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The effect of brine on the collection efficiency of cylindrical sediment traps

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ABSTRACT

Cylindrical sediment traps are frequently used to measure the downward flux of particles in the upper ocean. Some protocols recommend filling these traps with brine (50 psu in excess of ambient) before deployment to better retain the collected sample. However, this also changes the aspect ratio of the traps—a critical parameter affecting the trapping efficiency. We conducted controlled experiments in a flume that demonstrate filling traps with a 5 psu brine decreases their trapping efficiency to 54% at a velocity of 5 cm sec^{-1}, and to 75% at 15 cm sec^{-1} relative to the same trap with no brine. This suggests that a revision of the protocols and further experiments are needed.

1. Introduction

In many studies of biogeochemical cycles in the oceans (e.g. JGOFS—Joint Global Ocean Flux Study), one of the primary measurements of concern is the flux of particulate organic carbon out of the euphotic zone. In the upper water column, these fluxes are commonly measured using free-drifting, surface tethered traps of the Particle Interceptor Trap (PIT) design of Knauer *et al.* (1979). This is now a routine measurement at the Bermuda and Hawaii Ocean Time-Series Stations (BATS and HOT). Eight to twelve cylindrical traps are attached to a horizontal cross and deployed at one or more depths. The cylinders have an inside diameter of 7.4 cm and an aspect ratio (height/diameter = H/D) of 8.4. The cylinders are then completely filled with a brine solution prior to deployment.

The rationale for adding brines with densities greater than seawater is to isolate samples in traps, prevent resuspension of settled particles, retain poisons and preservatives, and retain dissolved or leached components of the sample. But one of the important variables controlling trap efficiency is the aspect ratio (Gardner, 1977, 1979, 1980a, b; Hargrave and Burns, 1979; Bloesch and Burns, 1980; Blomqvist and Kofoed, 1981; Butman *et al.,* 1986). The addition of a brine potentially introduces a hydrodynamic barrier that acts as a false bottom, thus changing the effective aspect ratio of a trap (the aspect ratio of the brine-free portion of the trap) and also excludes particles or aggregates whose density is less than the brine density.

The accuracy of vertical fluxes measured using floating traps in the upper water column has been questioned because the amount of ^{234}Th they collect does not always match the

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loss of excess ^{234}Th from surface waters over the same time periods (Buesseler, 1991; Buesseler *et al.,* 1994). Sometimes the trap ^{234}Th fluxes were higher than the ^{234}Th losses and sometimes lower, but the use of brine was not always reported for the experiments compared. The above authors argued further that based on the POC/^{234}Th ratio, the traps may undercollect or overcollect carbon. Michaels *et al.* (1994) calculated a 3-fold imbalance between the total carbon budget in the BATS study area and the carbon fluxes measured with floating sediment traps. They concluded that either floating sediment traps were undercollecting by a factor of 3 or there was strong seasonal advection of carbon into the area. Based on hydrodynamic principles and observations (Gardner, 1977, 1980a, b; Bloesch and Burns, 1980; Hargrave and Burns, 1979; Blomqvist and Kofoed, 1981; Butman *et al.,* 1986; Baker *et al.,* 1988), the low trap fluxes could result, at least in part, from the methodology used. Filling the traps with brine may change the effective aspect ratio of a cylindrical trap and is likely to inhibit particle collection. To test this hypothesis, we conducted experiments to demonstrate the effects of adding a 5 psu brine (in accordance with the International JGOFS protocols; IOC Manual and Guides No. 29, 1994, compared to the 50 psu used at BATS and HOT) on the collection efficiency of cylindrical traps.

2. Methods

a. Traps. To test the effect of adding brines under controlled conditions, cylindrical non baffled sediment traps 4.0 cm in diameter (ID) with an aspect ratio of 4.3 were tested in a recirculating racetrack flume (~20 m perimeter). The base of each trap was a 6 cm square block of PVC 1.5 cm thick so the trap tops were about 19 cm above the flume bottom.

b. Flume. The flume was 60 cm wide and was filled with tap water to a depth of 42 cm, creating a volume of about 5,000 liters. Circulation was generated by withdrawing water through a hose from around the bend of the racetrack and pumping it into the center of the return straight-away of the flume in a 4-cm jet. Five thin, curved, vertical plates around the final curve before the straight-away of the flume acted as a baffle to stabilize the flow by greatly reducing (but not totally eliminating) secondary, cross-stream flow (based on dye trails in clear water). Velocities tested were roughly 5, 10 and 16 cm sec^{-1}.

c. Particles. The particles used in the flume tests came from an organic-rich sediment core collected in the Baltic Sea and was composed primarily of terrigenous sediments. The homogenized sediment sample from the upper 30 cm was wet-sieved at 1000 μm, yielding a range of Stoksian settling velocities from ~0.4 cm sec^{-1} (~350 m d^{-1}) for 1000 μm particles down to ~0.0001 cm sec^{-1} (~0.08 m d^{-1}) for fine clay. More than 95% of the sediment was <63 μm in diameter. The rare 1000 μm particles should have quickly settled to the flume bottom at ~10 cm sec^{-1}.

d. Flume runs. The sediment was well mixed in the flume initially. Prior to each experiment the sediment was manually resuspended from the flume bottom for several minutes while the flume was at its maximum velocity (>25 cm sec^{-1}) to maximize spatial homogeneity of particle concentration, though vertical gradients could certainly have developed during the experiment. For each experiment, five traps were filled with brine to different levels; no brine, 1, 2, and 3 trap diameters (D), and to the top (Full Brine: FB). The NaCl brine was 5 psu and was colored with fluorescein dye to make it easier to determine the top of the brine before and after each experiment. Traps were placed 10 diameters apart downstream along the straight stretch of the flume to minimize inter-trap effects. Traps were covered and placed in the flume after sediment had been mixed in the flume and the flow velocity lowered to the desired rate. Trap lids were removed and the experiment was started. Trap lids were replaced before removal from the flume. The height of the dyed brine was noted, the water above the brine was siphoned off, and samples were processed. Trap samples were wet sieved at 63 μm at the end of each experiment to test for size fractionation in collection efficiencies. Samples were filtered onto pre-weighed 0.4 μm Poretics filters, rinsed to remove all salt, dried and re-weighed. During a preliminary experiment samples were also wet-sieved at 125, 250 and 500 μm, but so many of the larger particles had settled out in the flume before the experiment began that there was insufficient material in the larger size class to be statistically meaningful.

e. Brine erosion. In addition to noting the change in brine height within the traps for each experiment with sediment in the flume, an experiment was run without sediment (clear water) at 10 cm sec^{-1} to determine more carefully the rate of brine erosion (5 psu brine).

f. Fresh versus saltwater. To test whether our results were affected by salinity effects such as flocculation of particles upon contact with the brine in the trap, we repeated one experiment by adding enough salt to the flume water to create a salinity of 5 psu and then used a brine of 10 psu in the traps to maintain the same density difference (5 psu) as in the other experiments.

g. Particle concentration. The concentration of particles was monitored during the experiments by siphoning off a sample of water at the level of the trap tops at the beginning and end of each experiment. During the last two experiments with traps, the water samples were wet-sieved at 63 μm and filtered as above to obtain concentrations of particles greater and less than 63 μm. To determine more precisely the time history of particle concentrations in the water, experiments were run without traps at nominal velocities of 5, 10 and 16 cm sec^{-1} and samples were drawn from the same height every 30 minutes.

h. Experiment duration. Most of the flume experiments were run for 2 hours at a constant velocity. Comparison tests were made at 2 and 4 hours.

3. Results

A discussion of the results would be more universally applicable if presented in dimensionless variables such as Reynolds number ($Re = uD/v$, where u = approach velocity at the trap mouth, D = trap diameter, and v = kinematic fluid viscosity), but for familiarity to most readers using traps we will generally refer to velocities rather than Re. All traps had the same diameter and since the viscosity was essentially constant, Re is linearly related to velocity. (See Butman *et al.* (1986) for an excellent dimensional analysis discussion of the fluid dynamics of traps.) The graphs here include Re and these must be used when comparing conditions to traps used in the field.

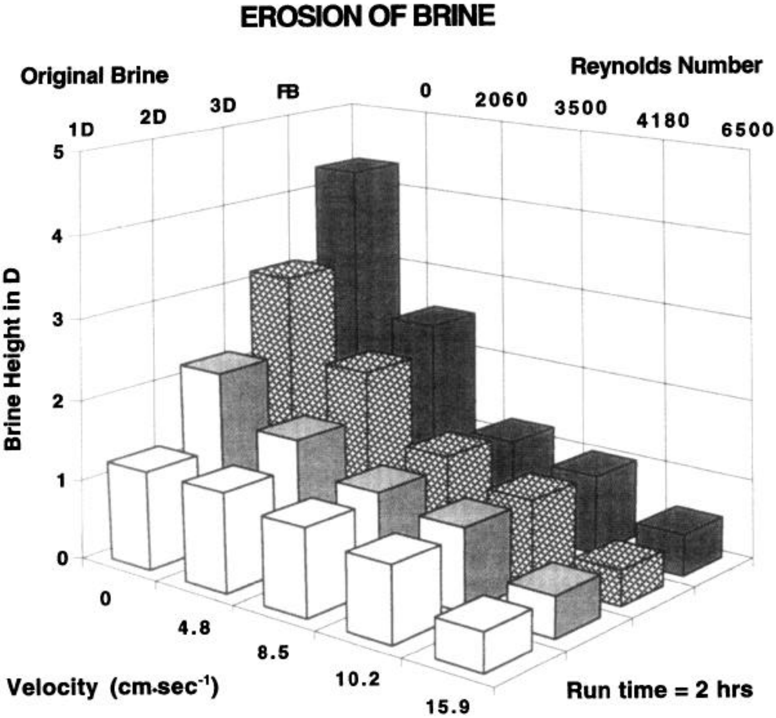
The low-density brine (5 psu) was eroded to increasing depths as the velocity increased from 5 to 16 cm sec^{-1} (Re increased from ~2,100 to ~6,500; Fig. 1a). Most of the erosion occurred within about 30 minutes, but erosion was greater at 4 hr than 2 hr for a velocity of about 5 cm sec^{-1}, and was greater at 8 hr than 2 hr for a velocity of 10 cm sec^{-1} (Fig. 1b). Figures 1a and 1b graph the height of brine remaining, but one could also view the decrease in brine height between the start and end of each experiment as the depth of brine erosion (Fig. 2). When water velocity was 16 cm sec^{-1}, the brine in all traps was eroded down fairly uniformly by about 4 diameters.

The concentration of particles in the water was similar, but not exactly the same for each experiment (Fig. 3, Table 1). The relative collection efficiency (RCE) of traps (relative to the collection rate of the trap with no brine) with different aspect ratios was tested at three velocities (Fig. 4a–c). At a given velocity the RCE increased as the initial height of brine decreased (i.e., as the aspect ratio of the brine-free region increased). At a velocity of 5 cm sec^{-1} the RCE of the trap filled with brine was only 54%. The RCE increased as the velocity increased for a given initial brine height. In our experiments the aspect ratio of the brine-free region increased over time as the brine was eroded, so we have defined the "effective aspect ratio" of the traps as the average between the beginning and ending ratio of the brine-free region of the trap over the time interval tested (usually 2 or 4 hr). Figure 5 clearly demonstrates that the collection efficiency is a function of the trap's effective aspect ratio.

We tested for the effect of running experiments for 4 hr versus 2 hr at nearly the same velocity and found no significant difference (Fig. 6a). The traps in the experiment run for 4 hours had a slightly higher RCE, but the velocity was also 10% greater, which could account for the small difference observed. The weight of sediment collected in traps with the same brine content, but run for twice as long, increased by a factor of two (Table 1).

There was little difference in the relative collection efficiencies between the freshwater and saltwater experiments (Fig. 6b). The total mass of particles collected in the saline

Figure 1. (a) Erosion of brine in traps containing different initial amounts of brine. Row 0 indicates the initial brine height in trap diameters. The amount of brine remaining after 2 hr is indicated by the height of columns for experiments at the Reynolds Numbers and velocities indicated above and below each row. (b) Erosion of brine in traps after 2 and 4 hr at a velocity of about 5 cm sec^{-1}, and after 2 and 8 hr at a velocity of about 10 cm sec^{-1}. D = trap diameter (4 cm); FB = full brine.


EROSION OF BRINE
Original Brine
1D
2D
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Reynolds Number
0
2060
3500
4180
6500
Brine Height in D
0
1
2
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Velocity (cm·sec-1)
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4.8
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Run time = 2 hrs

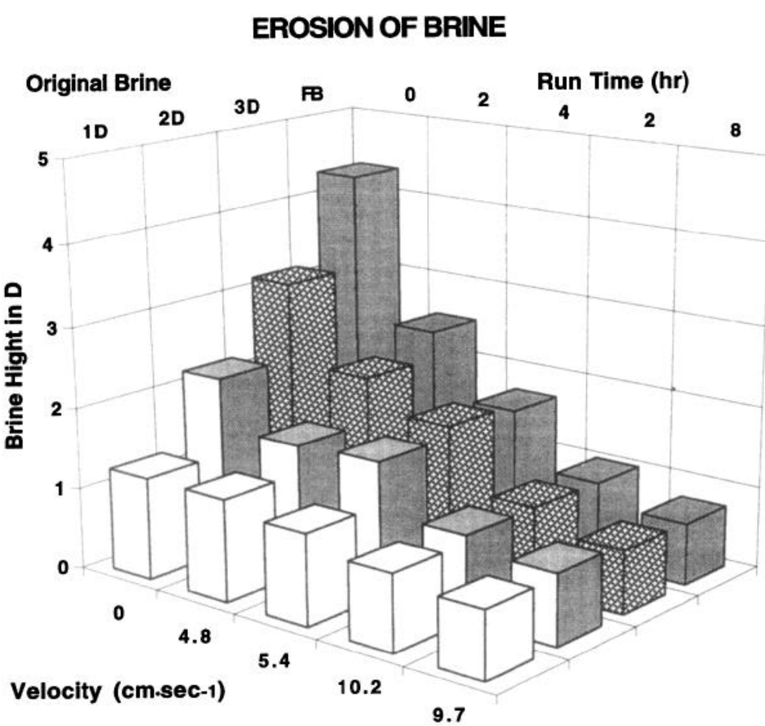
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Figure 1

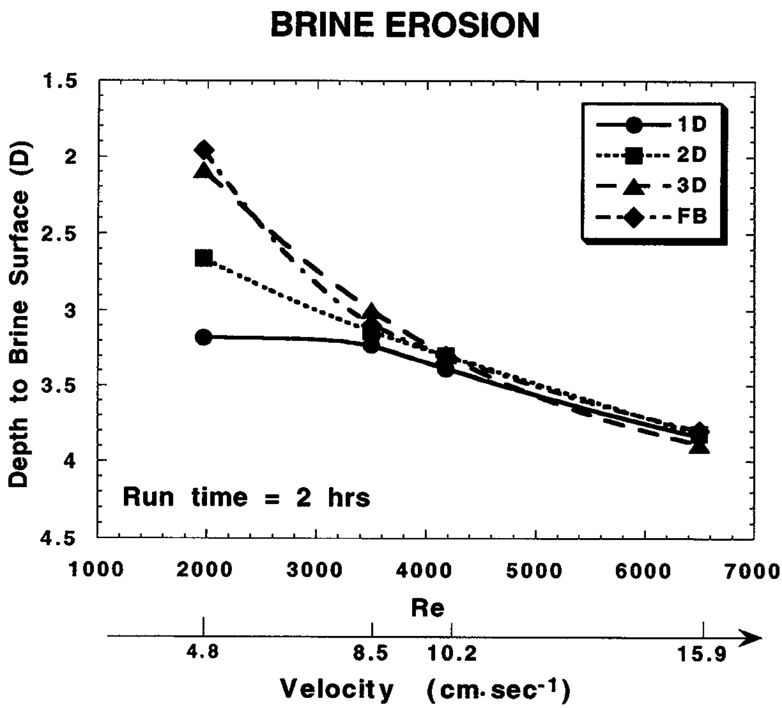


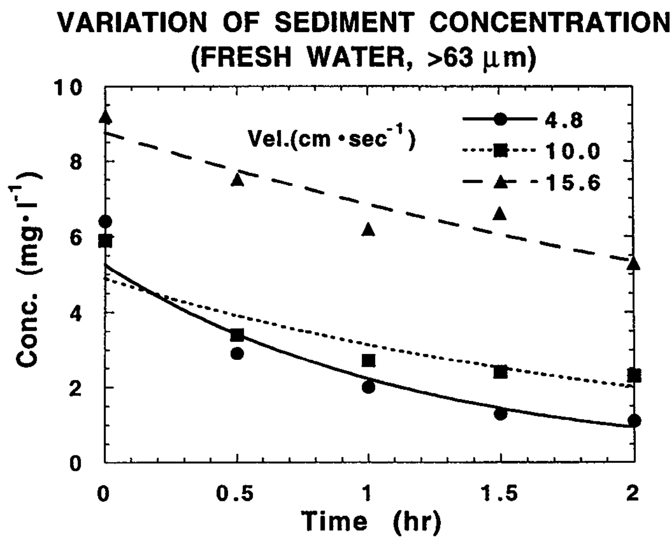
Figure 2. Depth to brine surface as a function of Reynolds number (or velocity). D = trap diameter and FB is the trap with full brine.

experiment was much larger, especially in the particles <63 μm (Compare Experiments 6 and 11 in Table 1). A possible salinity effect would be the flocculation of clay materials either in the saline flume water or, in the case of freshwater runs, as the clay materials contacted the brine in the traps.

During four preliminary experiments with a different batch of sediment from the same sediment core, a different placement order of traps showed the same trapping results reported here. However, in order to eliminate sediment type as a variable in the flume, all experiments reported here were run with the same sediment sample. The closest complete replicates were experiments 7 and 8 (Table 1), which differed mainly in the length of time they were run. No exact replicate experiments were made, which precludes some statistical analysis, but all experiments had the same trends of decreasing collection efficiency with increasing initial brine.

4. Discussion

a. Mechanisms of particle collection. To understand our flume results, let us consider how traps collect particles. This has been discussed at length in other papers (Gardner, 1977, 1980a,b, 1997; Hargrave and Burns, 1979; Bloesch and Burns, 1980; Blomqvist and



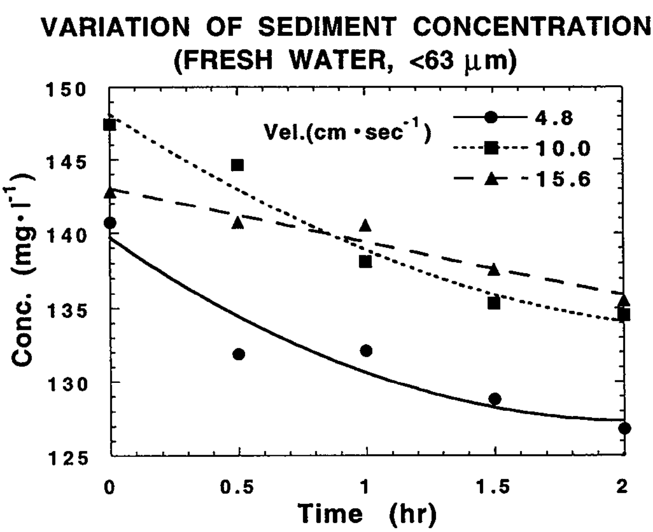


Figure 3. Concentration of particles >63 μm (upper) and <63 μm (lower) at different flow velocities in the flume during three experiments without traps. Note the different concentration scales of the y-axis. In two hours 5–10% of the <63 μm particles settle out of suspension while 40–80% of the >63 μm particles settle out in the same time.

Kofoed, 1981; Butman *et al.*, 1986). Briefly, particles enter traps through a process of fluid exchange in eddies that are generated at the top of traps. The depth of eddy penetration is a function of *Re* (Gardner, 1985; Hawley, 1988), with large temporal variations in the depth of penetration at any given *Re*, especially in the natural environment where traps encounter

Table 1. Velocity, particle concentration and flux data for flume experiment.

Expt. no.-trap no.	Vel. (cm/sec)	PM >63 µm (mg/l)	PM <63 µ (mg/l)	Total wt. (mg/l)	Hrs.	Wt. >63 (mg)	Wt. <63 (mg)	Total wt. (mg)	% >63
Pre-PM*	15.6	9.2	142.8	152.0					6%
Post-PM*		5.3	135.5	140.8					4%
Pre-PM	15.9			197.0	2				
Post-PM				170.0					
5-NB						25.8	32.3	58.1	44%
5-1D						24.0	31.5	55.5	43%
5-2D						21.4	29.7	51.1	42%
5-3D						20.7	27.5	48.2	43%
5-FB						20.8	23.1	43.9	47%
Pre-PM*	10.0	8.5	193.1	201.6					4%
Post-PM*		1.9	155.5	157.4					1%
Pre-PM	10.2			177.0	2				
Post-PM				170.0					
6-NB						6.5	19.7	26.2	25%
6-1D						4.8	14.3	19.1	25%
6-2D						5.1	12.6	17.7	29%
6-3D						4.6	11.8	16.4	28%
6-FB						4.1	11.3	15.4	27%
Pre-PM*	4.8	6.4	140.7	147.1					4%
Post-PM*		1.1	123.8	124.9					1%
Pre-PM	5.4			183.0	4				
Post-PM				132.0					
7-NB						4.8	32.7	37.5	13%
7-1D						4.6	24.0	28.6	16%
7-2D						4.0	23.4	27.4	15%
7-3D						3.5	20.5	24.0	15%
7-FB						3.7	18.0	21.7	17%
Pre-PM*	4.8	6.4	140.7	147.1					4%
Post-PM*		1.1	123.8	124.9					1%
Pre-PM	4.8			157.0					
Post-PM				117.0					
8-NB					2	3.1	16.6	19.7	16%
8-1D						2.3	12.9	15.2	15%
8-2D						2.8	10.4	13.2	21%
8-3D						2.0	9.3	11.3	18%
8-FB						2.1	8.5	10.6	20%
Pre-PM*		8.5	193.1	201.6					4%
Post-PM*		1.9	155.5	157.4					1%
Pre-PM	10			199.0	2				
Post-PM				168.0					
11-NB	Salinity-5 ppt					6.3	32.2	38.5	16%
11-1D						6.8	23.1	29.9	23%
11-2D						6.5	19.8	26.3	25%
11-3D						6.2	19.8	26.0	24%
11-FB						5.4	18.1	23.5	23%

*Pre- and Post-PM values are particulate matter (PM) concentrations run with the same sediment and velocity conditions in separate runs without trap.

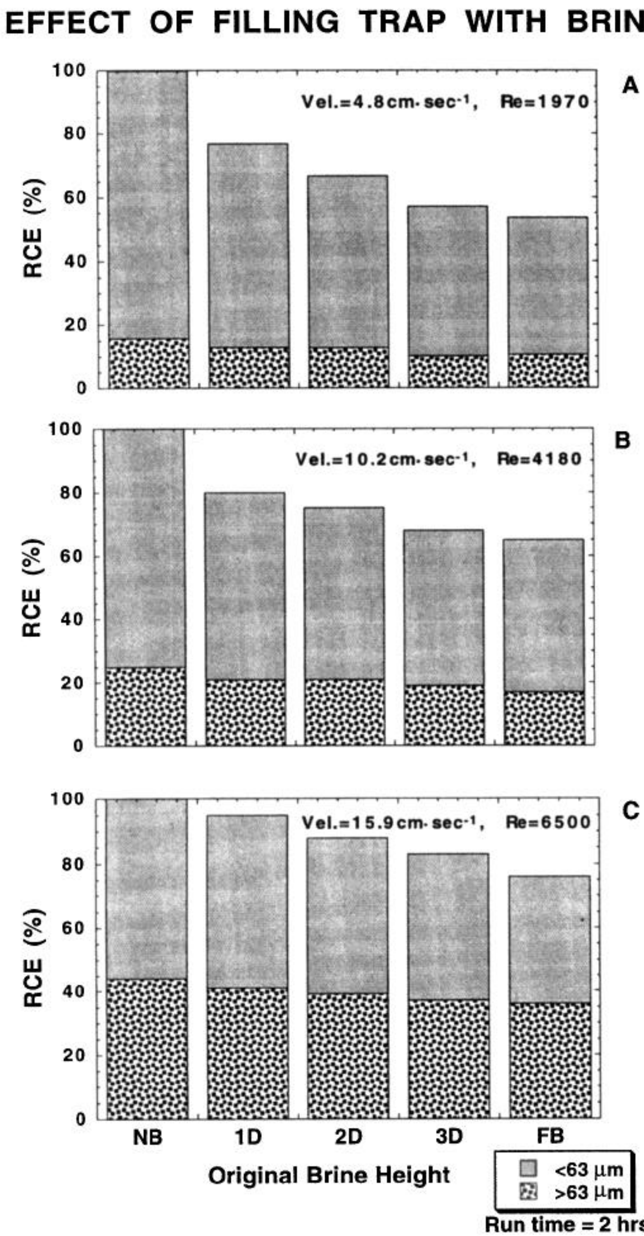


Figure 4. Relative collection efficiency (RCE) of traps during experiments at velocities of (a) 4.8 cm sec^{-1}, (b) 10.2 cm sec^{-1}, and (c) 15.9 cm sec^{-1}. Collection rates were normalized to the traps with no brine (NB).

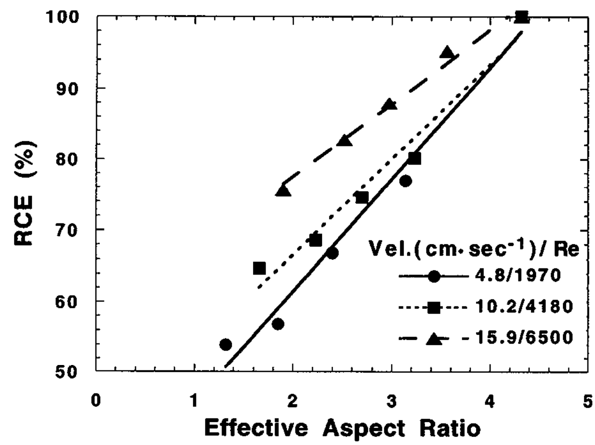


Figure 5. Relative collection efficiency (RCE) as a function of the "effective aspect ratio" (see text) of each trap for experiments at three velocities/Reynolds numbers.

many scales of turbulence. Turbulence and eddy size decrease with depth in the trap until a region is reached in which particles can settle out into a "tranquil" layer before the next eddy has a chance to re-entrain the particle and carry it out of the trap. In the "tranquil" layer particles settle at their terminal sinking speed independent of the trap-induced turbulence and are not resuspended (Gardner, 1977, 1980a, 1985; Butman *et al.,* 1986). Without a tranquil layer at the trap bottom, only the most rapidly-settling particles will reach the trap bottom rather than being flushed out of the trap.

Hawley (1988) showed that the tranquil region ceased to exist in brine-free cylinders when *Re* was 6,000 for cylinders with an aspect ratio of 3 and at 8,000 for cylinders with an aspect ratio of 5, but in cylinders with an aspect ratio of 8, the bottom tranquil layer was still one trap diameter thick at $Re = 20{,}000$. Based on his experiments, Hawley derived an empirical equation predicting the tranquil layer thickness as a function of *Re* for a cylinder with aspect ratio of 8; thickness (cm) = 18.29–1.74*ln(*Re*). For PIT traps with no brine ($H = 62$ cm, $D = 7.4$ cm), fluid exchange via eddies would extend 32 cm into the cylinder with an approach velocity of 5 cm sec^{-1}, 47 cm at 15 cm sec^{-1}, and 56 cm at 30 cm sec^{-1}.

The addition of brine decreases the effective aspect ratio of a trap, and may reduce or eliminate any tranquil region above the brine where particles can settle at their terminal velocity and enter the brine. The effective aspect ratio of a trap completely filled with brine is zero but increases with time as currents erode the brine. Personnel who use traps filled with brine report that the brine in the upper half of the trap washes out by the time the traps reach deployment depth based on observations by divers and by rapidly deploying and recovering traps, so one might reasonably assume the brine won't influence the results. However, unless the brine in all traps is eroded to the same depth, traps would have different effective aspect ratios. Furthermore, the depth of brine erosion is likely to vary with current conditions, which could alter the collection rate of traps, since efficiency is a

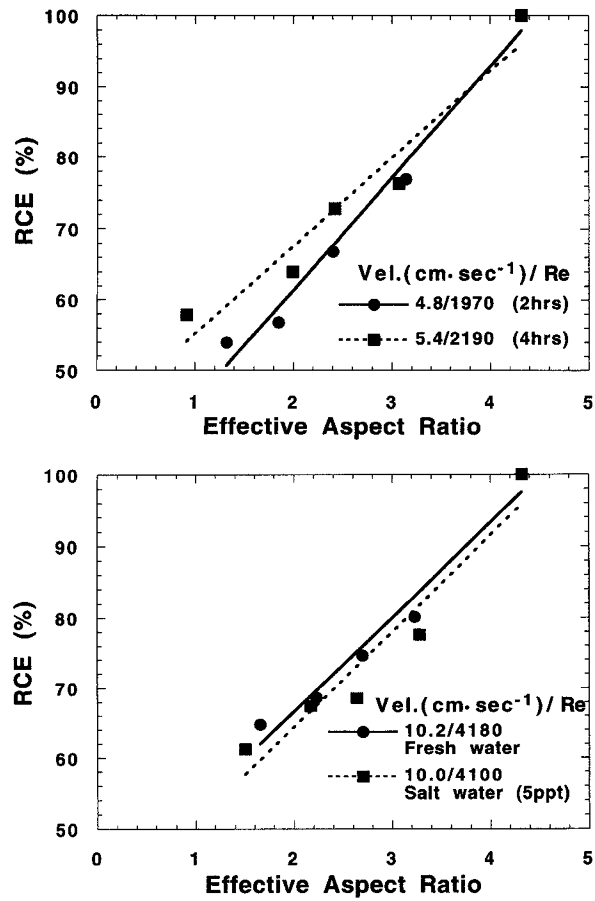


Figure 6. (a) Relative collection efficiency (RCE) for experiments at about the same velocity, but for 4 hr versus 2 hr. (b) Relative collection efficiency for experiments at ~10 cm sec^{-1} in fresh and saltwater (5 psu).

function of aspect ratio. The brine layer is tranquil, but with too much brine, the episodic fluid exchange in traps extends down to the top of the brine layer and leaves no space for particles to settle to and into the brine layer. A tranquil layer must exist above the brine in which particles can settle naturally before they settle across the brine interface.

b. Flume versus field conditions. How representative were these flume experiments compared to the natural environment for testing trapping efficiency? First, in the flume a boundary layer develops along the bottom and its thickness can be calculated as $\delta = (v/U)^{0.2}0.37\chi^{0.8}$ (Schlichting, 1979) where U is the free-stream flume velocity, χ is taken as the distance from the baffled end of the flume, and v = kinematic viscosity (0.01 cm^2 sec^{-1}). The maximum δ was 8.8 cm, so the mouths of all traps were above the boundary layer and the frictional effects of the bottom did not affect the flow at the trap mouth. However, the jet-like nature of the circulation system probably resuspended and vertically mixed particles on the far side of the racetrack, so there was only a brief time during which particle settling could create concentration gradients.

Second, the particles used were mainly terrigenous sediment, so the density of the individual particles was on the order of 2.7 g cm^{-3}, yielding a density difference between particles and seawater of about 1.7 g cm^{-3}. Particle size and density control particle settling velocity, which is difficult to measure directly, but which influences mass fluxes significantly. In the open ocean much of the flux of particles is carried in rapidly-settling aggregates (Asper, 1987), yet the density of aggregates is often barely greater than that of seawater; the density difference may be 10^{-3} to 10^{-5} g cm^{-3} (Alldredge and Gotschalk, 1988). In an attempt to simulate particle density more realistically, we tried one flume experiment with cornflakes ground up in a food processor, but visual observation suggested that settling velocities and densities of the wetted particles were much greater than for marine aggregates. Nevertheless, the same trends in particle collection as a function of brine height were found with ground up cornflakes as in our experiments with higher-density sediments.

Third, large aggregates in the ocean are often very delicate and may break up in the turbulence generated at the top of a trap even if the approach velocity is only a few cm sec^{-1}. No quantitative measurements have been made on the changes in aggregate characteristics upon encountering a trap in the ocean. Thus, while it is possible to scale the dynamics of flow between models in a flume and full-scale traps in the ocean using dimensional analysis (Butman *et al.*, 1986), we may not be able to scale simultaneously the dynamics of natural marine particles within that flow. This is especially true if the particle size and density change rapidly as might happen with aggregates being torn apart in trap-induced turbulence. Furthermore, in the dynamic region of the upper ocean one must consider whether other factors such as large-scale flow, tilt, and mooring dynamics are more important than hydrodynamic parameters such as Reynolds number.

c. Flume versus floating traps. In addition to the above caveats, there were also differences between the conditions we tested in the flume and the floating traps of the PIT variety. First, the flume experiments were run for only 2–4 hours compared to 3–21 days for PIT trap experiments. By comparison, earlier flume experiments have been run for 11–42 hours by Gardner (1977, 1980a), 24 hours by Hargrave and Burns (1979) and 8.5 minutes by Butman (1986). None of those experiments used brines.

Second, we used only a 5 psu salinity difference in the traps (in accordance with the International JGOFS protocols) instead of the 50 psu often used in PIT traps. Hawley (1988) tested the fluid exchange at the bottom of traps at different Reynolds numbers with experiments that generally lasted only 10–15 minutes, but no brines were used, so the erosion of density gradients was not an issue. Hawley ran one test for 3 hours, and found a slight increase in erosion depth between 15 minutes and 1 hour, but no further erosion of the bottom tranquil layer was observed between 1 and 3 hours. Our empirical data on brine erosion (Fig. 2) fit quite well the predictions of Hawley (1988) for the depth of erosion and resulting tranquil layer thickness of a cylindrical trap whose aspect ratio is 5 (tranquil layer (cm) = 20.04–2.24*ln(*Re*)), despite the fact that his data were based on experiments without brine. This suggests that the depth of brine erosion (which determines the effective aspect ratio) is not a function of brine density or aspect ratio, only of Reynolds Number. The depth of erosion in these flume experiments was consistent with the amount of erosion reported for PIT traps that have an aspect ratio of 8 (U.S. GOFS Report No. 10, 1989). Nevertheless, with a 50 psu excess brine in a trap rather than 5 psu, particles and aggregates must still overcome a larger density difference in order to settle to the bottom of the trap.

Third, flume tests were conducted with stationary traps that experienced no wave-induced vertical motions, whereas surface-tethered traps will experience vertical motions if not adequately decoupled from surface waves.

d. Interpretation of results. These experiments were not designed to measure absolute vertical fluxes of particles in the flume or the absolute collection efficiency of the traps. The intent was simply to determine the collection efficiency of traps filled with different amounts of brine relative to the collection rate of an identical trap with no brine. For a given experiment, all traps were exposed to the same particle and flow fields. Thus, all fluxes were normalized to the flux of the brine-free trap, so that results could be compared between experiments.

All of our flume experiments demonstrated a decrease in trapping efficiency with the addition of brine (Fig. 4). At slow speeds there is less erosion of brine, so the effective aspect ratio of each trap is smaller and thus they have a lower RCE because the particles get carried into the trap and right back out again because there is not a sufficiently tranquil region of the trap for particles to settle. An unexpected result was that in every case the trap containing merely one diameter of brine also collected less material than the trap with no brine, even at 5 cm sec^{-1} when there was no indication of erosion of the brine in that trap (Fig. 1). We presently have no explanation for this result.

Traps collected a greater percentage of particles >63 μm during experiments at high velocities than at low velocities (Fig. 4). The primary cause was one of availability of particles in the flume. The bed shear stress on the flume bottom was more likely to keep the larger particles in suspension at higher velocities, so the concentration of particles >63 μm was 2–3 times greater at flows of 16 cm sec^{-1} than at 5 or 10 cm sec^{-1} (Fig. 3, Table 1). Large particles contribute more to the particle flux than smaller particles of equal density. Because of their higher settling velocity, larger particles are also more likely to be retained once they have entered a trap rather than being carried up and out in turbulent eddies.

Despite the large differences in total weight collected as a function of brine height for a given velocity, there was only a slight decrease in the relative collection of particles >63 μm with increasing effective aspect ratio (Fig. 7). Velocity had a much larger effect on the weight of material collected as more sediment was in suspension at higher velocities (Fig. 8). Much of the increase at 16 cm sec^{-1} was in the particles >63 μm (Table 1).

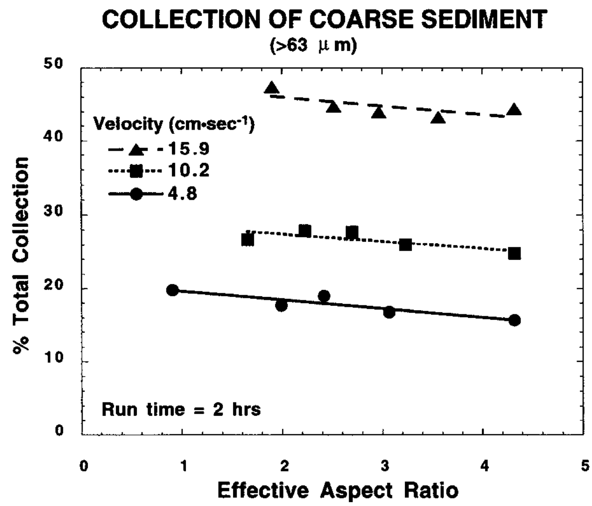


Figure 7. Percentage of large particles (>63 μm) in the total trap collection as a function of effective aspect ratio.

One might ask if the traps are simply collecting the horizontal flux of particles moving through the traps. As was argued by Gardner (1980a), we could multiply the mean particle concentration by the flow velocity times one half the trap cross-section (since to a first approximation flow enters the downstream half of the trap and exits the upstream half of the trap, but this ratio decreases as velocity increases) to determine a first-order approximation of the flux of particles through the trap. The result is that 3–4 orders of magnitude more mass went through the traps than was collected in the traps, making them very inefficient collectors of the horizontal flux.

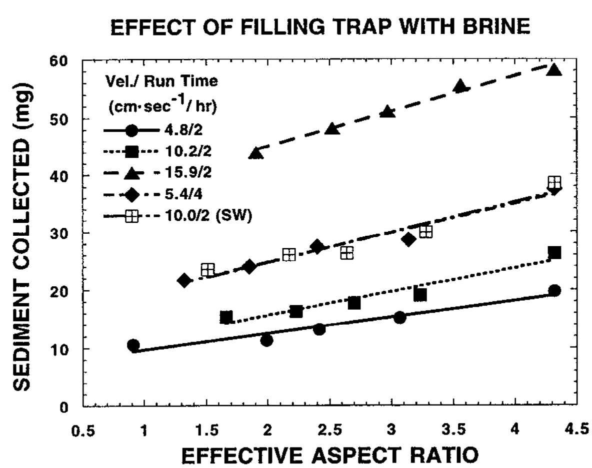


Figure 8. Amount of sediment collected in each experiment as a function of the effective aspect ratio. SW is the experiment run with saltwater in the flume.

e. Particles and traps in aquatic environments. Traps deployed in actively overturning boundary layers in the ocean may "over-collect" particles (Gardner and Richardson, 1992) because the residence time of particles is increased and they have more than one opportunity to be collected in traps. In the tranquil zone within a trap, particles can settle and yield a vertical flux of material unaffected by the natural turbulence and overturning in the boundary layer. Trap measurements in boundary layers might represent the flux that would occur if the overturning of the boundary layer were suddenly turned off and particles settled unimpeded. Outside of boundary layers we know of no evidence to demonstrate that turbulence inhibits the mean settling speed of particles. Thus there is no force that "suspends" particles in most of the ocean even though the density difference between seawater and small organic particles or large aggregates may be so small that they settle slowly or not at all. Their lack of settling is a matter of buoyancy, not suspension, and it can affect particles of all sizes. Thus, outside of boundary layers it is misleading to refer to small particles as "suspended" or large particles as "settling." Both are simply "particles" or "particulate matter," not suspended particulate matter. More needs to be learned about the coupling between fast- and slow-settling particles and large and small particles as they encounter traps.

In the open ocean much of the vertical flux is carried in large, low-density aggregates (Asper, 1987). If there is no tranquil zone above the brine in a trap, an aggregate is unlikely to have sufficient time to settle across the brine interface before the turbulent exchange of eddies carries them back into the main flow and out of the trap. Aggregates whose density is less than the density of the brine (as appears to be true for most aggregates, based on analyses by Alldredge and Gotschalk, 1988) will collect at the brine interface until they are: (1) resuspended from the interface, (2) exchange interstitial water with the brine and settle, or (3) consolidate and expel water until their bulk density exceeds the density of the brine (Fig. 9). The behavior in scenario 3 was observed when a low-density gel was used at the bottom of a time-series sediment trap (Jannasch *et al.,* 1980) with the intent of collecting settling material while maintaining its structural integrity, but the material rolled up into a ball before it would sink into the gel (Hans Jannasch and John Farrington, personal communication and the first author's personal observation, 1978). Although the viscosity of a brine is much less than that of a gel, the density effects are likely to be similar. Thus, if brine is added to a trap, the aspect ratio of the trap must be large enough to maintain a tranquil layer above the brine in which aggregates can settle before encountering the brine.

Ideally, floating traps should move with the water to reduce flow past the traps. However, when traps are attached at multiple depths to drifting arrays, each trap is likely to experience a different flow past its opening. Indeed, Gust *et al.* (1994) measured differential velocities in field experiments in the range of velocities we tested in the flume. The unsettling fact is that our results show that if you fill the traps with brine, the relative undercollection of particles increases at lower velocities; i.e. as you successfully couple the trap movement with the advecting water, the brine-related errors are likely to increase if you fill traps with brine.

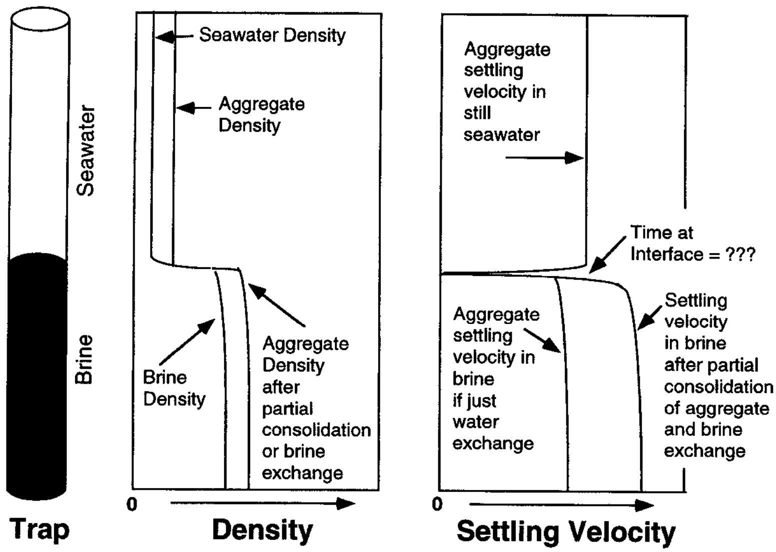


Figure 9. Cartoon of the fluid and aggregate densities (increasing to the right) and settling velocity of aggregates (in the absence of any flow or turbulence) in a cylindrical trap half-filled with brine.

f. Tranquil-layer development. In order to produce a tranquil region in which particles can settle, the brine must be eroded deeper than the mean eddy penetration depth for the highest velocity experienced by the trap during a given deployment. The density interface in traps filled with brine does indeed get eroded down to the mean eddy penetration depth in a few hours or less based on the steady-state conditions we tested. The problem is that the brine must be eroded deeper than the eddy penetration depth to create brine-free space for a tranquil layer. Thus, the velocity history experienced by a trap could influence the net trapping efficiency.

Two hypothetical examples of a velocity history for a 3-day trap deployment and the occurrence and thickness of the tranquil layer demonstrate the above issue (Fig. 10). The depth of eddy penetration and tranquil layer thicknesses are from our observations in the flume, and they match very well the observations of Hawley (1988), suggesting that over time (a few hours) eddies will erode a 5 psu brine to the same depth of eddy penetration if no brine was present.

In the first example (Fig. 10a), the velocity past the trap is 15 cm sec^{-1} for the first 12 hours, after which the velocity decreases. At 15 cm sec^{-1} the brine will be eroded to a depth of 3.8 trap diameters. When the velocity decreases to 10 cm sec^{-1} the eddies penetrate only to 3.5 diameters, leaving a tranquil layer of 0.3 diameters thickness. A further decrease in velocity increases the thickness of the tranquil layer, but the tranquil layer may disappear if the velocity increases to the previous maximum. Overall, the trap has a reasonable collection efficiency as long as the velocity is high in the beginning and decreases with time.

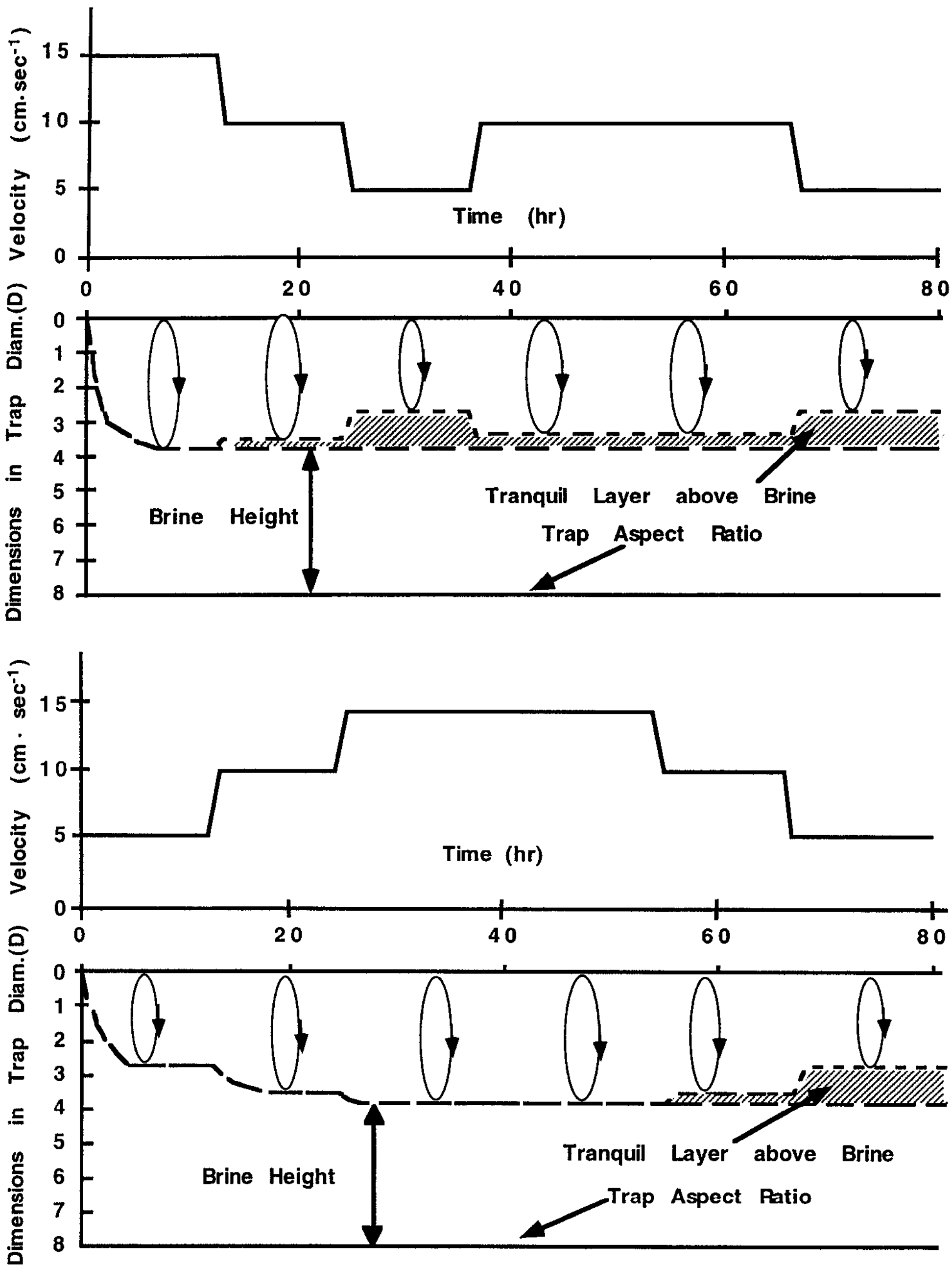


Figure 10. Two hypothetical examples of the velocity history experienced by traps with an overall trap aspect ratio of 8:1. Lower panels in A and B show the empirical depth of penetration of eddies as a function of approach velocity (upper panel), and the presence and thickness of the tranquil layer above the brine. Ovals with arrows imply depth of eddy penetration or fluid exchange. For actual flow patterns, see Gardner (1980a, 1985) and Hawley (1988).

If the velocity history of the trap has low or slowly increasing velocities for much of the early part of the trap deployment (Fig. 10b), there will be no tranquil layer and trap efficiency will be low. Only when the velocity decreases will a tranquil layer exist so the trap can perform normally. The longer a trap is deployed, the smaller should be the impact of adding brine because the probability increases for having the brine eroded down to a maximum penetration depth, and the longer the trap will have a tranquil layer which will allow collection of particles in the normal manner.

The simplest solution would be to use no brine in traps and thus avoid an additional complicating parameter—a variable aspect ratio. However, one of the purposes of adding brine is to retain poisons, preservatives and any dissolved components from the collected particles. Therefore, only the minimum amount of brine needed to cover the depth of particles one expects to collect during a deployment should be used. Brine can easily be added to a trap by first filling the trap with filtered seawater from the site of deployment and then gravity feeding the brine through a tube to the trap bottom. The trap should be tall enough to ensure that there will always be a tranquil layer at the bottom of the trap above the brine. If poisons are not used, brine may not be necessary.

g. Comparisons with field tests. Johnson *et al.* (1991) deployed baffled PIT traps with and without brine and found that brine-free traps collected larger amounts of material for most classes of particles than brine-filled traps. The mass flux was 0–60% greater in brine-free traps (Tony Michaels, personal communication, 1995; Gardner, 1997). We have tested cylindrical traps with and without brine on 6-week moored deployments in high-velocity flows on the shelf of Louisiana and preliminary analysis showed smaller differences than those found in the flume. In both cases the velocities may have been large enough to erode the traps deeply in the early part of the deployment. Scott Nodder (New Zealand, personal communication, 1995) tested cylindrical traps (D = 9 cm, aspect ratio = 10.6) filled with a 50 psu excess brine for 24 hours on frames 3 m above the harbor floor and found that they collected ½–⅓ the material collected with traps that were only partially filled with the same brine (equivalent to 1–3 trap diameters of brine). More tests are needed, but a three-fold difference would account for the entire carbon imbalance observed by Michaels *et al.* (1994).

5. Conclusions

It is of utmost importance that the measurement of vertical fluxes use protocols based on scientifically founded principles. Calculations based on the loss of excess ^{234}Th from surface waters and the total carbon budget at BATS indicate that in many cases floating sediment traps should collect much more material. Our flume results conclusively demonstrate that filling a cylindrical trap with a 5 psu brine can decrease the amount of material collected by nearly 50%, and Nodder (personal communication) has reported a 2–3 fold decrease in bottom-moored traps in the field. This decrease is sufficient to account for the 3-fold undertrapping suggested by Michaels *et al.* (1994). Field tests of floating traps with and without brine have shown an increase of 2–60% in collection rates in brine-free traps over brine-filled traps. More experiments should be run to test a wider dynamic range of a few key variables, especially in the field. Specifically: (1) Traps should be tested at velocities greater than 16 cm sec^{-1} and less than 5 cm sec^{-1}, (2) Experiments must be run using a brine of 50 psu excess salinity to simulate the protocols used in JGOFS Time Series Stations, (3) Tests must be made using lower-density particles since theory suggests that the biasing effects of brine will be greater for low-density particles, and (4) To ensure the applicability of the flume experiments to the natural environment, more deployments must be made in the field with and without brine.

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