde and glutaraldehyde, are fixatives which are chemically incorporated into tissues.

The choice of poison or preservative will depend on the particular application, experimental design, and scientific objectives. However, several important considerations for choosing an additive include:

1) use of an additive which effectively preserves sample integrity as required for the specific application;

2) minimizing problems associated with use of the additive, such as:
   a) attraction and eventual inclusion of swimmers,
   b) contamination of sample (both soluble and particulate phases) by impurities present in the additive,
4.4 Use of Poisons and Preservatives

c) possible effects on the sample matrix if the additive is incorporated into the sample,
d) degradation of one part of the sample matrix by a treatment preserving another part of the sample;

3) ensuring that an effective concentration of the poison/preservative is maintained throughout the trap deployment period.

Poisons, preservatives or other additives should be prepared in a seawater-based medium of a density equal to, or greater than the seawater surrounding the sediment traps. If the density of the solution needs to be increased this should be done by the addition of analytical grade NaCl which has been combusted to remove organic contaminants. Other substances (e.g., commercial density solutions, sugar solutions, etc.) can be used in specific applications. Each of these, however, possesses characteristics which are incompatible with most experimental designs. The density differential between the trap solution and the seawater should be minimized so as to reduce the possibility of transformations induced by osmotic effects but should be large enough to prevent diffusive loss of the trap solutes. Also, aggregates have a bulk density only slightly greater than seawater and will settle into a brine only when their density exceeds that of the brine through exchange of pore water or collapse of the aggregates. A density differential of 0.005–0.010 g/cm³ should be sufficient for most applications. Trap solutions must be filtered (0.2 μm) before use, and a subsample of the solution retained for the determination of the initial concentrations of various constituents of interest. Ideally, these blank solutions should also be exposed to the same environmental conditions as the samples (pressure, temperature, light, time, etc.) to monitor changes that may occur in the blank during the deployment period. Brines extending above the bottom portion of a trap could change the hydrodynamic response of the trap (see section 3.2.4).

Listed in Table 3 are commonly used poisons and preservatives (not an all-inclusive list), some advantages and disadvantages or necessary precautions, and a range of effective concentrations to be maintained during trap deployment.

RECOMMENDATIONS:

1. For most applications, a poison or preservative should be used in sediment trap deployments, regardless of duration of deployment. If short-term experiments are conducted without a poison/preservative, then replicate traps with poison/preservative should be used.

2. The specific poison/preservative to be used (or lack thereof) should be determined by the scientific objectives of the trap experiment.

3. The concentration of the poison/preservative should be determined both before and after deployment to ensure an effective concentration level during deployment.

4. Poisons, preservatives or other additives should be prepared in a seawater-based medium of a density greater than the seawater surrounding the sediment traps.

5. For carbon flux (soluble + particulate) measurements, there is no universally adequate poison/preservative; all of the treatments listed either add soluble carbon for which adequate corrections are not feasible at present or introduce potentially serious artifacts from swimmers which cannot be removed completely.
Table 3: Common poisons and preservatives — advantages and disadvantages.

<table>
<thead>
<tr>
<th>Additive</th>
<th>Advantages</th>
<th>Disadvantages/Precautions</th>
<th>Concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>- live in situ experiments</td>
<td>- transient swimmers can alter apparent flux&lt;br&gt;- sample may degrade during collection</td>
<td>—</td>
</tr>
<tr>
<td>Preservatives</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Formaldehyde</td>
<td>- hardens tissue (advantage for physical removal of swimmers)&lt;br&gt;- good for SEM&lt;br&gt;- effective biocide</td>
<td>- binds proteins&lt;br&gt;- may interfere with total (soluble) C determination&lt;br&gt;- may be titrated during deployment as it is incorporated into tissue&lt;br&gt;- interferes with stable isotope measurements&lt;br&gt;- pH sensitive, needs careful buffering to prevent carbonate dissolution&lt;br&gt;- may be contaminated with N and interfere with soluble N determination</td>
<td>2-5% buffered</td>
</tr>
<tr>
<td>Glutaraldehyde</td>
<td>- as for formalin&lt;br&gt;- good for SEM and TEM</td>
<td>- may precipitate in seawater&lt;br&gt;- needs careful buffering with arsenic (which interferes with the measurement of P)</td>
<td></td>
</tr>
<tr>
<td>Salt (brine)</td>
<td>- used as gradient to retain poison/preservative in trap</td>
<td>- poor biocide&lt;br&gt;- may attract swimmers&lt;br&gt;- enhances carbonate dissolution</td>
<td>30-300 g/l</td>
</tr>
<tr>
<td>Poisons</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chloroform</td>
<td>- high density keeps it in the bottom of trap&lt;br&gt;- may preserve extra-cellular enzyme activity</td>
<td>- dissolved pigments and lipids&lt;br&gt;- causes difficulty in splitting of samples&lt;br&gt;- may attract swimmers</td>
<td>neat or saturated seawater</td>
</tr>
<tr>
<td>Sodium azide</td>
<td>- introduces no particulate carbon&lt;br&gt;- good buffer for calcium carbonate</td>
<td>- interferes with N determination&lt;br&gt;- may interfere with particulate N determination</td>
<td>10-15 g/l</td>
</tr>
<tr>
<td>Mercuric chloride</td>
<td>- good biocide</td>
<td>- may introduce heavy metal contaminants&lt;br&gt;- precipitation in sulfidic waters, may reduce effective concentration&lt;br&gt;- may alter redox state in trap (e.g., reduction of Hg in metal cod end in sub-oxic waters)</td>
<td>10 ml/l saturated solution</td>
</tr>
<tr>
<td>Antibiotics</td>
<td>- useful for specialised biocide applications</td>
<td>- ineffective generally</td>
<td>200 mg/l</td>
</tr>
</tbody>
</table>
4.5 Loss/Contribution from Dissolution/Leaching

Particulate organic carbon flux determined after picking of macro-zooplankton swimmers should be regarded as a best estimate until adequate prevention of swimmers can be developed. Picking swimmers can result in either an underestimation or overestimation of flux depending on the community present.

6. Future work should be directed at eliminating swimmer problems and in determining whether soluble carbon measurements can in fact be made in the presence of the large C background resulting from the use of formalin.

4.5 Loss/Contribution from Dissolution/Leaching

Previous sediment trap studies (Knauer et al., 1979, 1984; Lee and Cronin, 1984; Harbison and Gilmer, 1986; Lee et al., 1988) have shown that failure to remove swimmers may seriously bias measurements of many components of interest. Such components include C, N, (Table 2) and P, organic compounds and a number of metals (Fig. 17). A large portion of these components (up to 50% of total N, see Karl abstract; up to 90% of total P, see Dymond and Knauer abstracts) contained in sediment trap collectors can be in solution. This soluble phase includes materials which (1) originally arrived as particles but were subsequently converted into dissolved matter through the combined efforts of physical, chemical and/or microbiological processes, and (2) arrived as dissolved matter contained in the interstitial fluids of the sinking particulate matter. Thus, the loss of a particulate component to the soluble pool can potentially bias total downward flux calculations and must be further evaluated.

Phosphorus appears to be particularly susceptible to dissolution. Knauer and Tuel (unpublished data and Fig. 18) have shown that the dissolved P present in sediment traps can be contaminated by swimmers. They found that 50–100% of total measured dissolved P can be contributed by swimmers through the leaching of their tissues after they have entered the sediment traps. Thus, the effect of swimmers on both the particulate and soluble P pools represents a serious problem.

Although it is clear that dissolution of material from both swimmers and sinking particles is a serious problem for many bioactive elements, the full extent of these effects is not known. For example, it is unclear what the contribution of swimmers is to traps in the deep ocean. Swimmers and the effect of their leaching may be less important there than in shallow or coastal waters. Similarly, the partitioning of the particulate flux into the soluble pool has been evaluated for only a few elements. For some trace refractive, and non-bioactive elements (Knauer et al., 1984), dissolution effects may be insignificant. Obviously increased research is required to define the appropriate preparation and analytical procedures necessary for many applications of sediment traps.

The soluble component of the particulate flux can also be lost through diffusion during the period the cup is open for collection or by mixing with normal seawater during trap recovery. Losses by mixing can be minimized by using density solutions in the trap cups and through use of trap designs which incorporate positively sealed cups. In any case, the extent of solute loss should be evaluated. This can be done either by determination of the fraction of fixative or poison which remains upon recovery, or by use of tracers which identify exchange of cup solution during the trap experiment.
Figure 17: Trap collected Zn and Cd (October deployment) in the dissolved (open bars) and particulate (solid bars) phases, together with total metal fluxes (upper panel). Flux = $\mu$g dissolved + $\mu$g particulate/0.0039m$^2$ x 20.6 days. (From Knauer et al., 1984).

Figure 18: Phosphate release from four categories of swimmers over time. Swimmers were leached using standard VERTEX trap solutions consisting of filtered seawater and additions of formalin (2%) and NaCl (50gl$^{-1}$). (From Knauer and Tuel, unpublished.)
RECOMMENDATIONS:

1. Methods are required to allow determination of which organisms collected by sediment traps are, in fact, swimmers and not part of the passive flux.
2. Because the swimmer problem seems pervasive, all sediment trap samples should be examined microscopically to determine whether swimmers are present.
3. Swimmers should be removed if at all possible, or it should be demonstrated that these contaminants do not affect the particulate or soluble pool of the components of interest.
4. The components of the particulate flux dissolved during the deployment should be evaluated in any sediment trap experiment.
5. If the component of interest is significantly soluble, the investigator should insure that the integrity of the soluble pool is maintained in order to avoid loss due to mixing or diffusion processes.

4.6 Sample Splitting and Sieving

Large sediment traps (typically with collection areas of 0.5 m²) are used to collect large samples sufficient for a variety of chemical analyses and require that representative aliquots of the sample be split. In contrast, small traps (typically multiple or single cylinders) collect small samples used for specific purposes; the entire sample is generally subject to a single or series of analyses. Multiple small traps also provide for the acquisition of replicate samples and analyses without the introduction of potential splitting bias. Because the material collected in sediment traps is frequently heterogeneous, sample splitting should be avoided if possible. In addition, removal of swimmers from the entire sample collected by large traps may not be feasible. If swimmers are not removed, their effects on the particulate and soluble pools of the trap sample should be quantified.

When samples must be sieved or split for a particular application, this should be carried out with as much care as possible. Samples should be wet-sieved using filtered sea water or supernatant water from above the particulate sample. A gentle stream of water is recommended to minimize disaggregation of large particles. This procedure will dilute the dissolved portion of the sample and any poison, if present. Immersing the sieves in seawater (except for the top sieve), lifting the stack up and down gently, and allowing the particles to settle by gravity has also been found effective (see Bailey et al. abstract). This method will result in loss of dissolved material and any interstitial fluids transiting with the particles. An advantage to sieving (330 μm) is that it can remove the majority of the macrozooplankton swimmers. Splitting can be accomplished using a rotary sample splitter which has been shown to yield representative aliquots of sample (Honjo, 1978).

5 In-situ Investigations of Flux

Several of the potential artifacts associated with sediment traps discussed above could be investigated by in-situ photographic observations of traps. Such artifacts include the collection of zooplankton in traps by an active or passive response to the flow over and in
a sediment trap, behavioral responses which attract organisms to traps, and the breakup of fragile aggregates (and size fractionation of particles) due to fluid flow within a trap. *In-situ* hydrodynamic measurements of the flow field in and around sediment traps could be combined with appropriate optical observations of the organisms and particles there to provide information about these processes. Moored traps could be compared with truly free-drifting traps.

In moored traps, swimmer activity around and within traps could be measured as a function of active and passive response to flow, the degree or rate of attraction into the trap, the presence of transient visitors, and the colonization of the waters around the mooring line. An *in-situ* camera could monitor particle response to flow over the trap, the fate of fragile aggregates within traps, and observable size fractionation of particles within traps.

*In-situ* hydrodynamics and optical monitoring of a free-drifting (i.e., neutrally buoyant) reference trap could also include investigations of particles and swimmers. In a truly no-flow situation, the flux of observable particles (i.e., >.1 mm), their sinking rates, and the distribution of flux according to different size classes of particles could be measured. The reaction of organisms to a trap with little associated flow or pressure field and to a diffusion-controlled scent field would provide valuable information on swimmers.

Visual documentation by attached camera systems (Asper, 1988), remotely operated vehicles (ROV’s) and submersibles of swimmer activity and large aggregate behavior occurring at trap openings of currently moored systems would provide valuable information, where and when such vehicular instrumentation is available. However, it is likely that swimmers might respond to the sound, light and turbulence associated with the presence of an ROV, submersible, or even the flood lights of an *in situ* video system.

It has also been suggested (Wassmann, 1985; Asper, 1988) that traps be evaluated in environments where both swimmer and hydrodynamic biases are minimized. For example, collections from traps deployed in anoxic zones of fjords or other basis with restricted circulation could be compared to collections from traps at the same location but in surface water. Asper (1988) used a camera-equipped trap at 500 m in the Black Sea to investigate the nature and rate of sedimentation and found that, at that depth, no interference from swimmers or current activity were found. In contrast, a similar trap deployed in the Panama Basin (Asper, 1987) was repeatedly disturbed.

**RECOMMENDATION:** We suggest that camera systems located on the traps (i.e., viewing the edge and inside of the trap) should be developed. These optical observations should be coupled with hydrodynamic measurements within and over the trap.
6 Summary of Recommendations for Sediment Trap Studies

6.1 Hydrodynamic Recommendations

6.1.1 Long-Range Recommendations

6.1.1.1 Laboratory Studies:

a. Laboratory experiments indicate that within a range of dimensions and conditions, cylinders appear to be the least biased collectors. For practical reasons cones are also used. Additional flume studies are required using particles that behave dynamically similar to the particles collected in the field (though possibly impossible) over Reynolds numbers up to $10^5$ using both cones and cylinders.

b. The effect of baffles, screens, and lips around traps also need to be tested further, but will probably require field testing because of scaling problems.

c. Studies are needed to identify the mechanisms by which particles are retained in traps by using flow visualization studies and flow sensors.

6.1.1.2 Field Studies:

a. More extensive field measurements are required to characterize the trapping environment, to determine trap performance, and to interpret particle/flow/trap interactions.

b. Engineering studies using flow sensors are required to evaluate flow relative to traps using various mooring configurations (floating vs. moored) and environmental conditions (upper/deep ocean, high/low energy).

c. Develop neutrally buoyant sediment traps for use as a standard against which to judge the performance of other trap designs subjected to flow past the trap. (We assume that no hydrodynamic particle trapping bias occurs in conditions of no flow relative to the trap mouth.)

d. Until neutrally buoyant traps can be designed, intercomparison experiments between single, instrumented floating traps and moored traps will help evaluate relative trap efficiency under varying flow conditions.

e. Tracers: Continue to use the measured accumulation rates of conservative substances in the sediments, and/or radionuclide tracers to calibrate traps over appropriate time and space scales.

6.1.2 Recommendations for Immediate Application to Research Programs

a. Measurements of the approach velocity at each trap depth are recommended for all moored and floating traps and should be published with flux data. Temperature sensors should be included for traps located in the upper ocean to the base of the thermocline.

b. Cone traps should always have baffles at the top to decrease turbulence and mixing within the cone.
c. In using cylinders, the Reynolds number of the environment should be used to select an aspect ratio (measured to the top of the brine layer) sufficiently large to maintain a tranquil layer of fluid at the trap bottom. Studies of fluid motion in traps indicate that $A = 3$ would suffice up to $R_t = 6,000$ (about 6 cm/s for $D = 10$ cm), $A = 5$ up to $R_t = 8,000$ and $A = 8$ is sufficient for at least $R_t = 20,000$ (about 20 cm/s for $D = 10$ cm). Velocities cannot always be predicted, so traps should be designed for the maximum velocity expected.

d. Sediment trap programs should be designed to minimize the flow velocity past a trap. For the upper ocean, floating (surface tethered) sediment traps conceptually experience lower relative flow than moored (bottom tethered) traps.

e. Floating trap configurations should maximize the trap's tendency to follow the water mass, and to minimize 'pumping' due to transfer of wave energy through the mooring line.

f. Bottom tethered moorings should be sufficiently taut to minimize trap and mooring tilt and to retain traps at their intended collection depth. Tiltmeter and pressure data would be useful.

g. Publications should be explicit about the size and geometry (including use of brines, types of baffles, closure devices, etc.) of traps used, the mooring design and current regime to allow later analysis of trap performance as we increase our understanding of trap hydrodynamics.

6.2 Sample Integrity Recommendations

6.2.1 Long-Range Recommendations

a. All sediment trap samples should be examined microscopically (at least with a dissecting scope) and their composition noted.

b. All metazoans over 335 μm should be removed from the sample. Anything removed from the trap should be recorded. Living protozoans should be left in the trap, but large ones noted.

c. Some additive appropriate to the experiment should be added to sediment trap solutions to retard bacterial activity. Currently the use of poisons and preservatives is incompatible with the measurement of dissolved organic carbon (and perhaps nitrogen), so no good method exists for determining the quantitative importance of this pool. The extent to which this biases the total carbon flux is unclear.

d. Care should be taken to account for material lost from the particulate to the dissolved pool and material contributed to the dissolved pool by the leaching of soluble components from swimmers.

e. Trap solutions containing poisons or preservatives should be added at a density greater than that of seawater.
f. Under certain conditions, screens can be an effective tool in reducing the number of swimmers. However, we don't recommend their use until there is a reliable way to evaluate and correct for the \textit{in-situ} bias against large, passively-sinking materials that are excluded by the screens.

6.2.2 Recommendations for Immediate Application to Research Programs

a. Find a way to exclude swimmers from traps. Learn more about the behavior of organisms to better determine which are swimmers and which are not. Determine whether traps promote passive introduction of swimmers, and if so, design a trap to prevent this.

b. High priority should be focussed on methods which could be used to measure dissolved organic carbon in traps while still preventing bacterial activity.

c. The presence of swimmers is perhaps the major problem facing sediment trappers today. We recommend that more effort and resources be directed toward solving this problem.
7 References


REFERENCES


REFERENCES


8 Appendix A

Abstracts

8.1 Sediment-trap Measurement of Particle Fluxes: Effects of Bacteria and Zooplankton

Cindy Lee, Stuart Wakeham and John Hedges

The use of sediment traps to measure oceanic particle fluxes has become widespread. Because particles can be significantly degraded during the two-week and longer periods over which traps are frequently deployed, the use of poisons and preservatives has become common to prevent microbial decomposition. We have conducted experiments on the effectiveness of several different treatments to retard bacterial activity (measured as uptake of thymidine and glutamic acid), both in the laboratory using simulated sediment trap material and in sediment traps deployed in Dabob Bay, WA. We measured the minimum effective concentration (concentration necessary to reduce activity to 1% of the initial activity) in the laboratory experiments, and the percent reduction of activity from the unpoisoned control (100%) in the sediment trap experiments. Some of our initial results are:

<table>
<thead>
<tr>
<th>Minimum Effective Concentration</th>
<th>Percent Reduction in Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Winter</td>
</tr>
<tr>
<td>Antibiotics</td>
<td>None (&gt;2.6 g/l)</td>
</tr>
<tr>
<td>Salt</td>
<td>None (&gt;350 g/l)</td>
</tr>
<tr>
<td>Sodium azide</td>
<td>None (&gt;10 g/l)</td>
</tr>
<tr>
<td>Formalin</td>
<td>0.3%</td>
</tr>
<tr>
<td>Chloroform</td>
<td>50% satd. soln.</td>
</tr>
<tr>
<td>Mercuric chloride</td>
<td>0.5 g/l</td>
</tr>
</tbody>
</table>

These results indicate that some of the treatments, sodium azide for example, worked better under our field conditions than in the laboratory. There may also be differences in the effectiveness of the poisons depending on the exact nature of the organic material.

With the use of poisons, however, another potentially more significant bias is introduced to sediment trap collections. This is the collection of zooplankton which swim into the trap and die from contact with the poison. In shallow traps placed in some coastal areas, most of the material collected can be swimmers, although the 850 μm swimmers never made up more than 10% of the dry weight of material in our Dabob Bay experiment. Physically picking the swimmers from the trap material can lead to a significant improvement in accuracy of bulk flux measurements but is liable to considerable subjectivity on the part of the picker. Some elements and organic compound fluxes can be significantly biased by small errors in the picker's judgement. In addition, it is not always possible to determine which zooplankton swam into the trap and died and which died first and fell into the trap. Zooplankton can also be a problem in calculating particle fluxes in the absence of poisons. They appear to be capable of swimming into traps and consuming sedimented material. Evidence from organic geochemical studies of open ocean sediment trap studies suggests
that swimmers can influence sediment trap flux calculations for samples from as deep as 1,500 m to 2,700 m.

8.2 Can the Effects of Swimmer Leaching in Sediment Trap Studies be Corrected?

George Knauer

In previous sediment trap studies, Knauer et al. (1979; 1984) reported that failure to remove "swimmers" (zooplankton which swim into the traps and die) could seriously bias the results of CNP and metal analyses. This problem was tentatively handled by these and other researchers by the tedious procedure of removing each individual swimmer before analysis. However, we now know that such procedures are only partially successful since both swimmers and passively sinking particulate materials can leach significant quantities of organic/inorganic materials into the surrounding trap solutions (regardless of whether preservatives/poisons are employed). This represents further error as both a loss (from the passive particles) or contaminant (from the swimmers). That is, the total flux of 

\[ X = X_p + X_d \]

where \( X_p \) is \( X \) from the particulate phase and \( X_d \) is \( X \) from the dissolved phase.

We have been exploring ways of determining the magnitude of this leaching problem and whether or not effective solutions can be found. Our initial results with phosphorus have been encouraging. In formalized trap solutions, maximum swimmer phosphorus (P) contributions to the trap solution are reached by the first 2–3 days and remain constant thereafter. This suggests that correction factors can be obtained by determining the total P released per mg swimmer into the surrounding trap solutions and subtracting this amount from the total dissolved P. We have determined that the swimmer contribution to total dissolved P ranges from 50–100+% indicating that implementation of this approach will require further refinement.

8.3 The Measurement of Total C, N and P Flux

David Karl

Most measurements of sediment trap collected materials have focused on a determination of the particulate phase. Recent results, however, indicate that for certain elements a large portion (up to 50% of total N, for example) of the material contained in the sediment trap collector is in solution (<0.22 μm). This soluble phase includes materials which: (1) arrived as particles, but were subsequently converted into dissolved matter through the combined effects of physical, chemical and/or microbiological processes and, (2) arrived as dissolved matter in the form of interstitial fluids of the sinking particulate matter. The latter pathway comprises an important mechanism for the removal of dissolved materials from the epipelagic zone that has generally been ignored in sediment trap field studies conducted to date. The inclusion of the dissolved N component to derive an estimate of total flux is necessary for obtaining more accurate estimates of new production and material flux in the marine environment.
8.4 The Use of Screens as a Potential Solution to the Swimmer Problem: Results from a Field Experiment

David Karl and George Knauer

Actively swimming macrozooplankton ("swimmers") are often inadvertently collected in sediment traps, especially when traps are deployed in the upper 500 m of the water column. As they are not part of the passive particle flux field, their presence will result in an overestimation of the true rate of particle flux. In the upper 200 m, the swimmers often comprise the bulk of the trap-collected POC, PON and POP; they are truly the scourge of the sediment trap business. Generally, their presence is either: (1) acknowledged and their impact reduced by manually removing the zooplankton carcasses before further sample processing, (2) acknowledged, but only in passing, or (3) totally ignored. Neither of these three treatments is acceptable, if the desired outcome is to obtain accurate flux estimates for the upper water column. One potential solution is to place a screen at the base of the baffle near the opening of each sediment trap as a means of preventing these nasty swimmers from ever entering the sediment trap. This simple-minded treatment appears to perform well under field conditions and produces the desired outcome of a swimmer-free particle collection. A discussion will focus on the advantages and disadvantages of the use of 335 μm mesh screens and will provide a comprehensive set of data to evaluate the field performance of this approach.

8.5 Biological Mediation of the Oceanic Carbonate System: A Proposal Assessment

Peter Betzer, Robert Byrne, Giselher Gust, Kenneth Carder and Richard Feely

The carbonate system in the worlds oceans is controlled by both physical/chemical and biological processes. One of the major unresolved questions concerning this system is the relative importance of the three dominant biogenic carbonate sources: coccolithophorids, foraminifera, and pteropods. Much of the recent work which has implicated pteropods as being the biggest contributors to carbonate fluxes was based on flux measurements made in the Pacific Ocean. Here undersaturated waters intrude into the upper layers of the Pacific where the bulk of the carbonate-producing organisms live. As a result, the carbonate fluxes determined in the upper kilometer of the vast region are a function of: (1) biogenic production, (2) dissolution and, (3) animal-sampler interactions. Because of its markedly different saturation profile, the Atlantic Ocean presents us with a good opportunity to obtain carbonate fluxes which are not greatly influenced by dissolution processes. Specifically, the water column at the primary Global Ocean Flux Station in the Atlantic Ocean near Bermuda is saturated with regard to the most labile carbonate phase, aragonite, to more than two kilometers. Thus, carbonate flux measurements can be made deep enough to essentially eliminate animal/sample interactions (only a few, extremely rare, bathypelagic pteropods live below one kilometer) and yet shallow enough that settling materials are not modified by solution. An experiment is proposed whereby the inputs of the three major carbonate producers are quantified for this portion of the Atlantic Ocean.
8.6 What is a “Swimmer”?
Mary Silver

From light and electron microscopic surveys of the VERTEX trap materials, we have been impressed by the variety of living organisms that occur in sediment traps. Some of these, such as the larger crustaceans, are readily identified as trap intruders. These “swimmers” are obviously not part of the “particulate flux” and many can be removed comparatively easily. Others, such as single eggs, sometimes can be quite abundant, are not associated with obvious swimmers, and can contribute a substantial fraction of the trap carbon. Should they be removed? Others, such as some radiolarians, are covered by feeding residues—thereby appearing to be detritus—and some do not have the tell-tale skeletons that conveniently identify them as living organisms. In the VERTEX cruises between 1981–1985, such cryptic organisms contributed about 1/3 of the trap carbon at the base of the euphotic zone, after the obvious “swimmers” were removed. A further, more complicated problem is the contribution of marine snow by swimmers. Larvaceans can occur abundantly in traps and undoubtedly enter with their houses, which are richly supplied with fecal pellets, microorganism(s) and small detrital particles. Such “swimmer snow” may contribute 10% or more of the trap carbon near the base of the euphotic zone. Such organism-related problems are most serious in the upper few 100 m and decline with depth. Overall, the decreasing contribution of the cryptic “swimmers” and their snow below the euphotic zone accounts for some of the depth related loss in the particulate flux, a loss that is interpreted as regeneration.

8.7 Seasonal Variation in the “Swimmer” Problem at the VERTEX Seasonal Station in the North Pacific
Anthony Michaels, Mary Silver and Marcia Gowing (submitted by Alan Shanks)

“Swimmers,” especially crustacean zooplankton, are widely recognized as artifacts in sediment traps. Here we report the presence and seasonal magnitude of 3 other significant “swimmer” problems in flux measurements by sediment traps. We examined trap samples (Knauer MULTITRAPS, 0.0039 m² collecting area) from 3-month deployments over a period of 18 months.

1. The most conspicuous and best known problem resulted from the presence of metazoan invertebrates. Crustacea are usually recognized and removed, but other zooplankton are more difficult. For example, larvaceans were very numerous in VERTEX traps, the smaller ones difficult to remove, and they represented “fluxes” of 500–1,000 animals/m/day, (equal to approximately 10–20 mg C/m/day) in the upper 200 m, with the higher values in winter and spring. “Fluxes” of siphonophore bells, which often collapse or are inconspicuous, were 20–130 bells/m/day (1–5 mg C/m/day) in the upper 200 m, with the lower values in summer. The carbon in larvaceans and siphonophore bells was approximately 10–50% of the carbon fluxes measured after swimmer removal. Flatworms, carrying abundant symbionts,
rounded into balls resembling mucus commonly found in traps. Screens to keep out swimmers were only partially effective: 300 μm mesh netting excluded most large zooplankton, but large numbers of small copepods still were present.

2. Swimmer products and less recognizable parts of zooplankton (larvacean houses, siphonophore tentacles and other body parts, invertebrate eggs, fish scales) occur in traps. In VERTEX traps, mucilaginous houses likely brought in by larvacean swimmers, and thus "swimmer-snow," may have constituted an artificial flux of approximately 5–10 mg C/m²/day.

3. Large, living protozoa are often difficult to recognize or are misinterpreted as dead, sinking specimens from the surface. Some phaeodarian radiolarians resemble fecal pellets. Other large protozoans, bearing more recognizable skeletons, may descend during particular life history stages or live at the trap depth and, like the invertebrates, be drawn into the trap as alive specimens. These protozoans may constitute major fractions of trap carbon, especially in the mesopelagic.

8.8 The Fecal Pellet Fraction of Open-Ocean Particle Flux: Is a Major Portion Disintegrating in the Traps?

Cynthia Pilskaln

Fecal pellets produced by crustacean zooplankton have been identified as an abundant as well as a ubiquitous constituent of sediment trap particulate samples collected in the world oceans. Many have hypothesized that crustacean pellets produced in the pelagic ocean represent one of the most quantitatively important modes of vertical transport through the water column of various biogeochemical components and that these biogenic particle packages are responsible for the majority of the mass flux of material to the deep-sea benthos. The hypothesis is based upon: 1) high pellet production rates by copepods and euphausids of up to 150 pellets/individual/day, 2) fecal pellet settling velocities of up to 200 m/day, 3) the collection in meso- and bathypelagic sediment traps of large numbers of pellets containing well-preserved calcium carbonate and opaline silica algal skeletal elements and, 4) chemical analyses of the composition of pellets collected at such depths showing that the pellet contents are not primarily refractory but often rich in organic matter (up to 50% of the individual pellet mass).

Detailed pellet mass flux calculations however, show that crustacean fecal pellets may not be as important to the particle mass flux as previously assumed, contributing less than 8% to the total mass flux of particulate matter at depths below 500 m. Only under anoxic depositional regimes and/or in regions of intense coastal upwelling and along the ice edge zones in the Southern Ocean, have we found fecal pellets to be quantitatively important to the particulate mass flux and the delivery of material to the sediment/water interface. These results are most likely a reflection of 1) the lack of biodegradation of organic-rich pellets under anoxic depositional conditions and, 2) the extremely high pellet production occurring in the productive coastal upwelling and Antarctic ice edge environments.

The questions then arise: Could we be underestimating pellet fluxes in the open-ocean due to disaggregation occurring in the traps? How much of the amorphous organic material
in open-ocean trap cups (poisoned and non-poisoned) represents disintegrated fecal pellets? If we could assess this amount, would our pellet contribution values be much greater and by how much? Answers to these questions revolve around determining how efficient the poisons and fixatives which we use in the traps are in retarding or arresting microbial and protozoan activity, and determining what portion of the pellet material delivered to the trap disaggregates within the cups and/or through processes of post-recovery sample preparation.

8.9 Swimmers in the Northeast Atlantic: A Serious Impediment to Flux Estimates in the Upper Water Column

Richard Lampitt

Sediment traps are a source of attraction to a number of species of zooplankton. These species swim into the traps where they then modify the collected material by ingestion or defecation. They may then die within the trap cups or swim out but in neither case is it possible to assess with confidence their effect on the trapped material. The problem is most severe in the upper water column and if poisons as opposed to fixatives are used in the trap cups, these “swimmers” may not be readily distinguished from the carcasses which should rightly be considered as part of the flux. Swimmers can contribute significantly to the material collected in sediment traps and although these have usually been removed prior to analysis, details in most cases remain unpublished.

In June 1988 drifting traps were deployed at “BIOTRANS” (47°N, 20°W), one of the JGOFS sites, at depths of 20, 50 and 230 m. Upon recovery all the trap cups were found to contain very large numbers of the amphipod *Thermisto compressa* (formerly *Parathermisto gaudichaudii*). On the first deployment there was no fixative and after 2 days drifting a putrid mass of carcasses was recovered. On the second deployment, 2% formalin was added beforehand. The amphipods still swam into the traps but in this case the bodies were well preserved. The amphipods comprised about 98% of the mass of material collected in the cups a value which is no doubt considerably higher than has been found previously. With this level of “contamination” such samples are of little use in particle flux studies.

*Thermisto compressa* has a wide geographic range within the cooler waters of the North Atlantic and although present throughout the year, it has a strong seasonal cycle. This seems to be not only related to the abundance of its prey (other zooplankton) but also to water temperature and possibly to the availability of sites to moult (gellatinous organisms). As far as the JGOFS 20°W transect is concerned the species will not be a problem at 15°N and 33°N, but at 47°N it will be abundant in May and June and unpredictably so from July to October inclusive. At 60°N, peak abundance will not be found until later in the year, possibly August, and at 72°N the peak will probably be later still although data are scarce. Larvae and juveniles of the species typically remain above the thermocline (Bigelow, 1926; Williams and Robins, 1981), juveniles often being in association with medusae. In some regions adults migrate vertically from their nocturnal habit in the surface zone to depths of several hundred meters in the day. However at “BIOTRANS” this year there was no evidence of such vertical migration.
It seems that swimmers are likely to be a much greater problem in boreal and temperate waters than has previously been encountered in low latitudes at least at certain times of the year. All of the obvious methods for deterring them have serious drawbacks and these will be discussed.

8.10 Preliminary Results of Preservative Investigations

Rolf Peinert

**In-situ** degradation of materials collected by sediment traps can severely bias particle flux measurements by altering the biochemical composition of settled particulates and by releasing various compounds into the dissolved phase. Numerous trap deployments by the Kiel Group in different environments and seasons as well as ongoing laboratory studies suggest that in-situ preservation/poisoning of trap samples is a must even with short-term deployments to counterwork both microbial degradation and grazing by swimmers.

A sediment trap sample preservation study was carried out with natural trap samples from Kiel Fjord (unpublished data of H. Maske, M. Meyerhofer, IFM Kiel, and R.F.C. Mantoura, IMER Plymouth). Subsamples were treated with different preservations/poisons and different final concentrations (formaldehyde: 0.12 M, 1.7 M; glutaraldehyde: 6 mM, 20 mM; sodium azide: 25 mM, 150 mM; mercuric chloride: 4.4 μM, 0.25 mM; chloroform: saturated solution). After laboratory storage for 3 weeks at 10°C, preservation was tested for carbon, nitrogen and different pigments. Preliminary results strongly indicate that chloroform interfered with nitrogen measurements and a 20 mM solution of glutaraldehyde biased carbon analyses. Bacterial activity (14-C glucose respiration) was efficiently suppressed by all agents if applied in high enough concentrations (lower concentrations of sodium azide and mercuric chloride were not sufficient).

Field experiments with floating sediment traps (N.E. Atlantic, 150 m depth, 3 weeks deployment during summer (unpublished data from K. Kremling, IFM Kiel) showed a release of dissolved compounds from collected particulates despite sample preservation by a 1% formaline solution. For biogenic compounds, this is indicated by high nutrient concentrations (PO₄, SiO₄, NO₃) in the supernatant water of the sampling cups. In a second experiment, leaching of heavy metals (Cd, Cu, Co, Ni, Pb) from collected particles yielded high concentrations in the supernatant water. Data for the respective sedimented particulate parameters and for swimmers contaminating the trap sample are not available yet. An educated conservative guess, however, suggests that up to 50% of sediment particulate phosphorous and cadmium (and smaller portions of the other compounds) could have gone into solution. This stresses the importance of measuring dissolved compounds in trap sampling cups after retrieval. Also, cups must be tightly sealed in situ after a sampling period to prevent losses by exchange with surrounding water.
8.11 Particle Sedimentation in Polar Oceans: Preservation Problems

Dierk Hebbeln and Gerold Wefer

We deploy time-series sediment traps in polar oceans over time spans of one year or more.

The aim is to study the carbon cycle with respect to export productivities in different areas (e.g., in open and ice covered waters). A strong seasonality in particle sedimentation has been observed. As a result of this the equipment used shows signs of increased corrosion and problems have arisen regarding the fixation of samples with high amounts of organic carbon content.

Results from sediment trap investigations in the Fram Strait—the seagate between Spitsbergen and Greenland—are shown in Fig. 1. There is a significant particle flux maxima in the summer/autumn and a corresponding minima in the late winter. One important aspect is the temporal offset in the annual flux pattern with a maximum in July/August in one year and in October/November in the other. Another important aspect is the significant difference between the total annual fluxes noted in these two experiments. The total annual flux in sediment trap FS 3 (1987-1988) was more than 4 times higher than the total annual flux in sediment trap FS 1 (1984-1985). These differences are most probably due to different sea-ice conditions.

An even stronger seasonality in the particle fluxes was observed in the Bransfield Strait, Antarctica (Fig. 2). More than 90% of the whole annual sedimentation settled in only two months. The rest of the year was marked by very low particle fluxes. A comparable temporal offset like the one in the Fram Strait was not observed in the Bransfield strait.
As already mentioned, these strong seasonalities lead to problems regarding the fixation of the samples. Normally the samples are poisoned with 1 ml saturated HgCl$_2$ solution per 100 ml seawater. During times of high particle flux this poisoning might not be sufficient, resulting in the development of an anoxic environment in the sample bottle, along with all the problems caused by such an environment (e.g., organic carbon decomposition, organic nitrogen decomposition, etc.). On the other hand, during times of low particle flux, concentrations of 1 ml saturated HgCl$_2$ solution per 100 ml seawater could lead to the precipitation of various mercury compounds such as calomel. Such compounds add to the particle flux and therefore change the total flux results. Although the precipitation of mercury compounds is not restricted to a special flux pattern or to a certain time of the year, we assume that this type of precipitation has considerable effect on the flux data, especially during times of very low particle flux encountered in high latitudes.

From our data, it seemed that during times of high particle flux a fixation with at least 1 ml saturated HgCl$_2$ solution per 100 ml seawater is necessary, whereas during times of low particle flux this concentration will almost certainly be too high. One possibility to solve the preservation problem is to vary the HgCl$_2$ concentration according to the level of particle flux. However, without first data on the seasonal particle flux, it is not possible to predict the time of the year when particle flux is high and how high it will be. Other preservatives, like formaldehyde, are not an alternative for mercuric chloride in our studies with special emphasis to the carbon cycle. Previous studies have shown that especially in long term deployments formaldehyde can act as an organic solvent, dissolving and releasing...
organic component from the trapped particles to the trap solution. Thus, formaldehyde will possibly bias the flux data of the organic components in the particle flux.

8.12 A Non-disruptive Sieving Technique

Thomas Bailey, Marsh Youngbluth and Peter Davoli

Our work has been conducted in the Gulf of Maine where we have measured the flux of fecal pellets (primarily from the euphausiid *Meganyctiphanes norvegica*) out of the euphotic zone. Our sediment traps are 8-in. OD × 32-in. long cylinders. These cylinders are configured in an array (rosette) of eight traps. The arrays are free-drifting for periods of 24–48 hours, with only one rosette on each deployed line.

Recognizing that each sample must be “picked”, for studies involving repetitive short-term sets with multiple-trap arrays, sieving is an absolute necessity. In our case, it is virtually impossible to process 16 samples every 48 hours if we don’t sieve before picking.

Our technique involves passing each sample through a nested series of sieves. These sieves consist of acrylic cylinders fitted with Nitex mesh (1-mm, 500, 200, 64, 33 and 10-μm). Just before pouring a sample onto the uppermost sieve, the nested stack is immersed in a bucket of filtered seawater such that only the top half of the upper (1 mm) sieve is not under water. Once a sample has been placed in the uppermost chamber, the entire stack is lifted up and down slowly, allowing the particles to settle through the stack by gravity. Our experience with this procedure has shown that it provides a gentle and relatively rapid segregation of particles. The majority of the swimmers are retained on the larger (1-mm, 500 and 200-μm) screens. Small cyclopoid copepods (e.g., *Oithona* spp.) and nauplii usually reach the 64-μm sieve. These small zooplankton are subsequently removed by picking. Most of the fecal pellets in our samples are collected on the 200 and 64-μm meshes. Pellets caught on the larger meshes are removed by pipet. Amorphous floc is retained primarily on the 10-μm mesh. After separation, the size fractions are rinsed into jars and either preserved or frozen. Swimmers are preserved for taxonomic identification.

Microscopic examination of sediment trap samples, before and after sieving, has revealed only minor disruption (breakage) of large fecal pellets, and no apparent disruption of smaller particles. The integrity of flocculent particles is obviously compromised with any sieving technique. Because we are not really concerned with total organic flux, we have not attempted to determine the proportion of the total floc that is retained by the 10-μm mesh, how much is lost to the larger meshes and particles (e.g., some floc sticks to the swimmers) and how much is lost through the smallest mesh. From our perspective, the advantage to sieving is the speed of processing samples at sea (in terms of separating swimmers from particles). Disadvantages include the disruption of fragile particles (especially flocs) and the loss of pore water from particles.
8.13 Commercial Fishing Operations as Hazards to Sediment Traps

Robert Anderson and Pierre Biscaye

As GOFS moves into basin-scale studies, an important objective will be to evaluate organic matter fluxes at highly productive ocean margins and the lateral flux of margin-derived organic matter into the ocean interior. High levels of primary production at ocean margins often support major fish stocks that are in turn exploited by commercial fisheries. Instrumented moorings used to support sediment traps are viewed as undesirable obstructions to fishing; for example, nets, lines, and other fishing equipment may be caught and damaged on the moorings.

The SEEP (Shelf-Edge Exchange Processes) program is now involved in its second major field experiment designed to study, among other things, the fate of organic matter produced in continental shelf waters of the Middle Atlantic Bight. The field program began with 10 instrumented moorings incorporating (nominally) 20 time-series sediment traps as well as current meters, fluorometers, transmissometers, in-situ oxygen electrodes, in situ pumps for chemical sampling, thermister chains, etc. in shelf and slope waters in the region offshore of Chesapeake and Delaware Bays. Three sequential deployments of the instruments will cover a period of 15 months, including 2 spring blooms. Initially, 8 of the instrumented moorings located at water depths of about 400 m or less were each protected by 2–3 guard moorings (total of 20) equipped with large, highly visible (lights and radar reflectors) surface buoys positioned 100–200 m on either side of the instrumented mooring.

During the course of the first 2 mooring deployments, SEEP lost or had damaged 3 instrumented moorings, 15 guard moorings (some of which also were equipped with VMCM's), and an acoustic doppler current profiler. Some of the equipment has been recovered by dragging. Other equipment, attached to floatation, has been found by fishermen as far away as Nova Scotia. One entire mooring was physically picked up from between 2 guard moorings and set down again about 1/2 mile away, with loss of 2 sediment traps in the process. Despite the emplacement of guard buoys, publishing the locations of the moorings in the U.S. Coast Guard Notice to Mariners, and our attempts to inform fishermen of the locations of the moorings, we continue to suffer equipment losses to fishing activities. The attitude of some fishermen is reflected by the bullet holes found in 2 of the guard buoys recovered by dragging. Other fishermen, on the other hand, have been extremely helpful in recovering and returning lost equipment.

The third SEEP-II mooring deployment is going into the water at the time of this meeting. As a new approach to protect our equipment, we have identified sites of "hangs" (wrecks of ships, barges, airplanes, etc.) known to, and avoided by, fishermen. To the extent possible, instrumented moorings will be placed in the vicinity of these hangs.

The principal lesson learned from this experience is that mooring sites cannot be selected on scientific merit alone. During the course of our field program, we have made helpful contacts within the National Marine Fisheries Service and through Sea Grant who, in turn, have good working relationships with the fishermen in the area of our field program. These contacts have been helpful in pointing out: a) why certain of our initial mooring sites were poor choices with respect to conflict with fishermen, and b) where better choices might have been (e.g., fishermen know of, and avoid, cable crossings). Research programs intending to
deploy moorings in heavily fished areas need to solicit input from fishermen on potential mooring sites before deployments are made. Within U.S. waters, the NMFS and Sea Grant may be used. In foreign waters, particularly in third world countries, it may be much more difficult to make helpful contacts with the fishermen. Even with the best of planning, some risk of damage to, or loss of, moorings placed in heavily fished areas will inevitably remain.

8.14 A Trap for all Seasons?

Wilford Gardner

For more than a decade the dynamics of sediment traps have been studied in a variety of laboratory and field experiments to assess whether or not the geometry of any trap design will yield a quantitative vertical flux of particles across a horizontal plane, i.e., one that is not biased in the mass, size, density or composition of particles that would gravitationally settle through that plane in the absence of the obstruction produced by flow around and inside a particle trap. The potential for bias is great because it has been well documented photographically that flow past any container of even 1–2 cm/s will generate eddies and turbulence with vertical velocities much greater than the settling velocities of most particles found in the ocean. The standing crop of particles collected in water bottles has a mean size on the order of 5–8 μm but theoretical work shows that the mass flux of particles should be carried in larger particles, so the dominance of larger particles (> 20–63 μm) in trap collections is to be expected, and by itself is not proof of a bias. Baker et al. (1988) have conclusively shown, however, that as current velocity increases from < 12 cm/s to 12–30 cm/s and greater, collection efficiency decreases as particle fall velocity decreases. Further work is needed to determine whether the hydrodynamic size/density sorting occurs in eddies generated at the trap mouth or as particles settle across some interior trap boundary layer. The complexity of analyzing this problem increases with recent findings that most particles settle as large aggregates whose original size cannot be determined after trap recovery.

The dynamics of particle trapping have been described in terms of dimensional analysis by Butman et al., (1986), providing the proper framework in which to study the problem. Generalities that have persisted through trap studies are that cylinders are likely to produce the most reliable and reproducible fluxes because of axial symmetry and constant cross section. Collection rates in cylinders increase as a function of aspect ratio and level off above a ratio of 3–5. The addition of brines to traps will alter their effective aspect ratio. Funnels generally undertrap compared to cylinders, but steep walls and baffles at the top improve efficiency. Funnels are difficult to quantify in dimensional analysis because of sloping walls. Traps with mouths even slightly smaller than the body cause an over-collection of particles.

The aspect ratio of sediment traps must be great enough to prevent scouring of the entire trap, a process which is a function of Reynolds number. Collection efficiency is also a function of Reynolds number, but whether the same efficiency function is obtained by varying either velocity or trap diameter has yet to be demonstrated. Butman (1986) and Baker et al., (1988) found decreasing trap efficiency with increasing Reynolds number, but Blomqvist and Kofoed (1981) found opposite trends for organic and inorganic matter in cylinders less than 3–4 cm in diameter, suggesting that particle dynamics may be different in cylinders of that diameter and should not be used in predicting dynamics of large traps. Other studies have shown erratic collection rates for narrow cylinders. Field studies show
cylindrical traps sometimes collect more organic carbon than wider funnel-shaped traps (Noriki and Tsunogai, 1986). Dimensional analysis alone may not distinguish whether changes in trap efficiency result from size/density discrimination as particles enter the trap or in the manner in which particles cross boundaries and become part of the trap sample, or are resuspended.

Tilting cylindrical traps either up or down stream increases the apparent flux by as much as 250% at a rate proportional to the angle of tilt. Similar studies need to be made on funnel traps, which, because of flow considerations, might be affected more by tilt than cylinders. Traps held vertically in the upper water column can experience an effective tilt due to the passage of internal waves.

Although horizontal processes are important in the dynamics of sediment traps, collection rates in cylindrical traps appear more closely related to vertically settling particles than the horizontal flux of particles in a flow. This follows from a field experiment in the open ocean where currents, particle concentrations and trap fluxes were measured during a one-year period. The horizontal flux at different locations within a 35 km transect varied by over a factor of 70, but trap fluxes varied by only a factor of 3. Interpreters of trap data still must carefully consider absolute vertical fluxes and the influence of nearby particle sources, especially those with significant horizontal transport as they settle.

Further advancements in the study of trap dynamics are likely to come only through carefully controlled experiments. Controlled experiments suggest the need for a laboratory environment, but the inability to reproduce many in situ ocean conditions argues for field experiments. Attention should be paid to geochemical studies as well as particles and hydrodynamics.

8.15 Sedimentation of Particulate Matter by Marine Snow Aggregates

Vernon Asper

Previous concepts of marine particulate matter consisting of individual particles settling slowly through the water column have been replaced by an understanding that most sedimentation occurs via some form of aggregates. Fecal pellets are quite important in some places and over certain seasons but contribute a small fraction of the total flux in most cases. Marine snow aggregates are currently under investigation using a variety of methods in an attempt at determining their role in sedimentation. The difficulty in studying snow arises due to the extreme fragility of the aggregates; even mild turbulence can alter or destroy them, rendering traditional sampling methods useless.

Using a series of photographic techniques, it has now become possible to determine the in situ sinking speeds, fluxes and concentrations of marine snow aggregates. Results from these investigations indicate that aggregates settle at widely varying sinking speeds ranging from near 0 m/day to > 150 m/day. In both the Panama Basin and Black Sea, aggregates contribute nearly all of the observed sedimentation of particulate matter, although these results should only be applied to the specific site and time of their collection.

If snow is contributing substantial fractions of the flux in other areas, we may need to allow for its importance in modeling sediment trap performance for the following reasons:
1. Flume-based studies using small, monodisperse particles may not represent the best approach at understanding in situ particle sedimentation.

2. Investigations of in situ particle sizes and shapes must allow for the fragility of the aggregates; most widely-used techniques provide measures of the size spectra of the constituent particles and not the aggregates themselves.

3. Models of particle sinking speeds based on pump- or bottle-sampled material may yield results which are an order of magnitude or more too low.

8.16 Settling Particles in the Oceanic Interior; Trapping Efficiency Depends Upon the Reality of the Descent Mechanism

Susumu Honjo

While examining the collection efficiency of sediment traps, the actual transportation mechanisms of oceanic particles have to be examined carefully. The majority of particles provided to the water column, whether produced biologically in the upper ocean or as lithogenic particles supplied from all sides of the ocean, are either too small or too light to settle by themselves in sea water without the provision of some sinking speed accelerator. One mechanism known today to accelerate sinking speeds of fine particles is via fecal pellets of metazoan zooplankton that package filter-fed fine particles which then descend, typically, at a speed of a few hundred meters per day. Another mechanism, although not clearly defined, is via amorphous aggregates (marine snow). Although speculative, it appears that independent suspended particles are caught by hydrated, adhesive objects of relatively large diameter. While an aggregate descends through the upper water column, it gains settling velocity and agglutinates more independent suspended particles. When it leaves the upper ocean, an aggregate thus gains a specific speed. The fast descent of settling particles has been observed at a number of deep ocean stations, indicating the bulk settling speed of particles is a few hundred meters per day. In either mode of settling, some component particles are often freed from their host and return to being suspended particles. Then they are rescavenged by another host and resume settling. The relationship between settling and suspended has not yet been modeled; however, recent radiotracer studies show that nearly 100% of transuranium elements generated in the water column above were found in a sediment trap, suggesting that all particles settle through the water column. The production of settling particles is controlled by surface water biology. Thus, flux signals at the ocean interior are highly variable. For example, generally weak current signals at an abyssal station are usually overwhelmed by the upper ocean productivity signal.

8.17 Flow Effects on Sediment Trap Efficiency

Keith Stolzenbach and Cheryl Ann Butman

The most important general features of flow in and around sediment traps are the vortex shedding at the upstream edge that results in unsteady exchange of fluid with the trap interior and the formation of circulation cells within the trap that can efficiently carry
momentum and turbulent energy to interior trap surfaces. These fluid motions directly influence the trap particle collection efficiency in a number of ways: fluid exchange increases the effective trapping area for small-mouth traps; boundary shear stress resuspends settled particles even in relatively deep or baffled traps; and turbulent motions induce particle-particle aggregation in the trap interior and particle adhesion to trap walls. Studies of trap particle collection in the laboratory and the field implicate each of these processes in producing biases of as much as 300% in trap efficiency. Intercomparisons and calibration with geochemical tracers have not been sufficiently resolved to confirm or deny the existence of flow-induced biases of this magnitude in current trap configurations. Despite the potential importance of fluid motion, we have little quantitative understanding of the relationship between trap efficiency and trap geometry (including baffling, density layers, and tilt), flow speed, and particle characteristics (fall velocity, critical resuspension shear stress, and cohesiveness). Integrated combinations of laboratory and field measurements of trap hydrodynamics are needed for more accurately interpreting trap collections data and for the evolution of new trap designs and deployment strategies.

8.18 Particle Collections in Sediment Traps: A Barometer of Horizontal Processes in the Ocean?
Giselher Gust, Peter Betzer and Robert Byrne

For more than a decade, the particulate matter collected in sediment traps has been used as a quantitative measure of the vertical flux of particulate matter in the worlds oceans. It is well known that sediment-water interactions in the deep sea can, over very short time scales, produce major changes in particle concentrations and also in turbulence intensities. Inasmuch as traps represent another interface there will be also fluid-trap interactions as well. Given the importance of such devices to the GOFS effort, the relationships between approach velocities, turbulence, shearing stresses, particle concentrations and particle fluxes inside and outside of traps need to be examined systematically in the field.

Initially, we have used a laboratory flume to examine some of the relationships and also test some of the concepts advanced by Butman et al. (1986). A video record has provided data on the flow features inside fixed cylindrical traps. For both high and low Reynolds numbers, the materials collected in the traps have been compared to that deposited on the bottom of the flume. Our results suggest that horizontal processes exert an important control over flux estimates with sediment traps and that there needs to be a careful examination of fluid-trap interactions in the oceanic environment.

Although people have long recognized the need for such work, it has only been recently (Gust, 1988) that scientists have had access to a set of rugged, small scale, high resolution velocity and wall shearing stress sensors which can be used in the field. This instrumentation, coupled with careful measurements of particle concentrations, particle size spectra and particle mass accumulation rates, will provide a quantitative means of answering the following questions:

1. Is the whole trap mouth area involved in the collection process?
2. Does the structure of interior flow resemble the hypothesis advanced by Butman et al. (1986) for small traps?
3. Does the interior flow in small traps simulate that of larger field traps?
4. Under identical conditions, do different traps collect different particle size spectra?
5. Can the results of laboratory experiments carried out at low velocity (< 10 cm/s) be applied to the field where advective velocities can be much higher?

From results which are neither exhaustive nor statistically secured, we speculate on the relationship of particulate matter collected in present-day traps and the extent to which they are a barometer of oceanic vertical fluxes.

8.19 Understanding Sediment-Trap Performance: An Evolutionary Process

Giselher Gust

Evaluating the available literature on trap performance leads to the conclusion that the flow dynamics around and inside sediment traps are actively involved in the accumulation process of particulate matter (e.g., Baker et al., 1988). Most early papers did not consider fluid flow effects. Subsequently, fluid flow was included in volume balance equations (Bloesch and Burns, 1980), but eddies shed from the trap mouth were considered moving with the outside flow and only occasionally entering the traps. Then it was qualitatively observed that advective flow cells inside traps rather than mouth-shed eddies deposit fractions of the suspended sediments (Gardner, 1980a; Hawley, 1988). Further observations showed the approaching flow to accelerate close to the trap, and fluid parcels entering the trap were not drawn from the height of the trap mouth (Butman, 1986). Ongoing experiments indicate that fluid enters the trap in a small confined area at the downstream edge, that replaced fluid is pushed out over ~75% of the trap-mouth area at the upstream edge, and that the internal advective flow is generating its own turbulence and stress patterns (Gust, unpublished data).

From all those studies it appears that the process of sediment accumulation inside traps is intimately linked to the fluid flow inside traps, and while experimental data were lacking on how the approaching flow field transforms into the internal sediment-releasing trap flow, a similar concept (Butman et al., 1986) proposed a combination of relevant input parameters which includes approach velocities and wall shearing stresses inside traps.

While a large data base of chemical/biological results obtained with traps suggests that on time scales longer than months to years vertical fluxes in situ correlate with trap-derived results (section 2.2, this report), the fluid dynamics and actual accumulation processes of traps assessed on short-term scales have grown more complex with each newly published study. Integration of the short-term processes has to be consistent with the long-term results. On the short-term dynamics of trap-induced particle accumulation we have not yet reached clarity, as well as for the relationship between trap-internal and approaching flow, the breaking-up of aggregates and/or winnowing of particle size classes through trap-internal flow and turbulence, and — most prominently — how far the material accumulated in a
trap is actually representing the vertical flux of particles in the adjacent, unconfined water column. A video clip presented at the workshop showed that sediment particles (quartz and resin beads) entering the trap with the approaching fluid left the trap interior at the upstream edge of the trap aperture once the flushing speed exceeded the particle settling velocity, with only a small amount of particles retained.

To substantiate the visual, qualitative observations reported to date and to augment the yet scarce short-term, flow based calibration efforts of traps calls for the measurement of velocities, stresses and turbulence inside and outside of traps during the actual collection of particles both in field and lab. Subsequently, they need to be linked to the collection process by identifying the forces acting on particles during their pathways through the traps. These studies require small-scale, rugged, sea-going flow sensors which can be placed into and outside of traps yet do not disturb the collection process. Sensors meeting this task have recently become available (Gust, 1982; 1988). The NSF is currently funding such field and lab evaluation effort as GOFS component (Gust, Byrne, Betzer, grant OCE 8813436). Data from flume experiments show that for VERTEX pits with original size and configuration and approach velocities ranging from 1 to 30 cm/s the flushing rates lie between 0.03 and 2.0 l/min, while for a 1:4 scaled-down version of the MARK II cones with $A_c \approx 2$ the rates increased by a factor of $\sim 20$ for the same approach velocity range.

Maximum velocities beneath the baffles inside the VERTEX pit occurred at the downstream edge and reached $\sim 20\%$ of the approach velocities, with turbulence spectra of comparable intensity as in the approaching (flume boundary layer) flow. The maximum velocities in the cone were as high as $\sim 60\%$ of the approach velocities, and turbulence intensities inside the cone exceeded those in the approaching flow by one order of magnitude. Experiments are presently conducted to link these internal flow fields to the absolute and relative accumulation rates of particles (quartz, clay, diatoms) entering traps at known concentrations to serve as ground-truths for field experiments with VERTEX and MARK II traps equipped with inside/outside hydrodynamic sensor packages at the GOFS Bermuda site.

Recommendations: To ensure that particles accumulating in traps of any design represent the vertical mass flux, measure in the open water column the flow field at spatial scales $\geq$ particle sizes. At time series stations, measure particle fluxes in the water column by a combination of optical (acoustical) and hydrodynamic sensors to provide an independent calibration test for all trap designs including the neutrally buoyant, free-floating trap which is anticipated to emerge as the future calibration standard for trap-derived fluxes.

8.20 Sediment Trap Design and Ground Truth Cycle off Southern California

Andrew Soutar

A persistent problem for a specific marine sediment trap methodology employed to resolve geo-biologic processes is the determination that collections are qualitatively and quantitatively representative of natural sedimentation. Given such verification then extension to other regimes having similar water and deployment characteristics (but where direct verification would be impossible) is perhaps justified.
Direct comparison of bottom sedimentation and near bottom sediment trap accumulation at a resolution of 1 year can be made in the nearshore basins off southern California. Santa Barbara and Santa Monica basins with their annually layered sediments can be considered as very large sediment traps of moderate preservational capability that sequence about every 6 months.

Deployment of sediment trap devices near the bottom of these basins has occurred periodically over the past 22 years. The sophistication of comparison ranges from the short term (days) initial observations on trap and suspended particles in Santa Barbara Basin to the present day extended (almost years) mass balance comparisons for organic carbon and total flux in the Santa Monica Basin.

8.21 Use of Natural Radionuclides to Assess Sediment Trapping Efficiency in the Field

Michael Bacon

Within the natural radioactive decay series are a number of radionuclides which are (1) reactive, in the sense that they are strongly bound to marine particulate matter, and (2) are supplied to the oceanic water column at known rates from decay of their parent nuclides in the decay series. The radionuclides are said to be chemically "scavenged" from the water column. To maintain steady state, a balance must exist between supply of a reactive nuclide on the one hand and removal by the sum of radioactive decay and scavenging on the other. Both the supply and the loss by radioactive decay can be determined very accurately from simple concentration measurements of the parent and daughter nuclides. The rate of scavenging is then easily calculated and can be used to predict the flux of reactive radionuclide that should be captured by a sediment trap. This is the basis for estimating trapping efficiency.

There are two important limitations: (1) horizontal advection and diffusion can redistribute the radionuclides, thus upsetting the vertical flux balance, and (2) the balance between supply and removal can only be assumed to hold for times that are long compared to the residence time of the reactive nuclide. It can be argued that the Th isotopes are the best candidates for minimizing the effect of horizontal redistribution. Flux records should be integrated for at least one year. Records of Th-230 flux captured by PARFLUX-type conical traps in the deep sea away from deep boundary currents do not indicate significant trapping error.

8.22 The Easily Soluble Fraction of the Settling Particle Flux

Jack Dymond and Robert Collier

Several studies have shown that portions of the particulate load caught by sediment traps enters into solution within the sediment trap cup. The importance of this soluble fraction appears to vary for different elements, and for any given element the depth of the sediment trap may be an important variable. The type of preservative (formalin or azide) may also be an important factor in determining the fraction which enters the solution. The
discussion which follows is based on our studies which use sodium azide in concentrations of approximately 0.8 molar as a preservative. The fraction of particulate phosphorus which is soluble in cup solutions shows a strong relationship to depth. At depths shallower than 500 m more than 80% of the P can enter the cup solution. The fraction of P which is soluble decreases to values of less than 10% at depths greater than 4,000 m. This pattern is apparently a reflection of the fact that only the refractory component of organic matter survives settling to the deep ocean. Copper shows a similar pattern to P, in which a larger fraction of the copper (as much as 30%) enters into solution at shallow depths. Manganese, however, exhibits no simple depth pattern with approximately 60% being soluble at all depths. A small set of samples have been studied for the fraction of organic carbon that is in the trap cup solutions. At 700 m depth, 39 to 68% of the total carbon flux was in the cup solution. At a depth of 1,200 m 23% of a single sample was in the cup solution. The soluble organic carbon to soluble P ratio in these samples is approximately 10 (molar).

These studies demonstrate the more labile components of the particle flux enter into cup solutions. This portion of the flux could be lost if the cup solution is exchanged with seawater by diffusion or mixing processes. Clearly more studies are needed to ascertain the effects of different preservatives on the soluble fraction.

8.23 JGOFS Expert Group Recommendations

Rolf Peinert

1. General:

1.1. Trap design:
If new traps are constructed existing expertise from trap design should be considered with respect to H/D ratio and baffles. Preferably one type of trap should be used per mooring/drifting array.

1.2. Intercalibration:
Comparisons of floating/moored traps should be carried out by all deployers for their respective traps.

2. Floating Traps:

2.1. Depth of deployment:
Shallowest depth of deployment should be below both the mixed layer and the euphotic zone. As a reference depth for the moored traps 300 m is recommended. Depths for additional floating traps should be selected according to the encountered bloom situation for optimal vertical resolution in the upper 300 m.

2.2. Temporal resolution:
Sampling intervals should be adjusted to the frequency of parallel water column measurements. Two-day resolution is desirable but may not be practical for greater depths.
2.3. Preservative:
No final agreement on this important matter has been achieved. Future discussion is necessary as to whether an in-situ preservative (preferably formaldehyde: final concentration 1–2 per cent in the sampling cups) can be recommended for all cases, even with short-term deployments. Prior to deployment, NaCl should be added to water in sampling cups to give an excess salinity up to 5 per thousand.

2.4. Handling of the samples:

2.4.1. Immediately upon trap retrieval, supernatant water from the cups should be sampled for analysis of (1) dissolved inorganic nutrients (N, P, Si), (2) the respective dissolved organic compounds and (3) exoenzymatic activity (if possible). This serves to monitor releases from trapped particulate organic matter and results should be compared with water samples of the vicinity of the traps.

2.4.2. Prior to splitting, the samples should be inspected optically and photographed. Samples should be stored at refrigerator temperature. Most working groups agree that swimmers should be removed. This matter must be discussed further.

2.4.3. Splitting: The utilization of rotating high precision splitters is recommended if no other method of known precision is used.

2.5. Core parameters to be measured:
Dry weight, carbonate, total combustible, organic carbon, nitrogen, phosphorous, silica, pigments (HPLC), microscopical counts. For precision the recommendations of the other expert groups should be considered. Radioisotopes (e.g., thorium-230) should be measured as well though not as core parameter.

2.6. Responsibility for analyses:
For the Pilot Study, groups deploying traps should be responsible for sample analyses. Subsamples for measuring parameters not covered by the trap deployers should be held available for other qualified JGOFS groups. Future discussions may result in more integrated procedures.

2.7. Data release to JGOFS data base:
Floating trap samples should be processed at the same time scale as water column samples. In line with other working groups, February/March 1990 should be aimed for.

3. Moored traps

3.1. Depth of deployment:
Two reference water depths are recommended: (1) 1,000 m for comparisons between moored traps and (2) 300 m for floating/moored traps.

3.2. Temporal resolution:
In long-term moorings trap sampling intervals should, if possible, be programmed with higher resolution during the growth season, with emphasis on times of expected sedimentation events (i.e., spring). Intervals of two weeks seem reasonable.
Appendix A

3.3.-3.6. Same as for floating traps.

3.7. Data release to JGOFS data bank:
   Approximately one year after the respective trap recovery should be aimed for.

Sediment trap vagaries will be discussed at a U.S. workshop in Ocean Springs, MS, in
November 1988. The outcome of this meeting should be considered for further planning the
North Atlantic Pilot Study.

8.24 Measurement of Settling Particle Fluxes in the Ocean

Michael P. Bacon

Adapted from a working paper prepared for second meeting of SCOR WG-71

Introduction

This paper provides a brief discussion of some topics related to the determination of the
flux of settling particulate matter in the ocean. The principal measurement tool used in
particle flux investigations is the sediment trap (or particle interceptor). Several shapes and
sizes of sediment trap have been employed in oceanographic research. The common modes
of deployment are (1) attachment to a taut-wire mooring that is anchored to the bottom
and (2) suspension from a buoy that is free-floating at the surface.

Proper use of sediment traps and correct interpretation of results require that potential
collection biases be recognized and understood. In discussing this I think it is important to
distinguish between two kinds of questions:

1. Do traps (or can they if designed properly and employed under the right conditions)
yield an unbiased quantitative measure of the gravitational flux of particles through
a given horizontal plane?

2. Do traps yield samples that are qualitatively unbiased with respect to chemical, min­
eralogical, and biological composition?

It is conceivable that, under certain conditions, a trap might be a poor tool for measuring
flux but would still be a good tool for taking a sample of the settling material. On the other
hand, it is equally conceivable that the two kinds of bias might go together. For example,
in conditions of undertrapping, there might well be a selection for particles of higher fall
velocity. Conversely, in conditions of overtrapping, there could be bias toward lower fall
velocity. Such selectivity could lead to compositional biases as well.

It seems to me that an important aim is to determine how well it is presently possible
to judge the reliability of sediment trap results in both the quantitative and qualitative
terms stated above. For what conditions of deployment can one accept trapping results
with reasonable confidence? (The pessimistic view is that there are no such conditions, but
this is an extreme view that is not widely held.) Can we give a satisfactory answer to this
question now? It isn’t likely, and further research is needed to produce a better answer.

The questions posed above require a consideration of the physics of sediment trap design
and of the fluid in which the traps are immersed. Equally important is consideration of
biological and chemical factors that govern preservation of the sediment sample within the trap during the period before it is recovered. In what follows I give a brief summary of points that are important in considering these issues.

A final topic is the question of horizontally transported components in trapped material. Vertical fluxes can be either augmented or diminished because of convergences or divergences of horizontal fluxes. Remote sources and sinks at ocean margins can supply materials to the ocean interior or remove materials from it. This does not in itself lead to trapping errors, but it has a very important bearing on the interpretation of sediment trap results.

**Trap Efficiency**

There are available at least two published critical reviews of sediment trap methodology, both of which contain extensive lists of references to the literature (Bloesch and Burns, 1980; Blomqvist and Håkanson, 1981). Both papers reach the conclusion that simple cylinders are likely to yield the best results, as long as the aspect ratio (ratio of height to diameter) is sufficiently large. Bloesch and Burns (1980) state that the aspect ratio should be >5 for small lakes and >10 for more turbulent water bodies (large lakes and ocean basins). Blomqvist and Håkanson (1981) make a number of recommendations for further research, and it is perhaps useful to quote from their list here:

1. evaluations of free-drifting traps;

2. the relationship between deposition, Reynolds number, and H/D ratio for cylindrical vessels;

3. the relationship between orifice area and trapping efficiency of cylindrical vessels; and

4. the complex of selective trapping and qualitative representativity (composition, size, texture) of deposited matter in sediment vessels.

Since these two reviews were published, additional studies have been completed. I will try to summarize here some of their more important results.

Some important theoretical and experimental work was recently published by Butman et al. (1986) and Butman (1986). The first paper contains theoretical analysis, a description of the trapping mechanism based on observations of flow through traps, and a critical review of previous laboratory studies. Trapping efficiency is shown to be a function of several dimensionless parameters, among which are the following:

1. trap Reynolds number \( R_t = u_f D / v \), where \( u_f \) is the flow speed at the height of the trap mouth, \( D \) is the trap mouth diameter, and \( v \) is the kinematic viscosity (ratio of fluid viscosity to fluid density);

2. trap aspect ratio, i.e., the ratio of height to diameter \( H/D \); and

3. the ratio of fluid flow speed to particle fall velocity \( u_f / W \).

The analysis leads to five predictions. For fixed values of the other two parameters, it is suggested that the collection efficiency of cylinders may:
Appendix A

(1) decrease over some range of increasing $R_t$,
(2) decrease over some range of decreasing $W$, and
(3) increase over some range of increasing $H/D$.

Additionally, it is suggested that, for fixed values of $R_t$, $u_f/W$, and $H/D$,

(4) small-mouth, wide-body traps generally will be overcollectors relative to cylinders with
the same mouth diameters; and

(5) funnel-type traps generally will be undercollectors relative to cylinders with the same
mouth diameter.

The experimental work (Butman, 1986) involved flume studies that were designed to test
four of the five hypotheses listed above. (The dependence of collection efficiency on $W$ was
not studied. The particles used had fall velocities of $10^{-3}$-$10^{-2}$ cm/sec). The results all were
consistent with the four hypotheses tested. It is emphasized that the biases demonstrated
are for specific parameter combinations and cannot be generalized outside the range of
values tested, and it is concluded that detailed quantitative studies of trap biases under
conditions common in the field and of physical trapping mechanisms are needed before it
will be possible to declare any trap an unbiased collector in ocean flows.

Field deployments have also produced evidence of biased collections by sediment traps.
A recent example is a study by Bothner et al. (unpublished manuscript), in which traps
of different sizes and aspect ratios were deployed on the same mooring in a submarine
canyon. Current speeds averaged ~15 cm/s and reached maxima of ~50 cm/s. There was a
difference of nearly a factor of five between the highest and lowest trapping rate measured.
Efficiency decreased with increasing trap diameter and decreasing aspect ratio, trends that
are consistent with the findings of Butman cited above.

A novel field study has been reported recently by Baker et al. (1988). They deployed
identical traps on a mooring and on a drifting buoy in a 120-m-deep channel where current
speeds varied widely due to tidal flow. The traps were equipped with rotating fraction
collectors which, in this case, were controlled by current meters so that the samples could
be fractionated according to intervals of current speed (<12, 12–30, 30–50, and >50 cm/s).
Measured flux was found to decrease sharply with increasing current speed, and composi­
tional fractionation of the sample was also observed. Estimated average settling velocity of
the trapped particles increased as current speed increased. In contrast to the moored traps,
the drifting traps showed neither of these trends. In addition to the strong biases demon­
strated at the higher current speeds, however, it was also shown that agreement between
drifting and moored traps was within 10% when deployment mean speed was <15 cm/s and
the accumulated duration of speeds <12 cm/sec was >60% of the deployment period. One
can infer from this that reliable flux measurements are possible under the more quiescent
conditions specified.

Other trap intercomparison studies in the field have also given evidence that reliable
flux measurements are possible under quiescent conditions. The most extensive was the
Sediment Trap Intercomparison Experiment (STIE), which was carried out in the Panama
Basin in 1979 (Spencer, 1981). Good agreement was found among moored traps of widely
varying size and shape that were deployed simultaneously.
Mention should also be made of the use of natural radionuclides (e.g., $^{234}$Th, $^{230}$Th, or $^{210}$Pb) for calibrating sediment traps in the field. These are potentially useful because it is possible to construct exact geochemical budgets for them. We have, in essence, a natural “seeding” of the water column going on continually, so we know just how much of the radionuclide should be falling into a trap under ideal conditions. Requirements for this approach to work are:

(1) that there be a match between the duration of the trap deployment and the time over which the geochemical balance can be assumed to hold, and

(2) that the possible effects of horizontal transport be taken into account.

Several examples are reported in the literature (e.g., Knauer et al., 1979; Lorenzen et al., 1981; Bacon et al., 1985). In the cases studied, which were for drifting traps or for moored traps in quiescent conditions, it was concluded that the traps performed with good accuracy. It is generally not possible to use the radionuclide data to assess trapping efficiency in areas of energetic flow, because there the geochemical balances are more complex and not well enough known.

In summary, I believe we can conclude that good results can be obtained with properly designed sediment traps under favorable conditions but that poor results can be obtained under unfavorable conditions. We seem to have at least a pretty good qualitative understanding of the important factors that control trapping efficiency. Still lacking, however, are objective, quantitative guidelines for choosing conditions where use of sediment traps is appropriate and where it is inappropriate. Further studies designed to provide such guidelines should be given high priority.

Preservation

The question of the extent to which trapped particles are altered prior to recovery of the trap is a vexing one. A discussion of it is given in the review paper by Fowler and Knauer (1986). It has been clearly shown that major alterations can occur and that these can seriously bias both the measurement of flux and the measurement of the composition of the settling material. Poisons and preservatives of various kinds have been shown to have some effectiveness in retarding decay of the organic matter in traps. There is no general agreement as to which is best or even whether any should be used, though there may be a consensus developing for formaldehyde as the agent of choice (Gardner et al., 1983; Knauer et al., 1984).

One obvious recommendation that everyone seems to agree with is that deployment periods should be kept as short as possible. In this connection the advent of time-series collectors has been an important development. Each cup in a series is rotated sequentially under the trap, exposed to the flux for a predetermined length of time, and then sealed off as the next cup is brought into position. Analysis of the supernatant seawater allows one to correct for change in chemical composition of the solid phases that occurred after closure of the cup. This allows traps to be deployed in the field for long periods of time but to minimize the exposure time of the individual samples. This strategy is also used in the VERTEX traps, where solutes released from trapped particles are retained in a high-density NaCl solution.
An additional problem related to preservation of sample integrity is that of swimmers, which almost inevitably are found to visit traps deployed in the upper 500 m. Feeding and defecating by swimmers can lead to net transport of material either into or out of traps. There is no way known to prevent this, but by hand-picking it is possible to remove from trap samples those organisms that are obviously not part of the passive settling flux. Such procedures are tedious, subjective, and difficult to standardize. A great need exists for a better practical solution to this problem.

Lateral Transport

In the application of sediment traps to studies of biogeochemical processes, it is not just the ability to measure a particle flux that is important. One also wants to measure change in flux down a water column by deploying a depth-series of traps and, from the differences in flux between adjacent traps, to infer rates of chemical reactions and biological processes occurring in the intervening water masses. For example, if organic matter flux decreases with depth, then remineralization rates can be calculated. Or if manganese flux increases with depth, then a scavenging rate can be inferred. However, this kind of interpretation is often confounded by the effects of lateral transport. There is accumulating evidence that for some materials there exist sources or sinks at the ocean margins that are strong enough for their influence to be felt even at distant points in the ocean interior.

Several lines of evidence show the existence of these margin sources and sinks. Large horizontal concentration gradients in the water have been measured for a number of species (e.g., Bacon et al., 1976; Martin et al., 1985). Other studies have shown continental slope sediments to be strong accumulators of certain elements (e.g., Carpenter et al., 1981; Yang et al., 1986). The effects are often revealed very clearly in sediment trap data. For example, fluxes of aluminum measured in traps increase systematically with depth, indicating a supply of aluminosilicates by resuspension of slope sediments and lateral transport to the interior (Spencer, 1984). For some radionuclides (e.g., $^{210}$Pb and $^{231}$Pa) a strong sink exists at the continental margins, and traps deployed in the ocean interior collect much lower amounts than are expected from the known rate of supply (Bacon et al., 1985).

The best strategy to adopt for coping with the lateral effects described above depends on the scientific questions that are being asked. For many purposes we wish to follow the transformations in the biology and chemistry of a certain population of particles from their origin at the sea surface down to the seafloor. The lateral effects complicate any effort to do this, and clearly the best strategy is to select mid-ocean study sites where the effects are minimized. For other kinds of questions, however, the lateral fluxes of particles and dissolved chemical species are important phenomena to study for their own sake, and one deliberately chooses study sites where their effects are easily observed.
9 Appendix B

<table>
<thead>
<tr>
<th>Attendees</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dr. Robert Anderson</td>
</tr>
<tr>
<td>Lamont-Doherty Geol. Observ.</td>
</tr>
<tr>
<td>Columbia University</td>
</tr>
<tr>
<td>Palisades, NY 10964</td>
</tr>
<tr>
<td>(914) 359-2900</td>
</tr>
<tr>
<td>Telemail: R.ANDERSON.LDGO</td>
</tr>
<tr>
<td>Dr. Vernon Asper</td>
</tr>
<tr>
<td>Univ. of Southern Mississippi</td>
</tr>
<tr>
<td>Center for Marine Science</td>
</tr>
<tr>
<td>John C. Stennis Space Center</td>
</tr>
<tr>
<td>Stennis Space Center, MS 39529</td>
</tr>
<tr>
<td>(601) 688-3178</td>
</tr>
<tr>
<td>Telemail USM.CMS</td>
</tr>
<tr>
<td>Dr. Michael P. Bacon</td>
</tr>
<tr>
<td>Department of Chemistry</td>
</tr>
<tr>
<td>Woods Hole Oceanographic Inst.</td>
</tr>
<tr>
<td>Woods Hole, MA 02543</td>
</tr>
<tr>
<td>(508) 548-1400 ext. 2559</td>
</tr>
<tr>
<td>Telemail: M.BACON</td>
</tr>
<tr>
<td>Dr. Thomas Bailey</td>
</tr>
<tr>
<td>Harbor Branch Oceanographic Inst.</td>
</tr>
<tr>
<td>5600 Old Dixie Highway</td>
</tr>
<tr>
<td>Fort Pierce, FL 34946</td>
</tr>
<tr>
<td>(407) 465-2400</td>
</tr>
<tr>
<td>Telemail: M.YOUNGBLUTH</td>
</tr>
<tr>
<td>Dr. Peter Betzer</td>
</tr>
<tr>
<td>Dept. of Marine Science</td>
</tr>
<tr>
<td>Univ. of South Florida</td>
</tr>
<tr>
<td>St. Petersburg, FL 33701</td>
</tr>
<tr>
<td>(813) 893-9630</td>
</tr>
<tr>
<td>Telemail: K.CARDER</td>
</tr>
</tbody>
</table>
### Attendees

<table>
<thead>
<tr>
<th>Name</th>
<th>Affiliation</th>
<th>Address</th>
<th>Phone</th>
<th>Telemail</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dr. Giselher Gust</td>
<td>Dept. of Marine Science</td>
<td>Univ. of South Florida</td>
<td>(813) 893-9130</td>
<td>Kosmos: G.GUST; Telemail: K.CARDER</td>
</tr>
<tr>
<td>Mr. Deirck Hebbeln</td>
<td>Fachbereich-Geowissenschaften</td>
<td>University of Bremen</td>
<td>D-2800 Bremen, West Germany 49 421 218 3920</td>
<td>Telemail: G.WEFER</td>
</tr>
<tr>
<td>Dr. Susumu Honjo</td>
<td>Dept. of Geology and Geophysics</td>
<td>Woods Hole Oceanographic Inst.</td>
<td>(508) 548-1400 ext. 2589</td>
<td>Telemail: S.HONJO</td>
</tr>
<tr>
<td>Dr. David Karl</td>
<td>Dept. of Oceanography</td>
<td>University of Hawaii</td>
<td>(808) 948-8964</td>
<td>Telemail: D.KARL</td>
</tr>
<tr>
<td>Dr. George Knauer</td>
<td>Center for Marine Science</td>
<td>Univ. of So. Mississippi</td>
<td>John C. Stennis Space Center Stennis Space Center, MS 39529</td>
<td>Telemail: USM.CMS</td>
</tr>
<tr>
<td>Dr. Richard Lampitt</td>
<td>Inst. of Oceanographic Sciences</td>
<td>Wormley, Godalming</td>
<td>Surrey GU8 5UB, U.K.</td>
<td>44 0428 79 4141 Telemail: M.FASHAM</td>
</tr>
<tr>
<td>Dr. Cindy Lee</td>
<td>Marine Sciences Research Center</td>
<td>State University of New York at Stonybrook</td>
<td>Stonybrook, NY 11794-5000</td>
<td>(516) 632-8741 Telemail: C.LEE</td>
</tr>
<tr>
<td>Dr. Rolf Peinert</td>
<td>Institut für Meereskinde</td>
<td>Christian-Albrechts Univ. zu Kiel</td>
<td>D-2300 Kiel 1, F.R.G.</td>
<td>49 0431 880 2372 Telemail: IFM.Kiel</td>
</tr>
<tr>
<td>Dr. Cynthia Pilskaln</td>
<td>Monterey Bay Aquarium Research Institution</td>
<td>Monterey Bay Aquarium</td>
<td>160 Central Avenue</td>
<td>Pacific Grove, CA 93950</td>
</tr>
</tbody>
</table>
Dr. Alan Shanks
Institute of Marine Sciences
Univ. of North Carolina
at Chapel Hill
3407 Arendell Street
Morehead City, NC 28557
(919) 726-6841
Telemail: (none)

Dr. Mary Silver
Center for Coastal Marine Studies
Univ. of California, Santa Cruz
Santa Cruz, CA 95064
(408) 429-2908
Telemail: UCSC.IMS

Dr. Andrew Soutar
Scripps Inst. of Oceanography
Univ. of California, San Diego
Mail Code A-14
La Jolla, CA 92093
(619) 534-2171
Telemail: (none)

Mr. Merritt Tuel
Center for Marine Science
Univ. of Southern Mississippi
John C. Stennis Space Center
Stennis Space Center, MS 39529
(601) 688-1180
Telemail: USM.CMS

Dr. Stuart Wakeham
Skidaway Inst. of Oceanography
P.O. Box 13687
Savannah, GA 31416
(912) 356-2347
Telemail: S.WAKEHAM

Dr. Paul Wassmann
Norwegian College for Fishery Sci.
University of Tromsø
P.O. Box 3083
Guleng N-9001
Tromsø, Norway
47 83 44512
Telemail: (none)