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Predictions of sediment trap biases in turbulent flows: A theoretical analysis based on observations from the literature

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ABSTRACT

The physical variables affecting the trapping of particles in sediment collectors are grouped into a set of six dimensionless parameters, as a function of a dimensionless particle collection efficiency. Relevant laboratory calibration studies on sediment trap biases are evaluated to determine the quantitative dependence between collection efficiency and three of the parameters, trap Reynolds number, the ratio of flow speed to particle fall velocity and the ratio of trap height to mouth diameter, as well as trap geometry. We find that few of the parameters have been systematically tested in the laboratory and that trap Reynolds number-similarity for field conditions is maintained only for the slowest flow speeds and/or smallest trap diameters. However, the literature results do suggest some intriguing trends in biased trapping which also can be explained physically. The physical mechanisms are derived from a physical description of particle trapping based on observations of flow through traps, the mass balance for particles entering and leaving traps and a definition of particle collection efficiency, coupled with model development for cases where collection efficiency, as specified by the mass balance, deviates from one.

The following testable hypotheses for biased trapping by unbaffled, straight-sided cylinders and noncylindrical traps result from our analysis. For fixed values of the other two parameters, collection efficiency of cylinders will decrease over some range of increasing trap Reynolds number, decrease over some range of decreasing particle fall velocity and increase over some range of increasing trap aspect ratio. Traps will be undercollectors or overcollectors depending on the physical mechanisms causing the biased collections. Predicting biased collections for noncylindrical traps is more complex but, in most cases, small-mouth, wide-body traps will be overcollectors and funnel-type traps will be undercollectors. Future laboratory studies are required to test these hypotheses and, in particular, parameter combinations representative of field conditions, where traps are deployed, must be tested.

1. Introduction

Particle-collecting traps are presently a popular research tool for estimating the quality and quantity of material falling out of oceanic and limnologic water masses (see reviews of Bloesch and Burns, 1980; Blomqvist and Hakanson, 1981; and the

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annotated bibliography of Reynolds *et al.*, 1980). Concern regarding possible biased sampling by traps eventually motivated studies on the accuracy and precision of various trap designs. Most of these studies (over 40 listed in Reynolds *et al.*, 1980) involved comparisons, in the field, of particle collections either by several trap designs or by a trap and some other measure of particulate flux (e.g., ^{210}Pb flux in traps compared with ^{210}Pb flux from the atmosphere, see Knauer *et al.*, [1979]). Because no unbiased value for the "true" flux of particles in the field is available, these studies furnish only comparative data and estimates of trap precision (in the cases where replicates were deployed), but not estimates of trap accuracy.

Trap calibrations for accuracy estimates are possible in laboratory flows as long as all parameters dynamically important to the process of particle trapping are controlled and dynamic- and geometric-similarity to field conditions are maintained. The quantitative calibration studies to date (Hopkins, 1950; Davis, 1967; Peck, 1972; Tauber, 1974; Antsyferov *et al.*, 1977; Gardner, 1977, 1980a; Hargrave and Burns, 1979; Lau, 1979; Welton and Ladle, 1979) have provided valuable information on particle trapping for some specific trap designs, flow conditions and particle types. However, quantitative trap calibrations for the bulk of realistic field flows have not yet been performed (see 3.). Even so, results of calibration studies often have been extrapolated far beyond the range of hydrodynamic conditions actually tested. Recently, these extrapolations, coupled with the vast amount of information on field-tested traps, have been developed into general criteria for design, construction, and deployment of unbiased trap samplers (e.g., Bloesch and Burns, 1980; Reynolds *et al.*, 1980; Blomqvist and Hakanson, 1981). However, because traps have been calibrated only for a narrow range of field flows and particle types, flux estimates even from traps which meet the general criteria specified in these review papers should be viewed with caution. Suggesting that any particular trap design will unbiasly estimate particulate flux in a wide range of environments is premature.

The analysis presented here was motivated by the need to estimate particulate fluxes in a wide range of flow fields for which existing traps have been neither experimentally calibrated nor theoretically evaluated. The analysis seeks to identify the dominant hydrodynamical processes controlling particle trapping, thereby indicating the physical parameters that must be carefully monitored and the physical variables that must be carefully controlled during calibration experiments. In addition, a series of trap tests dictated by specific *a priori* hypotheses of biased trapping effects is the most efficient experimental procedure for determining the relative importance of several parameters to a particular physical process.

Given the plethora of studies which attempted to determine sediment trap collection efficiencies either by calibrations in the laboratory or by comparisons in the field (see annotated bibliography of Reynolds *et al.*, 1980), it is surprising that only two papers (Hargrave and Burns, 1979; Bloesch and Burns, 1980) provide formal theoretical treatments of the hydrodynamical processes governing particle collection by traps. Many of the calibration or comparison studies do offer hypotheses, based on some fluid dynamic principles, regarding the nature of particle trapping. However, because these discussions are not embedded in a theoretical framework, the resulting predictions often are ambiguous or conflicting (e.g., see disparate predictions for collections by the "Tauber" trap in the studies of Tauber, 1974; Gardner, 1977; Reynolds, 1979).

Neither of the previous theoretical analyses of particle trapping considered the characteristics or the behavior of particles moving in the flow; these studies analyzed only the nature of trap collections within the flow field. In addition, the scope of the theoretical analyses in these studies was limited. Hargrave and Burns (1979) determined the relative importance (using dimensional analysis) of the variables involved in only one aspect of particle trapping, that of resuspension of particles inside a trap. Bloesch and Burns (1980) described the general process of particle trapping using a control volume analysis (i.e., by balancing the mass entering and leaving a trap). They discussed only how various terms in this mass balance would be affected if the trap mouth area did not equal the trap base area.

The theoretical analysis presented here provides a more general analysis of the hydrodynamics of particle trapping and an analysis of some specific effects. First, the physical variables involved in the process of particle trapping are parameterized using dimensional analysis. Dimensional analysis is useful for reducing the number of variables affecting a particular physical phenomenon by grouping them into dimensionless parameters, using scaling arguments and the principal of dimensional homogeneity (Taylor, 1974; Isaacson and Isaacson, 1975). The selection of a physically meaningful group of parameters can lend insight into the specific nature of the physical relationship under study. The analysis indicates that the physical phenomenon is a function of each of the dimensionless parameters, but it cannot specify these functions mathematically (i.e., whether the relationship between efficiency and the parameter is directly proportional, inversely proportional, linear or otherwise). These functions sometimes can be derived theoretically, but generally must be determined empirically. Thus, to learn more about these functions, in the second part of this paper results of the published laboratory flume studies that determined particle collection efficiencies of various trap designs are evaluated relative to the dimensionless parameters. This exercise suggests specific relationships between some of the dimensionless parameters and particle collection efficiency and also identifies gaps in the literature. In the third part of this paper, some simple physical models are developed to account for these relationships. These models are presented in conjunction with a series of testable hypotheses regarding the nature of trap biases and serve two purposes. First, the theoretical models dictate various aspects of the experimental design, trap design and parameters to be tested in future trap studies. Second, the models and predictions may be used to gain insight into possible trap biases in existing field data.

2. Dimensional analysis

A dimensional analysis of the important independent variables involved in particle trapping requires few assumptions and is a useful way of determining dimensionless parameters to describe the process. The final choice of parameters requires some physical insight into the problem. Precise physical effects cannot be predicted from a dimensional analysis alone; the quantitative dependence between each parameter and particle collection efficiency can be determined experimentally. The dimensional analysis presented here is a necessary precursor to designing and interpreting laboratory experiments and to formulating more sophisticated models to explain the results.

For an unbaffled, straight-sided cylinder on a rigid mooring, the particle trapping rate, P, is a function of nine independent variables. The variables are defined and the basic dimensions (L = length, T = time, M = mass) of each variable are listed below.

P = particle trapping rate (in terms of particle number) or the number of particles trapped per unit area per unit time $(1/L^2T)$
d = particle diameter (L)
ρ_p = particle density (M/L^3)
ρ_f = fluid density (M/L^3)
μ_f = fluid viscosity (M/LT)
u_f = horizontal flow speed at the height of the trap mouth (L/T)
g = acceleration due to gravity (L/T^2)
D = trap mouth diameter (L)
H = trap height (L)
N_c = number of particles in the fluid per unit volume $(1/L^3)$.

The analysis carried out here is limited by the following conditions: (1) We assume that trap roughness (i.e., the smoothness of the surfaces of the construction materials) effects are negligible for the hydrodynamic flows considered here. (2) Turbulence in the oncoming flow regime is not parameterized. It is assumed that trap-induced turbulence dominates the flow through the trap so the trap "sees" only the mean-stream velocity of the oncoming flow and that a well-mixed particle suspension approaches the trap. (3) Trap geometries, other than straight-sided cylinders, are not parameterized here; parameterizations of other trap shapes would include terms other than just D and H. (4) Traps are assumed to be collecting particles in a horizontal, steady, uniform flow with no vertical shear. No tilt is allowed in the trap. (5) Details of flow disturbance resulting from trap-specific leading edge effects are not considered. (6) Particles are assumed to constitute a single size class and to be spherical in shape.

Three basic dimensions, with nine independent variables, stipulate a minimum of six dimensionless parameters; the particle trapping rate, P, also is parameterized. One set of parameters for the variables is

$$\frac{P}{\dfrac{(S-1)gd^2N_c}{\nu}} = f\left(\frac{u_f}{\dfrac{(S-1)gd^2}{\nu}}, \frac{u_fD}{\nu}, \frac{(S-1)gd^2}{\nu}\frac{d}{\nu}, S, N_cd^3, \frac{H}{D}\right), \tag{1}$$

where $\rho_p/\rho_f = S$ and $\mu_f/\rho_f = \nu$. Note that the third term also can be written in terms of $(d/4\nu)\ \sqrt{(S-1)gd}$, which is S_*. The grouping $(S-1)gd^2/\nu$ is the nominal fall velocity, W, of the particle so (1) can be further simplified as

$$\frac{P}{WN_c} = f\left(\frac{u_f}{W}, \frac{u_fD}{\nu}, \frac{Wd}{\nu}, S, N_cd^3, \frac{H}{D}\right). \tag{2}$$

The left-hand side of this expression is the nominal collection efficiency (E), $u_f D/\nu$ is the trap Reynolds number (R_t), and Wd/ν is the particle Reynolds number (R_p). Note, too, that for noncylindrical traps E also is a function of trap geometry.

Under certain conditions, the right-hand side of (2) can be considered to be independent of each of the dimensionless parameters. Assuming there is no resuspension of particles from the trap bottom, then for small relative particle concentrations, $N_cd^3 \ll 1$, such that particles move in the flow and settle independently, the function is independent of N_c, and thus, of N_cd^3. If particle inertia is negligible, such that particle motions are determined only by the flow velocity and the particle fall velocity (see 4.), then the function is independent of both S and R_p. If particle trapping depends only on processes exterior to the trap and if interior boundary processes (e.g., resuspension) are unimportant, then the function would be independent of R_t and H/D, which are associated with processes taking place inside the trap. Finally, for sufficiently large values of u_f/W, the function can be considered to be independent of this velocity ratio because trap collections may be dominated entirely by flow-induced flushing of the trap interior. However, if resuspension occurs inside a trap, then all these parameters must be retained.

Only the variables composing the three dimensionless parameters, R_t, u_f/W, and H/D, have been sufficiently measured during laboratory experiments to permit even a cursory evaluation of their effects on trap collection efficiency. Rough estimates for S can be made (see Table 1), but it is unlikely that S will be an important determinant of collection efficiency in the ocean because the potential range in values for S is relatively small (a factor of about two, versus several orders of magnitude for the other parameters). While the precise effects of S and the two remaining dimensionless parameters (N_cd^3 and Wd/ν) in (2) cannot be evaluated from existing experimental observations, models suggesting biased trapping mechanisms that involve some of these terms are discussed later.

3. Observations from the literature

Results from five laboratory studies on particle collection efficiencies of traps in quasi-steady flow (Peck, 1972; Tauber, 1974; Gardner, 1980a; Hargrave and Burns,

Table 1. Ranges of values for the dimensionless ratios, R_t, u_f/W, H/D, and S, and trap geometries tested in six laboratory studies.

Laboratory study	Approximate[α] range in R_t	Approximate[β] range in u_f/W	Range in H/D for cylinders	Approximate[γ] $S = \rho_p/\rho_f$	Trap geometries tested
Peck (1972)	1×10^4–2×10^4	4×10^3–7×10^3	NCT[δ]	1×10^0	Tauber trap (a "short" and a "tall" version)
Tauber (1974)	1×10^4–1×10^5	1×10^2–1×10^3	NCT[δ]	9×10^2	Tauber trap
Gardner (1977, 1980a)	5×10^2–6×10^3	7×10^3–2×10^4	1.0–2.3	3×10^0	Cylinders, funnel traps, baffled funnel traps, small-mouth wide-body traps, segmented basin, flat plate, horizontal tube with slit
Hargrave and Burns (1979)	1×10^3–6×10^3	1×10^1–4×10^3	1.2–20.4	3×10^0	Cylinders, baffled cylinders, funnel trap, small-mouth wide-body trap, covered cylinder, tray, trap with horizontal-facing aperture

Lau (1979)	2×10^3–3×10^4	NA$^\epsilon$	4.7–10.0	NA$^\epsilon$	Cylinders

α. R_t were calculated as described in the caption to Figure 6.

β. Estimates of u_f/W were determined as follows. For Peck (1972), we used $W = 1.6 \times 10^{-3}$ cm/sec for *Lycopodium* (as measured by Reynolds [1979]) and $u_f = 6.7$ to 11.3 cm/sec (the range in mean profile velocities from Peck's Fig. 3). For Tauber (1974), $W = 1.1$ cm/sec was calculated from Stokes' equation using $\rho_p = 1.06$ g/cm^3 and a shape-correction factor of 2.0 for *Lycopodium* (as measured by Reynolds [1979]), $d = 26.3$ μm, $\mu_f = 1.8 \times 10^{-4}$ g/cm sec and $\rho_f = 1.20 \times 10^{-3}$ g/cm^3 (20°C air); $u_f = 100$ to 1000 cm/sec. For Gardner (1977, 1980a), we used $W = 5.6 \times 10^{-2}$ cm/sec, calculated from Stokes' equation for $d = 2.6$ μm (the median diameter of Gardner's sediment mixtures), $\mu_f = 1.07 \times 10^{-2}$ g/cm sec and $\rho_f = 1.02098$ g/cm^3 (20°C, 30 ppt seawater), and $u_f = 4.0$ to 9.5 cm/sec. For Hargrave and Burns (1979), we used $W = 3.2 \times 10^{-1}$ cm/sec for a silt particle ($d = 62.5$ μm) and $W = 1.3 \times 10^{-3}$ cm/sec for a clay particle ($d = 3.9$ μm), calculated from Stokes' equation, as for Gardner above, and $u_f = 4.5$ cm/sec.

δ. NCT = no cylinders were tested

ϵ. NA = not applicable; Lau (1979) studied only water motion inside traps, not particle collection characteristics of traps.

γ These values were calculated using ρ_f for 20°C freshwater for Peck (1972), for 20°C air for Tauber (1974), and for 20°C, 30 ppt seawater for Gardner (1977, 1980a) and Hargrave and Burns (1979). For Peck (1972) and Tauber (1974), we used $\rho_p = 1.05$ g/cm^3, as measured for *Lycopodium* in Reynolds (1979). For Gardner (1977, 1980a) and Hargrave and Burns (1979), we used $\rho_p = 2.65$ g/cm^3 (for quartz sediments), but natural particle mixtures taken from the field were used in these studies so the actual range in ρ_p is unknown.

1979; Lau, 1979) are evaluated here; other published laboratory studies of traps were not included because they did not involve moving fluid (Hopkins, 1950; Davis, 1967) or quasi-steady flow (Antsyferov *et al.*, 1977), because no quantitative data were presented in the papers (Anderson, 1977; Honjo *et al.*, 1980; Soutar *et al.*, 1977), or because the trap was not designed for collecting falling particulates in lake or marine systems (Welton and Ladle, 1979). Of the studies considered here, two (Peck, 1972; Tauber, 1974) examined a single trap design (The "Tauber" trap, diagrammed in Fig. 1) collecting pollen, two (Gardner, 1980a; Hargrave and Burns, 1979) examined a variety of trap designs collecting natural sediments, and one (Lau, 1979) examined the flow of water through cylinders but not particle collections by the traps. The ranges in values of the dimensionless parameters, R_t, u_f/W, H/D, and S, and the trap geometries tested in these five published studies are given in Table 1.

The results of these studies are summarized in terms of specific relationships between particle collection efficiency and these dimensionless parameters and trap geometry. Relative differences in collection efficiencies between trap designs within a given study can be compared between studies (of Peck, 1972; Tauber, 1974; Gardner, 1980a; Hargrave and Burns, 1979). The exact values of the particle collection efficiencies cannot be compared between studies, however, because efficiencies in each study were measured and calculated as a function of only a limited range of parameter values (see Table 1); there was little overlap in these values between studies. In addition, results of the studies cannot be applied directly to the field because laboratory and field environments differ in particle characteristics (especially in the range of particle fall velocities and concentrations), and in flow characteristics (e.g., the range of mean flow speeds and turbulence).

a. Particle collection efficiency and trap Reynolds number. The only laboratory study where a single trap design collecting a given particle type was systematically tested over a range of R_t is that of Tauber (1974). The results give little insight regarding sediment trap collections of particles in ocean flows, however, because Tauber's study was designed to determine collection characteristics of the "Tauber" trap for airborne pollen grains. Because the study was conducted in a wind-tunnel, the range in values for the parameter u_f/W is significantly lower and for the parameter S is significantly higher than values for most particles falling through water (see Table 1). The ratios u_f/W and S indicate particle properties relative to flow and fluid properties, respectively. Tauber's relatively low u_f/W and high S indicate that particle paths do not necessarily follow flow streamlines and that inertial forces on the particles (other than just gravitational settling) may significantly affect particle behavior in flows. This contrasts distinctly with the situation in water, where particles accelerate nearly instantaneously with the flow and where inertial forces on particles usually are negligible (see 4.). This also means that the physical mechanisms governing particle collection during Tauber's (1974) trap tests may not be the same mechanisms governing sediment collections in water. In this regard, Tauber's (1974) study is not relevant to the focus of this paper.

Tauber's (1974) data are useful here for demonstrating how the definition of particle collection efficiency can affect the outcome of a given study. Tauber's data are plotted in Figure 1 for two definitions of "collection efficiency": (1) Tauber's definition, where trap collections are divided by an estimate of the *horizontal* flux of particles past the trap mouth, and (2) the definition given in Eq. (4) of this paper, where actual collections are divided by an estimate of the *vertical* flux of particles through the trap mouth (see caption to Fig. 1). The appropriate efficiency definition depends both on the scientific question and on the processes governing particle trapping (see 4.); we show these results only to demonstrate the necessity of using a consistent, physically sound efficiency definition in trap calibration studies and when comparing trap collections between studies. The changes in efficiency with R_t in Tauber's (1974) study clearly differ, depending on the way efficiency is defined.

Trap tests by Peck (1972), Hargrave and Burns (1979) and Gardner (1980a) were conducted within the ranges of u_f/W and S that occur in the ocean. These studies give limited insight regarding the dependence between R_t and collection efficiency because R_t varied simultaneously with other important parameters (e.g., particle type and H/D), in some cases, making data interpretation difficult. In addition, only a narrow range of R_t was tested, representing dynamically similar conditions only for the slowest flows or smallest traps used in the field (see below).

Peck (1972) tested the Tauber trap at two water velocities for about a factor of two change in R_t; however, different pollen grains were tested each time (Fig. 2). At a given R_t, collection efficiency varied considerably, depending on the pollen species tested (see Fig. 2 and discussion in 3.b.); thus, meaningful between-R_t comparisons are not possible for Peck's (1972) data.

Hargrave and Burns (1979) tested cylinders collecting sediments for R_t ranging from 1×10^3 to 5×10^3. There is a slight, but not a statistically significant, trend of decreasing efficiency with increasing R_t (Fig. 3); however, trap aspect ratio was not held constant. Aspect ratio decreased with increasing R_t, so it is not possible to determine the separate contributions of these two effects to changes in efficiency.

Gardner (1980a) tested three cylinder sizes (traps A, B and C in Fig. 4) at water velocities of 4.0 and 9.5 cm/sec, thus, for R_t from 1×10^3 to 5×10^3. In each case, efficiency slightly increased at the higher R_t tested (see Fig. 4; open circles are the high R_t, closed circles are the low R_t). However, if the error bars at the high R_t (where no replicate runs were made) are as large as those for the low R_t, then the efficiency differences are not significant, at least for traps A and B.

While there is no substantial evidence for a particular dependence between R_t and efficiency from the laboratory studies of traps collecting particles in water, results of Lau's (1979) study clearly demonstrate a dependence of the degree of water motion inside the trap on R_t. For a given aspect ratio, the degree of water motion at the trap bottom increased with increasing R_t. Neutrally buoyant oil droplets placed 1- to 2-cm

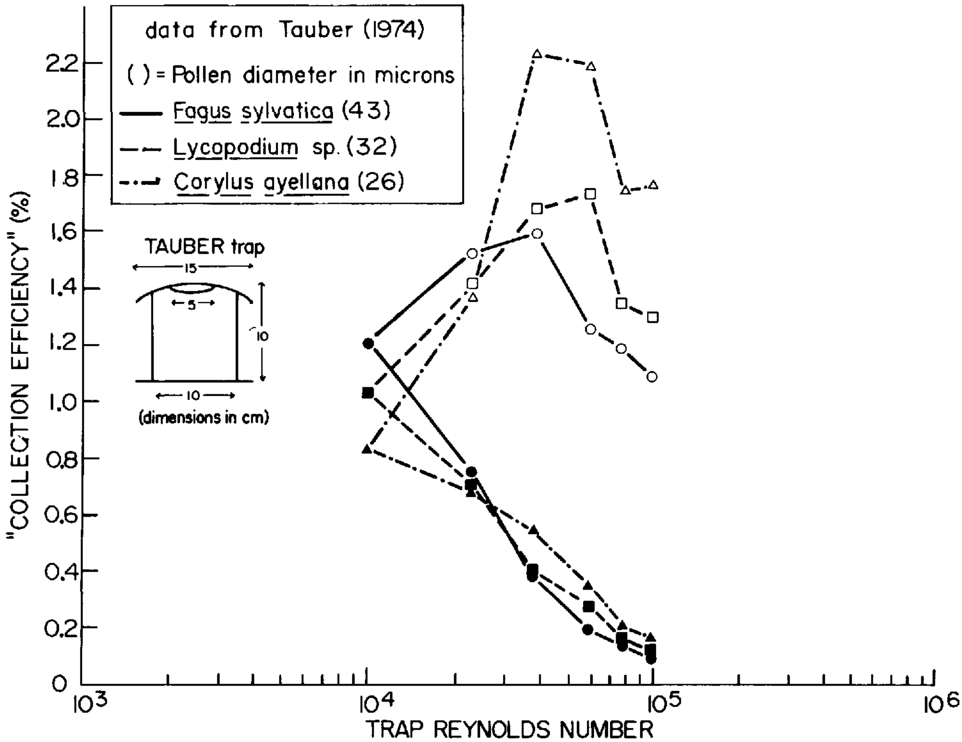

Figure 1. Effect of trap Reynolds number on "collection efficiency" in a wind-tunnel study of pollen collectors (Tauber, 1974). The Tauber trap (diagrammed in this figure) was tested for wind speeds ranging from 100 to 1000 cm/sec. R_t were calculated as described in caption to Figure 6. Tauber's (1974) results are plotted using two definitions of collection efficiency. (1) Tauber (1974) used the efficiency definition of Gregory (1961), where actual trap collections ("trap dose"/cm^2) are divided by an estimate of the *horizontal* flux of particles through a 1 cm thick space over the trap mouth ("area dose"/cm^2). The trap dose was the number of spores collected by a trap divided by the orifice area (19.63 cm^2). The area dose was determined from sticky impaction rods, where measured volumetric particle concentration was first corrected for impaction efficiency and then multiplied times the mean horizontal flow speed ($\overline{u}$) and the time interval of the collection. These are plotted by the solid symbols in this figure. (2) In the present study, collection efficiency is defined as the particles collected on the trap bottom divided by an estimate of the *vertical* flux of particles through the trap mouth area (see equation [4]). To convert Tauber's horizontal flux efficiency definition to our vertical flux definition requires multiplying Tauber's efficiencies by $\overline{u}/W$, determined for each trap collection. Because Tauber did not measure W for the pollen grains he tested, we assume here that W = constant for all trap tests and multiply each of Tauber's efficiencies by $\overline{u}$ for that particular trap collection. While this does not yield absolute efficiencies, it does allow comparisons across R_t within a pollen grain species, but not between species. Thus, only the shapes of the curves are meaningful; the absolute efficiencies will change by a constant (W) for each pollen species. For example, *Lycopodium* collection efficiencies would all change by a factor of ~0.90, if we use our calculated W of 1.1 cm/sec for this pollen species falling in air (see footnote β to Table 1). The vertical flux collection efficiencies are plotted by the open symbols in this figure.

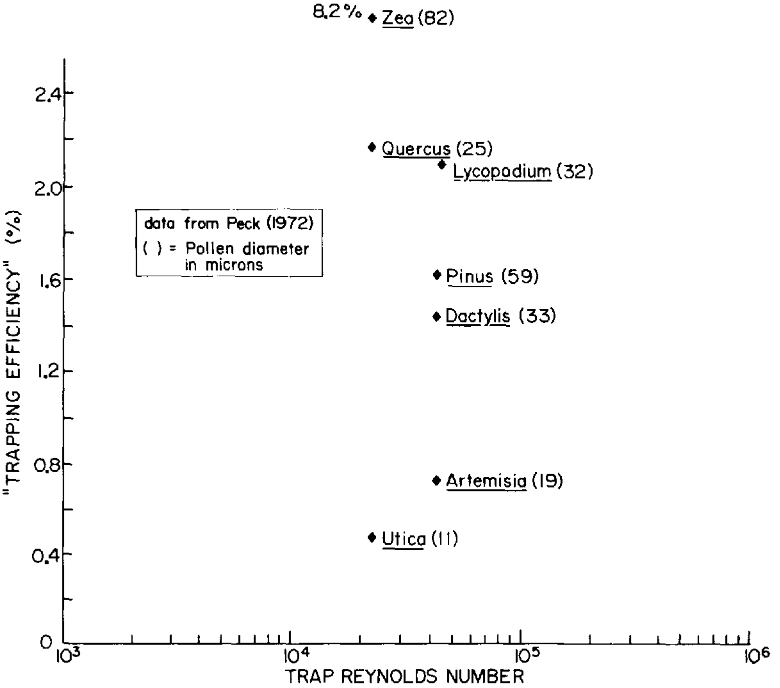

Figure 2. Effect of trap Reynolds number on "trapping efficiency" in a freshwater study of pollen collectors (Peck, 1972). The Tauber trap (diagrammed in Fig. 1) was tested for flow speeds ranging from 6.7 to 11.3 cm/sec (from Peck's Fig. 3). R_t were calculated as described in the caption to Figure 6. Peck (1972) calculated "trapping efficiencies" relative to the horizontal particle flux, as did Tauber (1974) (see [1] in caption to Fig. 1) except that Peck's "area dose" is $\bar{c}\,\bar{u}\,t$, where $\bar{c}$ = "average concentration per unit volume during experiment," as measured in large water samples (665 ml) taken from the flume, $\bar{u}$ = mean profile velocity and t = duration of the trap collection. To approximately convert Peck's calculated values to efficiencies normalized by vertical particulate flux (the efficiency definition used in the present study, see Eq. [4]), we multiplied Peck's efficiencies (*TD*/*AD* in her Table 3) by $\bar{u}$ ("Flow Velocity" in her Table 3). As for Tauber's (1974) data (see [2] in caption to Fig. 1), it was not possible to calculate absolute efficiencies, based on our vertical flux definition, because W was not measured for the pollen grains tested by Peck (1972) and W also could not be calculated with sufficient accuracy for these grains, based on the information available. For example, some of the pollen grain densities cited by Peck (1972), but determined in other studies, are less than one, indicating that the grains would not be falling in water and thus would not constitute part of the vertical flux. If this were true, then trap collections represent water samples only and there should have been no net sedimentation rate of these pollen grains. An alternative explanation is that the densities reported were determined for pollen with intact air vacuoles falling in air and not for the relevant "wetted" (*sensu* Reynolds, 1979) pollen falling in water.

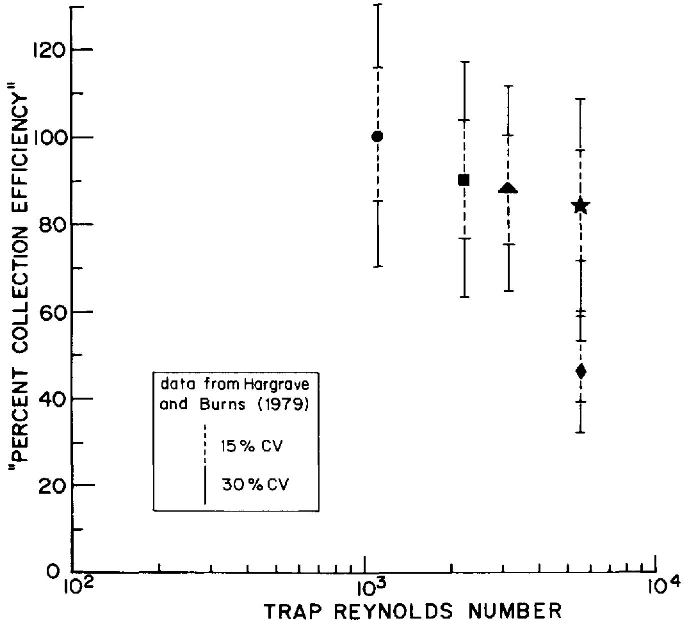

Figure 3. Effect of trap Reynolds number on "percent collection efficiency" in the seawater study of sediment collectors conducted by Hargrave and Burns (1979). Dimensions of the trap designs are given below Figure 7; data for their trap design 1 (circle), 2 (square), 3 (triangle), 4 (diamond) and 5 (star) are plotted here. Vertical lines represent 15 and 30% error bars around each point, the range in *CV* for Hargrave and Burns' experiments. Traps were tested at flow speeds of 4 to 5 cm/sec ($u_f = 4.5$ cm/sec was used in R_t calculations). R_t were calculated as described in caption to Figure 6. The flow was seeded with natural sediments <125 μm in diameter. "Percent collection efficiencies' were calculated as the weight of material deposited per unit area in the trap as a percentage of the "sedimentation rate" in the flume. The sedimentation rate was determined from "changes in the concentration of suspended matter in the tank."

above the bottom of each trap eventually escaped from all cylinders tested by Lau, but escape occurred at lower R_t for lower aspect ratios (Fig. 5).

If collection efficiency of a given trap design (i.e., holding aspect ratio constant) can change for different values of R_t, then collection results can be meaningfully compared only for similar R_t. Thus, it is important to determine how R_t in the laboratory studies compare with R_t for typical field deployment sites. In the laboratory, particle collection efficiencies of traps were determined for R_t ranging from the 5×10^2 to 6×10^3 for studies involving natural ocean sediments (Gardner, 1980a; Hargrave and Burns, 1979) and ranging from 1×10^4 to 1×10^5 for the studies involving pollen grains (Peck, 1972; Tauber, 1974) (Table 1). Lau (1979) looked at water motion in traps for R_t ranging from 2×10^3 to 3×10^4 (Table 1).

It is possible only to roughly determine the applicability of results from the laboratory studies to field conditions. While a few field studies using sediment traps

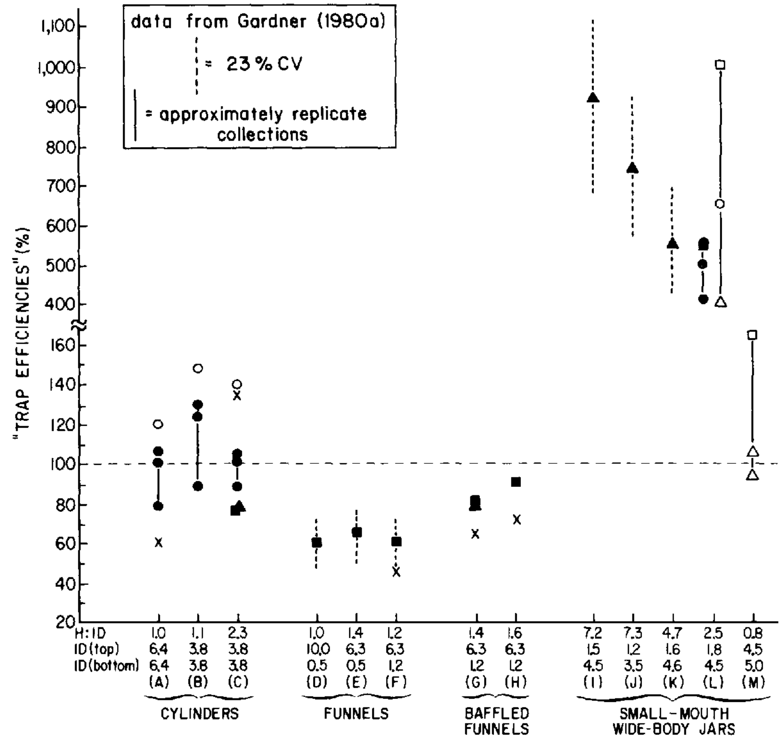

Figure 4. "Trap efficiencies" of several trap designs tested in the laboratory flume study of Gardner (1980a). "Trap efficiencies" were calculated as the "flux measured by the trap[s] (mass/cm^2/time)" as a percentage of the "sedimentation rate on the flume bed (mass/cm^2/time)." The sedimentation rate was calculated as the difference between the concentration of suspended particles at the beginning and at the end of each experiment. The efficiencies were taken from his Tables 3, 4, and 5 (pages 24–26) and are based on A_m (trap mouth area). Relevant trap dimensions (in cm) were taken from his Table 1 (page 21) and appear below this figure; the baffle cells were 1-cm high and 1-cm wide. The trap designs are labeled here by the letters A through M (appearing in parentheses below this figure). The points plotted in this figure were taken from nine separate flume experiments. The flow was seeded with natural sediments 63 μm in diameter (95% were <26 μm in diameter). The flow speeds (in cm/sec) and particle concentrations (in mg/l) for these experiments (taken from Gardner's Tables 3, 4, and 5) were, respectively: 9.0 and 11.8 for experiment 1 (open triangles), 8.9 and 11.5 for experiment 2 (open squares), 4.4 and 51.0 for experiment 3 (closed circles), 4.4 and 55.0 for experiment 4 (closed circles), 9.5 cm/sec and 58.2 for experiment 5 (open circles), 4.4 and 53.0 for experiment 6 (closed circles), 4.3 and 34.4 (also, traps were rotated during this experiment) for experiment 8 (crosses), 4.0 and 31.2 for experiment 9 (closed squares) and 4.0 and 82.4 for experiment 10 (closed triangles). Experiments 3, 4 and 6 are not distinguished in this figure (i.e., they are all indicated by closed circles) because the conditions were approximately replicated between these experiments. Trap efficiencies determined under similar experimental conditions (as judged by the present authors) are connected by solid vertical lines in this figure. Dotted lines represented as estimated CV of 23 percent surrounding the data point (as calculated in Hannan, 1984).

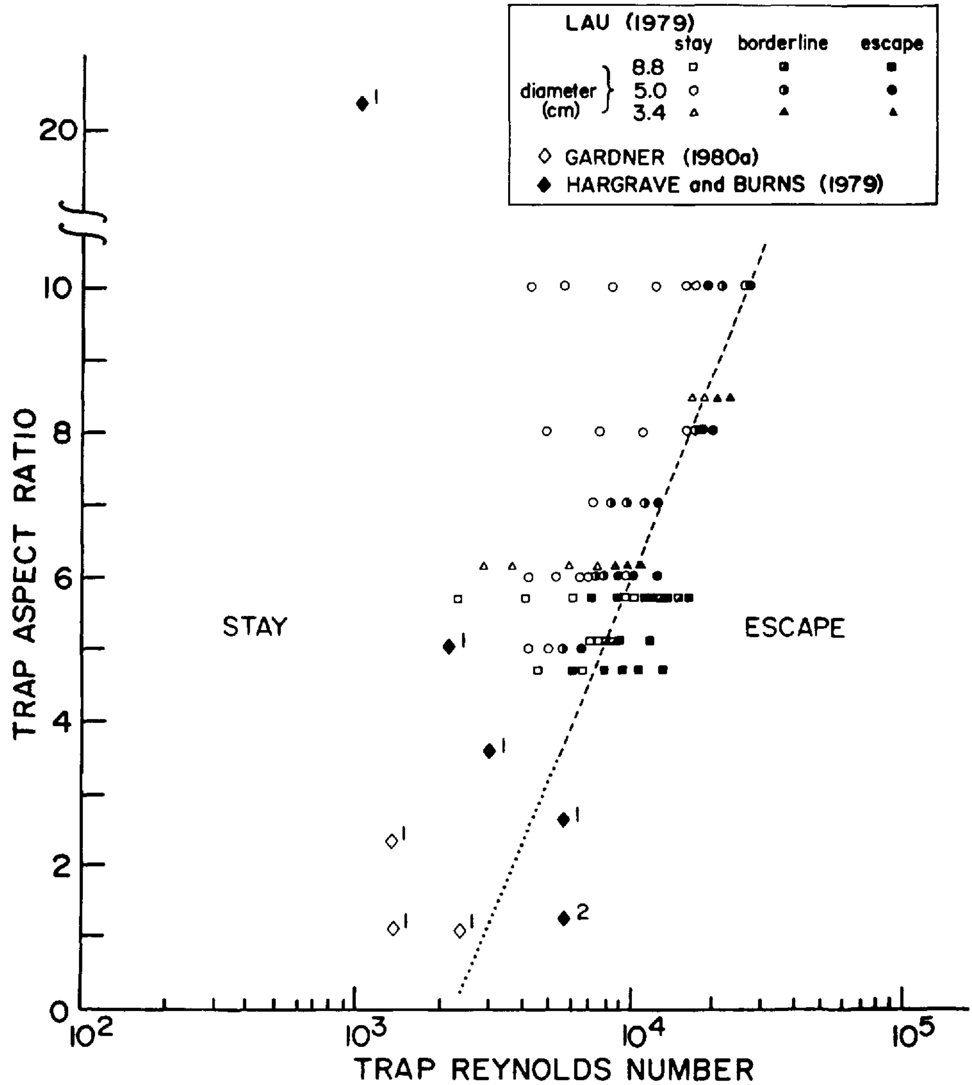

Figure 5. Behavior of oil droplets in the bottom of traps with various aspect ratios and R_t from the study of Lau (1979). "The dashed line indicates approximately the separation between the 'stay' and 'escape' regions" (Lau, 1979). The dotted part is an extension, by the present authors, of Lau's dashed line for lower aspect ratios and R_t. Also plotted on this figure are data from Gardner's (1980a) and Hargrave and Burns' (1979) studies of straight-sided cylinders (see Figs. 4 and 7, respectively). All of the cylinders tested in each of these two studies were ranked (separately for each study) in order of decreasing collection efficiency (where significant differences were demonstrated). Each rank is plotted on this figure by its coordinates for R_t and H/D. Data are plotted only for cylinders where replicates were tested and collection efficiencies are considered significantly different only if the error bars did not overlap (see Figs. 4 and 7).

have included measurements of flow velocities at or near the trap deployment site (e.g., see Table 2), no published study to date has actually measured the flow speed at the height of the trap mouth during the course of trap collections; thus, direct calculations of R_t for existing field measurements are limited. In addition, field flows generally are not steady, so R_t varies over a range of values during a single deployment.

The relationship between flow speed and trap diameter for lines of constant R_t is shown in Figure 6. Trap diameters used in the field usually are >8 cm; Gardner's 25 cm diameter cylinder is one of the trap designs most-frequently used in field experiments (e.g., Rowe and Gardner, 1979; Dymond *et al.*, 1981; Staresinic *et al.*, 1982; Gardner *et al.* 1983, 1984). Realistic field R_t for these traps may range from 2×10^4 to 1×10^5 for typical current speeds of 10 to 50 cm/sec (see below); no laboratory studies using sediments have approached these Reynolds numbers (see Table 2).

A wide range of current velocities is expected in various ocean environments and this variability must be considered when making estimates of R_t in regions where traps are typically deployed. While traps "see" instantaneous current speeds during collections, hourly-averaged flow statistics can be used to give typical ranges of current velocities expected in the field for calculating R_t. For example, throughout the water-column (during non-storm conditions), hourly-averaged current speeds reach a maximum of about 50 cm/sec in typical continental shelf environments (e.g., Butman *et al.*, 1979; Cacchione and Drake, 1982; Lee and Atkinson, 1983; Grant *et al.*, 1983) where traps are sometimes deployed. However, strong tidal currents up to 100 cm/sec occur near the bed in some regions of the continental shelf (e.g., Moody *et al.*, 1984) and storm flows well over 100 cm/sec are not unusual (e.g., Forristal *et al.*, 1977). Recent deep ocean (~4700 m at the "HEBBLE" site) current measurements indicate extreme storm flows up to 73 cm/sec within 100-m of the bottom (Richardson *et al.*, 1981). At the base of the continental rise at the HEBBLE site, typical storm flows at 1 m above the bottom are 20 to 30 cm/sec, while typical nonstorm flows are 0–12 cm/sec at 1 m above the bottom (Grant *et al.*, 1985). Note that traps experience the *total* instantaneous current speed, which includes high-frequency currents such as wind-driven and internal waves, as well as the low-frequency current speeds. In the coastal ocean, surface waves can penetrate to the bottom in water depths up to 200 m during storms (e.g., Grant *et al.*, 1984), so they also must be considered in velocity estimates.

From Figure 6, it is clear that laboratory calibrations of traps collecting natural sediments are dynamically similar to collections by very small diameter traps (e.g., <2 cm) for a realistic range of field flows (2.5 to 60 cm/sec) or by more realistic trap sizes (>8 cm) for very low field flows (<7.5 cm/sec). From the data available (Table 2), the range of R_t for typical field conditions is greater than the range tested for traps collecting sediments in the laboratory (the studies of Gardner, 1980a; Hargrave and Burns, 1979) by at least an order of magnitude. Thus, traps have been calibrated in the laboratory (using natural sediments) only for the slowest flows occurring in the field. It is likely that the dearth in the literature of calibration studies such as Gardner's (1980a) and Hargrave and Burns' (1979) is partially responsible for

Table 2. Calculated trap Reynolds numbers for sediment traps deployed in the field.

Reference	Study site (depth in meters)	Trap depth (meters)	Depth of velocity measurements (meters)	Outside trap diameter at mouth (cm)	Measured flow speed (cm/sec)	Calculated$^{\alpha}$ R_t
Hargrave and Burns (1979)	St. Margaret's Bay, Nova Scotia (13)	10	not measured during trap collections$^{\beta}$	2.5–21.3	≤ 8	$\leq 1 \times 10^4$
Rowe and Gardner (1979)	North Atlantic		not measured during trap collections$^{\delta}$			
	(2192)	2156–2162		25$^{\tau}$	≤ 5	$\leq 9 \times 10^3$
	(2815)	2316–2803		25$^{\tau}$	≤ 30	$\leq 6 \times 10^4$
	(3577)	3059–3459		25$^{\tau}$	≤ 30	$\leq 6 \times 10^4$
Gardner (1980a)	Woods Hole, MA					
	(6.6)	3.3	3.3	3.9–25.1$^{\tau}$	≤ 3	$\leq 6 \times 10^3$
	(18)	6, 6.9	6, 6.9	3.9–25.1$^{\tau}$	≤ 21	$\leq 4 \times 10^4$
	(12)	6.6	6.6	3.9–25.1$^{\tau}$	≤ 50	$\leq 9 \times 10^4$
Dymond *et al.* (1981)	Santa Barbara Basin, CA (580)	213–318$^{\epsilon}$	330	25–57$^{\epsilon,\tau}$	0.8–17.5	2×10^3–7×10^4
Lorenzen *et al.* (1981)	Puget Sound, WA (110)	50	ING$^{\gamma}$	15$^{\tau}$	≤ 8	$\leq 9 \times 10^3$
Staresinic *et al.* (1982)	Peru upwelling (~150)	30	30$^{\lambda}$	40.6	10–28	3×10^4–8×10^4

Parmenter *et al.* (1983a)	Georges Bank, MA (65)	62	64	32	10–50	2×10^4–1×10^5
Parmenter *et al.* (1983b)	Lydonia Canyon, MA (250–590)	~110	~110	6.6–50	mean ≃ 15 SD ≃ 10	2×10^3–9×10^4
Gardner *et al.* (1983)	Nova Scotian Rise (HEBBLE site, 4158–5076)	10 mab[μ]	50 mab[μ]	25[π]	range: 1–73.5 mean: 8–32.1	2×10^3–2×10^5 2×10^4–8×10^4
Gardner (1985)	Piermont, NY	1.5	1.5	7.9[π]	range: <2–62	$<2 \times 10^3$–5×10^4

α. For all R_t calculations, the value for ν of 1.35×10^{-2} cm²/sec (10°C, 30 ppt seawater at one atmosphere) was used. Most studies did not give information on water characteristics during trap collections so ν could not be calculated exactly. Using one value of ν for all studies probably introduces an error of no more than a factor of two (e.g., for 30 ppt water at 5°C, $\nu = 1.56 \times 10^{-2}$ cm²/sec and for 30 ppt water at 20°C, $\nu = 1.05 \times 10^{-2}$ cm²/sec; ν is considerably more sensitive to changes in temperature than to changes in salinity).

β. Current speeds were inferred by Hargrave and Burns (1979) from the study of Webster *et al.* (1975).

δ. Current speeds were inferred by Rowe and Gardner (1979) from the study of Luyten (1977) for the two deep stations and from their own observations using DSRV *Alvin*.

ε. For the "Soutar cone traps" and the "Gardner cylinder traps" only.

γ. ING = information not given in the study.

λ. Current speeds were determined from the trajectories of free-drifting sediment traps deployed for ≤12 hr intervals concurrently with moored sediment traps.

μ. mab = meters above bottom.

ν. Current speeds from Richardson *et al.* (1981), as presented in Gardner *et al.* (1983).

π. Inside mouth diameter.

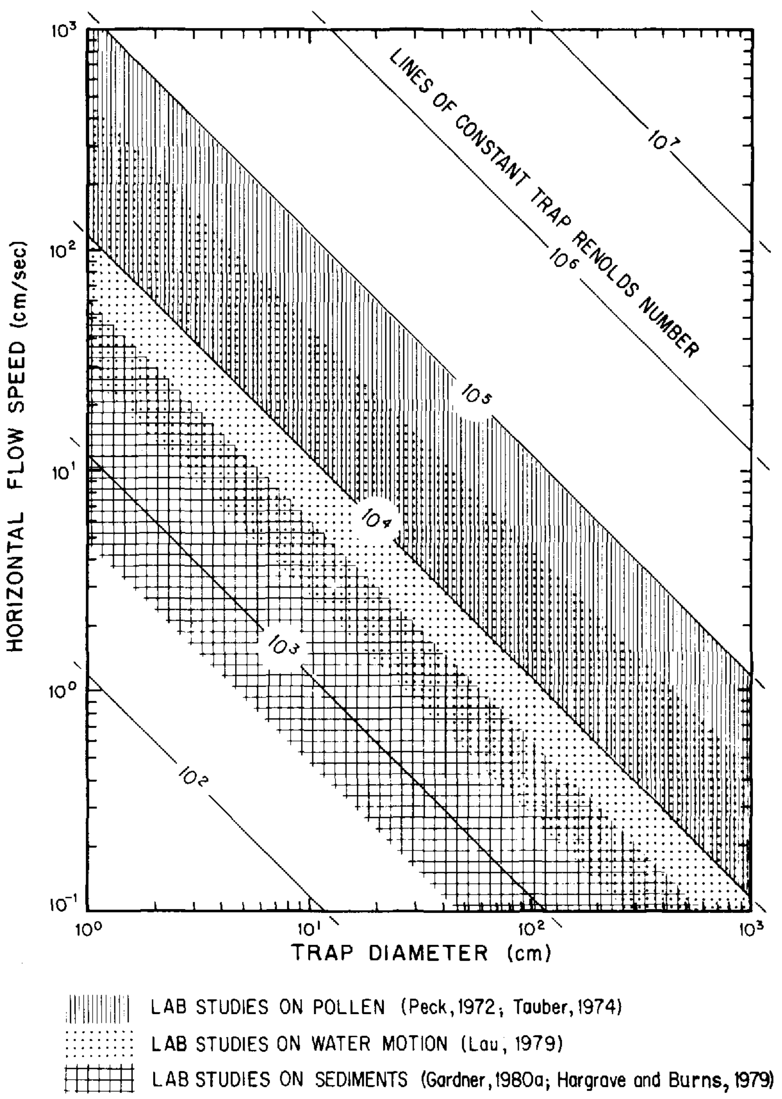

Figure 6. Relationship between flow speed and trap diameter for lines of constant trap Reynolds number, for traps collecting in a typical field environment (15°C, 30 ppt seawater, $\nu = 1.18 \times 10^{-2}$ cm^2/sec). Also shown are ranges in R_t of traps tested in the laboratory. Trap Reynolds numbers were calculated for the studies of Peck (1972), Tauber (1974), Gardner (1980a) and Hargrave and Burns (1979) based on the range of flow speeds and the range of outside mouth diameters (when available, otherwise inside diameter was used) of all traps with circular mouth openings, in each study. For the Tauber trap (diagrammed in Fig. 1) the 15 cm diameter of the concave collar surrounding the mouth was used for the trap length scale. Because none of these studies provided complete information on fluid temperatures or water salinities during trap tests, it was assumed that all studies were conducted at a room temperature of 20°C, for the R_t calculations made here. Kinematic viscosities used in R_t calculations were $\nu = 1.048 \times 10^{-2}$ cm^2/sec (30 ppt seawater) for the studies of Gardner (1980a) and Hargrave and Burns (1979), $\nu = 1.01 \times 10^{-2}$ cm^2/sec (freshwater) for the study of Peck (1972), and $\nu = 1.51 \times 10^{-1}$ cm^2/sec (air) for the study of Tauber (1974). Lau's (1979) calculated R_t also are plotted in this figure; note, however, that Lau did not give the exact values for D, u_f and ν that went into each R_t calculation, and thus, his R_t may not be strictly comparable to the other R_t calculated here.

the over-zealous application of the results of these studies to inappropriate fluid dynamical trapping situations by many authors in the years that followed.

b. Particle collection efficiency and the dimensionless velocity ratio. It is difficult to directly assess the effect of u_f/W, on particle collection efficiency because W was not measured or estimated in any of the available studies. In some cases, reasonable estimates of the range of fall velocities can be made from the stated range in particle sizes (usually particle diameters) used to seed the flows, since the variation in suspended particle density is relatively small, compared to the range in fall velocity. For Stokes' particles (Stokes, 1851), W is proportional to $d^2(\rho_p - \rho_f)$ and the range of ρ_p for suspended particles in the ocean usually varies only between 1.0 and 3.0 g/cm^3. However, these estimates give little insight into the precise relationship between E and u_f/W because the potential ranges in values of u_f/W are so large (see Table 1); for example, particles used to seed the flows in the studies of Gardner (1980a) and Hargrave and Burns (1979) theoretically spanned at least four orders of magnitude (based on Stokes' fall velocities for the particle mixtures used in these studies, see captions to Figs. 3 and 4). Efficiency was determined separately, for different particle types, in the pollen studies (Peck, 1972; Tauber, 1974); however, these data are of limited value here because reliable estimates of ρ_p and W are available for only one pollen species (see caption to Fig. 2 and footnotes β and γ to Table 1).

Peck's (1972) data give some insight into the relationship between pollen grain diameter and efficiency. For the various pollen species tested, at a given flow speed efficiency generally decreased with decreasing pollen grain diameter (Fig. 2). From these data, we are unable to make inferences regarding the relationship between u_f/W and efficiency, however, because there is not sufficient information to make reasonable estimates of W for the different grains (see caption to Fig. 2).

c. Particle collection efficiency and trap aspect ratio. Evidence that collection efficiencies of cylinders are a function of both H/D and R_t comes from the study of Lau (1979). Lau's data indicate that, for higher R_t, traps with higher H/D are required to prevent the escape of oil droplets from the trap (Fig. 5). However, Lau's study does not provide information on particle movement under these conditions.

The studies of Gardner (1980a) and Hargrave and Burns (1979) investigated the effect of H/D on particle collection efficiencies of cylinders. Results of these studies are difficult to compare with Lau's (1979) results because H/D and R_t of Gardner's traps were lower than the values that Lau tested (Table 1), and for all H/D (ranging from 1.2 to 20.4) tested by Hargrave and Burns, trap diameter decreased with increasing H/D (except for traps with H/D of 1.2 and 2.6) so that R_t-similarity was not maintained; thus, the only two traps with $H/D \geq 4.7$ (within Lau's range) had R_t of 1×10^3 and 2×10^3 (outside of Lau's range, see Fig. 5 and Table 1).

In Gardner's (1980a) study, no effect of H/D on collection efficiency is apparent for

H/*D* ranging from 1 to 2.3 at any of the R_t tested (Fig. 4). For the experiments where replicate traps were tested (experiments 3, 4, and 6, see caption to Fig. 4), the null hypothesis that no difference in collections between traps with *H*/*D* of 1.0, 1.1, and 2.3 could not be rejected at $\alpha < 0.05$ (nonparametric Kruskal-Wallis test). In Hargrave and Burns' (1979) study, efficiency decreased by about a factor of two between traps with *H*/*D* of 2.6 and 1.2, but with the same R_t (of 6×10^3), (Figs. 3 and 7). With increasing *H*/*D*, from 2.6 to 20.4, efficiencies increased slightly, but not significantly (i.e., all error bars overlapped).

The results of Gardner (1980a), Hargrave and Burns (1979) and Lau (1979) are compared in Figure 5. The justification for such a comparison is as follows. Lau observed that water motion in the trap bottom entrained oil droplets at the trap bottom and allowed them to escape from the trap. If these bottom currents generate sufficient boundary shear stress (τ_b) such that $\tau_b > \tau_c$ (the critical shear stress to erode the particle), then settled particles may be resuspended from the trap bottom. While Lau's study provides no data on τ_b relative to τ_c for any particle, his results do indicate the relative strength of water motion at the trap bottom among traps of different R_t and *H*/*D*. If his results are relevant for some class of particles, then traps falling within the "stay" region of Figure 5 represent the physical situation where $\tau_b < \tau_c$ and traps falling within the "escape" region are where $\tau_b > \tau_c$. It is interesting to see where Gardner's (1980a) and Hargrave and Burns' (1979) data fall on this curve. To handle the range of parameters in the two particle studies, it also must be assumed that it is valid to extend Lau's line (dividing the approximate "separation between the 'stay' and 'escape' regions" for oil droplets in his traps) below the range of values that he tested. Then, traps falling to the right of Lau's dashed line (Fig. 5) should be relative undercollectors, compared to traps falling to the left of the line.

Lau's line, and the extension of Lau's line divide the cylinders tested by Hargrave and Burns (1979) between the *H*/*D* of 2.6 and 3.6; however, in plots of these data where R_t is ignored (Fig. 7), the collection efficiencies for these two *H*/*D* cannot be considered significantly different. All of Gardner's (1980a) traps fall to the left of the extension of Lau's line.

The apparent ambiguities in the data from the studies of Lau (1979), Gardner (1980a), and Hargrave and Burns (1979) can probably be explained by the following: (1) Considerations of only water movement inside traps are not sufficient to predict particle movement. (2) The error bars are relatively large surrounding Lau's line, which was drawn by eye, and, in fact, several lines of various slopes would fit the data equally as well. (3) A linear extension of Lau's line, below the values he actually tested is questionable, since resuspension may not occur at lower R_t.

Peck (1972) looked at the effect of *H*/*D* on particle collection efficiency of the Tauber trap by testing a "short" (6 cm) and a "tall" (10 cm) trap for R_t of 1×10^4 to 2×10^4. The tall trap always collected more pollen per unit mouth area than did the short trap, but the mean difference between the two trap designs was only about 15%.

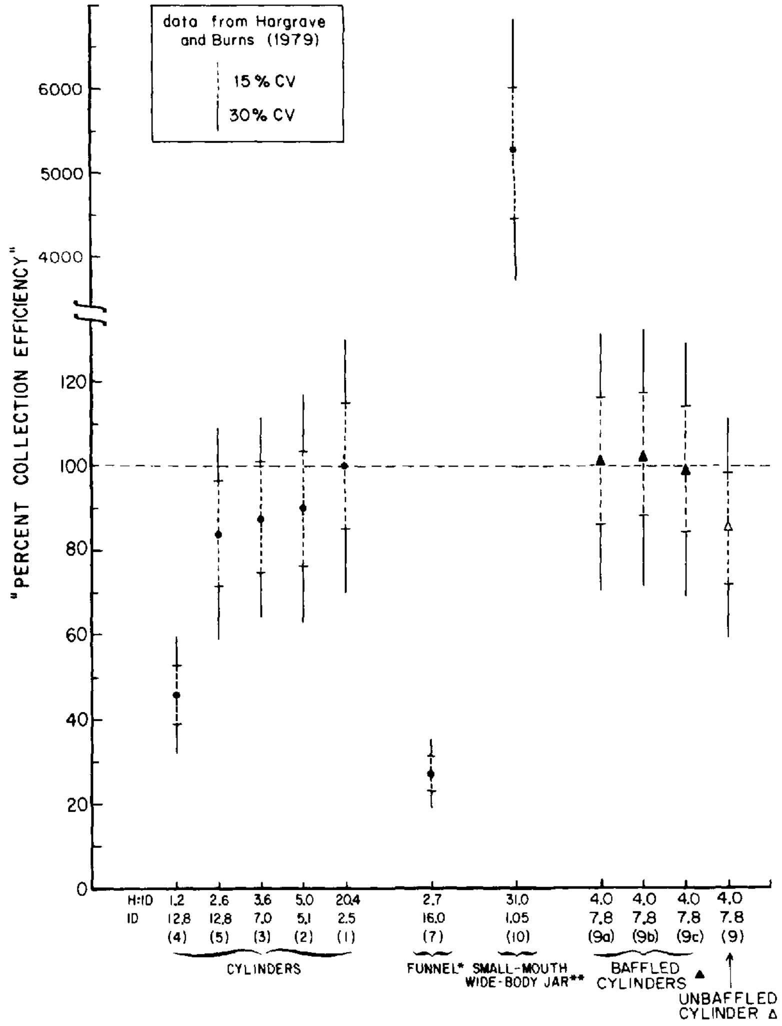

Figure 7. "Percent collection efficiency" of several trap designs tested in the laboratory flume study of Hargrave and Burns (1979). Except for trap 10, "Percent collection efficiencies" (defined in Fig. 3) were taken from Figure 2 (in Hargrave and Burns [1979], page 1130) and are based on A_m (trap mouth area). The "percent collection efficiency" for trap 10 was the value plotted on their Figure 2 (page 1130) times A_b/A_m (they used A_b in their efficiency calculation for this trap design). Relevant trap dimensions (in cm) were taken from their Figure 1 (page 1128) and appear below this figure. All traps were tested simultaneously at a flow speed of 4 to 5 cm/sec; the flume was seeded with natural sediments <125 μm in diameter. Vertical lines are 15 and 30% error bars around each point, the range in CV for their experiments (Hargrave and Burns, 1979). The diameters and *H:ID* ratios of the baffles inserted into trap 9 were 0.64 cm and 48 for trap 9a, 0.87 cm and 36 for trap 9b and 1.91 cm and 16 for trap 9c. *This funnel-type trap was a funnel (16.0-cm inside mouth diameter, <1.0 cm inside diameter at bottom, and 18.0 cm tall) inserted into a cylinder (7.0 cm inside diameter and 25.5 cm tall); the cylinder mouth was sealed to a <1.0 cm opening surrounding the bottom of the funnel. **This trap was a cylinder (7.8 cm inside diameter and 32.5 cm tall) covered by a watch glass cover (8 cm diameter) with a central hole (1.05 cm diameter). ( ) = trap number designated by Hargrave and Burns in their Figure 1 (page 1128).

The relationship between aspect ratio and collection efficiency has been studied in the field (e.g., Kirchner, 1975; Wahlgren and Nelson, 1976; Hargrave and Burns, 1979; Gardner, 1980b; Blomqvist and Kofoed, 1981), where traps with different aspect ratios were deployed simultaneously. In all cases but one (Kirchner, 1975) collections increased with increasing aspect ratio until some apparently asymptotic value was reached. The aspect ratio at the asymptote was usually between 3 and 5, but varied between studies, probably due to differences in flow speeds and particles collected.

All of the aspect ratio versus collection efficiency data suggest that if resuspension of particles occurs in the bottom of unbaffled, straight-sided cylinders and in the Tauber trap, then particle collection efficiencies will decrease. The H/D required to prevent significant resuspension evidently is R_t-dependent. The caveat is required, however, that water motion, by itself, does not indicate that resuspension will occur and some measure of entrainment, such as Shields' criterion (Shields, 1936), is necessary to quantify the values of boundary shear stress, sediment density and size which are stable or unstable in a given flow. Velocities, turbulent intensities or values of shear stress are not available from Lau's (1979) experiments.

d. Particle collection efficiency and trap geometry. It is reasonable to compare collections by noncylindrical traps, relative to collections by cylinders, only if both were determined in the same study. Thus, Tauber's (1974) and Peck's (1972) Tauber-trap results cannot be evaluated in this regard because cylindrical traps were not concurrently tested. Gardner (1980a) and Hargrave and Burns (1979) tested funnel-type traps and small-mouth, wide-body traps, as well as cylinders. In Gardner's study, funnel-type traps had lower collection efficiencies, by about 30%, than cylinders with similar aspect ratios and/or mouth diameters (and thus, similar R_t); compare especially funnel traps E and F with cylinder A (Fig. 4). Baffling the mouth opening of these traps raised their collection efficiencies to within the range of the cylinder collection efficiencies, but baffling a cylinder (with $H/D = 4.0$) also increased its collection efficiency in the study of Hargrave and Burns (1979) (see Fig. 7). All small-mouth, wide-body traps, except one, had higher collection efficiencies by factors of four to ten compared to the cylinders (Fig. 4). However, the mouth diameter (and thus, the R_t) of these small-mouth, wide-body traps was at least half the mouth diameter of the cylinders, so the increased efficiencies may also be an R_t-effect. The one small-mouth, wide-body trap (trap M in Fig. 4), which had a collection efficiency similar to the tested cylinders, also had a mouth diameter within the range of these cylinders. In fact, it may be inappropriate to classify trap M as a small-mouth, wide-body trap since the difference between the mouth and body diameter was so small; this was actually a screw-top cylinder and the reduced mouth opening was just in the region when the mouth was threaded (W.D. Gardner, pers. comm.).

The funnel-type trap tested by Hargrave and Burns (1979) collected 50 to 80% less material per unit area than the cylinders tested (Fig. 7), but the funnel-type trap also had the largest R_t of all traps tested. The one small-mouth, wide-body trap tested by Hargrave and Burns (1979) had a remarkably high collection efficiency. This trap had the lowest R_t and the highest H/D of all traps tested by Hargrave and Burns (1979), so the results are consistent with the previously observed R_t-effect.

For all of the trap designs discussed here, where $A_m \neq A_b$, (A_m = area of trap mouth and A_b = area of trap bottom), if A_b (or, for some of the funnel-type traps, the area at the bottom or neck of the funnel) is used instead of A_m in collection efficiency calculations most small-mouth, wide-body traps have collection efficiencies between 60 and 100%, while the funnel-type traps have unusually high collection efficiencies, of 1,600 to 24,000% (Table 3). As suggested by Hargrave and Burns (1979) and Bloesch and Burns (1980), the actual collecting surface probably varies between A_m and A_b in noncylindrical traps depending on the area where there is complete fluid exchange.

e. Summary remarks. While the literature review uncovered some interesting observations and trends in the data from relevant trap calibration studies, it uncovered considerable gaps in the data base, as well. To date, there is not a published laboratory study of the effect on collection efficiency of a range in values for any one of the parameters identified in the dimensional analysis, when the other parameters are held constant, for traps collecting particles in water. In certain cases, it also was not possible to determine if observed trends were statistically significant, because error estimates were not available. Finally, while the collective data base from all five studies certainly is stronger than data from each study taken alone, between-study comparisons of collection efficiencies is not valid because of the many differences in the way the studies were conducted and in the particles, traps and flows that were tested. However, armed with these observations from the literature on the dependence of efficiency on R_t, particle diameter, H/D and trap geometry, now it is useful to assess the physical mechanisms that may account for these trends, to further clarify the data and to help guide future trap studies. We draw upon physical arguments made in previous trapping studies as well as upon the theoretical analysis we present below.

4. Physical description of particle trapping

The literature review suggested possible relationships between trap particle collection efficiency and three of the dimensionless parameters identified earlier (see 2.). In the remainder of this paper, we attempt to further evaluate the available empirical information by presenting several simple models to explain the observed dependences and by suggesting specific testable hypotheses for biased trapping effects. Prior to presenting the biased trapping hypotheses, a simple physical description of the general process of trapping particles is given, which involves observations of flow through traps (e.g., dye studies), the mass balance for particles entering and leaving traps, and a definition of particle collection efficiency, E.

Table 3. Particle collection efficiencies of noncylindrical traps using an inside diameter, other than at the trap mouth, in calculations, for the studies of Gardner (1980a) and Hargrave and Burns (1979).

Trap[α] design	Inside diameter at mouth (cm)	Collection[β] efficiency (percent)	Inside diameter[δ] below mouth (cm)	Collection[ε] efficiency (percent)
Small-mouth, wide-body traps				
I	1.5	896	4.5	100
J	1.2	743	3.5	87
K	1.6	554	4.6	67
L	1.8	413	4.5	66
		550		88
		651		104
		508		81
		391		63
		994		159
M	4.5	106	5.0	86
		94		76
		163		132
10	1.05	5198	7.8	94
Funnel-type traps				
D	10.0	60	0.5	24000
E	6.3	65	0.5	10319
F	6.3	65	.12	1654
7	18.0	26	<1.0	5156

α. The trap designs corresponding to the letters listed here are given in Figure 4 (for the study of Gardner 1980a) and the trap designs corresponding to the numbers listed here are given in Figure 7 (for the study of Hargrave and Burns 1979).

β. These are the "Trapping Efficiencies" given by Gardner (1980a) for all lettered traps listed here and the "Percent Collection Efficiencies" given by Hargrave and Burns (1979) for trap 7; the efficiencies were calculated for A_m. For trap 10, the value listed here was calculated from the efficiency given by Hargrave and Burns (1979) (listed in the fifth column of this table).

δ. These are the body diameters for the small-mouth, wide-body traps and the diameters at the bottom or neck of the funnels.

ε. These were calculated for all traps, except one (trap 10), from the values listed in the third column of this table. For trap 10 this is the "Percent Collection Efficiency" given by Hargrave and Burns (1979), based on A_b.

Any proposed mechanism to explain a trap bias must affect one or more terms in the mass balance. By definition, the efficiency of a biased collector deviates significantly from one. Thus, we first define efficiency and then explore the quantitative constraints imposed by the mass balance on the efficiency equation. For all physical models presented here, the flow field is limited to two dimensions and fluid buoyancy effects are ignored because gradients in particle concentrations away from the immediate

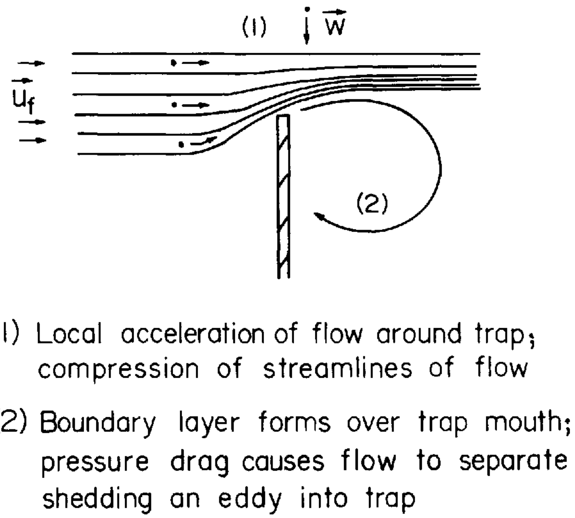

Figure 8. Diagram of two-dimensional flow past the vertical wall at the mouth of a cylinder, showing flow accelerations; u_f = mean-stream flow velocity, W = particle fall velocity.

vicinity of the seabed are small (e.g., Smith and McLean, 1977; Grant and Glenn, 1983).

During particle trapping, trap-induced flow accelerations occur in two ways (refer to Fig. 8). First, the oncoming flow locally accelerates as it changes direction to move over or around the trap. Second, turbulent eddies can develop in the internal boundary layer which forms over the trap mouth and within the trap itself. These eddies are observed to be unsteady and eventually are shed into the flow. Dye studies have demonstrated eddy shedding over straight-sided cylinders for R_t of about 5×10^2 to 2×10^4 in Gardner (1977, 1980a) and of about 1×10^3 to 1×10^4 in Butman (1986), over vertical and tilted straight-sided baffled cylinders for R_t of about 5×10^3 to 2×10^4 in Gardner (1985), and over Tauber traps for R_t of 1×10^4 to 2×10^4 in Peck (1972).

Particles are carried by the fluid only if the response time of the particles to changes in flow speed is very small (i.e., as long as particles follow the flow). It can be shown (e.g., Ho, 1964) that the particles of interest in ocean flows do accelerate nearly instantaneously with an accelerating flow field. Thus, eddies carry particles in the flow and can potentially carry particles into and out of traps, making an understanding of eddy dynamics important to understanding particle trapping.

a. Conservation of mass and collection efficiency. Bloesch and Burns (1980) have indicated that traps potentially collect particles by two different mechanisms: (1) particles fall directly into the trap mouth and are retained on the bottom of the trap and (2) particles are carried into the trap by the flow and then settle onto the trap bottom. Particles leave the trap only by being carried out with the flow. Assuming, over some time period, steady-state conditions, the total mass balance for any given fall velocity-class of particles is described by,

$$\underbrace{C_oWA_m + C_oQ + \phi_bA_b}_{\substack{\text{total mass flux } \textit{to} \\ \text{trap interior}}} = \underbrace{C_iWA_b + C_iQ}_{\substack{\text{total mass flux } \textit{from} \\ \text{trap interior}}} \tag{3}$$

where C_o = mass concentration of particles in the fluid outside a trap (assuming a uniform particle distribution), C_i = mass concentration of particles in the fluid inside a trap, ϕ_b = a generalized source/sink term for the mass flux of particles from the trap bottom per unit area (thus, ϕ_b is positive for resuspension), Q = volume flux of fluid through the trap (i.e., advected fluid), A_b = area of trap bottom, A_m = area of trap mouth, and W = particle fall velocity. When ϕ_b is positive (i.e., a source of mass flux), the three terms on the left-hand side of (3) describe the total mass flux to the trap interior, where C_oWA_m = mass flux of particles falling into the trap mouth, C_oQ = mass flux of particles carried into the trap by the flow (e.g., particles entering with an eddy), and ϕ_bA_b = mass flux of particles from the trap bottom (e.g., due to resuspension). When ϕ_b is negative (i.e., a sink for mass flux), then ϕ_bA_b would be another avenue for removal of mass flux from the trap interior and would belong on the right-hand side of (3). Otherwise, the two terms on the right-hand side of (3) describe the total mass flux out of the trap interior, where C_iWA_b = mass flux of particles settling onto the trap bottom, and C_iQ = mass flux of particles leaving the trap with the flow (e.g., carried out when an eddy leaves the trap). While (3) is written for steady state, in actuality, the advection terms (C_oQ and C_iQ) and the source/sink term (ϕ_bA_b) are likely to be time-dependent. Eq. (3) is similar to the mass balance given by Bloesch and Burns (1980), only we use a generalized source/sink term in place of their resuspension term.

This mass balance is written for a given fall velocity-class of particles. If several fall velocity-classes are present, then the total mass balance for the particle mixture would be the sum of the balances for each individual fall velocity-class. In particular, the terms affected would be those that are fall velocity-dependent so that $C_oWA_m = (\Sigma C_nW_n)_oA_m$ and $C_iWA_b = (\Sigma C_nW_n)_iA_b$, where n = each fall velocity-class of particles and the subscripts o and i refer to summations for particles in the fluid outside and inside the trap, respectively. Depending on the mechanism generating the source/sink term, the mass balance may be fall velocity-dependent (e.g., in a particle mixture resuspension affects particles with relatively low fall velocities, see 5.a.).

A typical definition for the particle collection efficiency, E, of a trap is the net deposition of particles onto the trap bottom divided by the total flux of particles settling through a unit area equal to the trap mouth area,

$$E = \frac{C_iWA_b - \phi_bA_b}{C_oWA_m}. \tag{4}$$

This efficiency is defined as the ratio of rates of particle movement in the traps; the two terms in the numerator account for the total flux of material that settles out of the trap volume and onto the trap bottom, while the denominator is the total flux of material that settles through the trap mouth and into the trap volume. This efficiency definition was chosen because of the basic scientific question that traps are often used to investigate: what is the downward flux of particulates through the water column (see reviews by Bloesch and Burns, 1980; Reynolds *et al.*, 1980; Blomqvist and Hakanson, 1981). The definition also evolved from the way trap samples are processed in the laboratory and because the suspended particles and water in the trap usually are readily flushed. Thus, particles suspended in the water above the trap bottom are not considered to be "collected" by the trap; most trap-users process only the material that has settled onto the trap bottom and not suspended material in the water above the trap bottom or material adhering to funnel walls (e.g., Rowe and Gardner, 1979; Honjo *et al.*, 1980; Parmenter, *et al.*, 1983a; Gardner *et al.*, 1984). However, it is possible that material adhering to containers (funnels or side walls) periodically falls into the trap and we do not account for this here.

Assuming that the concentration of particles in the trap interior (C_i) is fully mixed and uniform, (3) can be rewritten using the definition for E given in (4), yielding,

$$E = 1 + (C_o - C_i)\frac{Q}{C_o W A_m}. \tag{5}$$

Eq. (5) gives the relationship between the chosen definition of E and the mass flux into and out of the trap interior by advection for arbitrary trap geometry. This equation shows that if the mass advected in by the flow equals the mass advected out by the flow, then $E = 1$ (i.e., the mass flux of material to the trap bottom equals the mass flux of material settling through the trap mouth). Moreover, (5) demonstrates that a biased collector ($E \neq 1$) is not possible unless there is both advection through the trap and $C_i \neq C_o$.

For traps deployed in the field, E is the time-integral of the numerator divided by the time-integral of the denominator. During field collections, unsteady ocean processes undoubtedly occur, but it is usually possible to define some relatively short time period over which conditions are approximately steady. This steady case is presented here; in addition, some effects of flow instabilities (e.g., turbulence) on E are discussed later, regarding specific particle-trapping mechanisms.

b. Conditions for unbiased and biased trapping. Using the definition of efficiency in (4) with $C_i = C_o$ and $E = 1$ gives,

$$C_o W = \frac{\phi_b A}{(A_b - A_m)}. \tag{6}$$

For cylindrical traps ($A_b = A_m$), (6) is satisfied only if $\phi_b = 0$. Conversely, for $E = 1$, differences in concentrations inside and outside of any trap design can be maintained only if there is a net mass flux from or to the trap interior (i.e., $\phi_b \neq 0$, but see also the special cases, *G* and *M*, in Table 4).

For cylinders $A_b = A_m$ and (4) gives,

$$E = \frac{C_i W - \phi_b}{C_o W}. \tag{7}$$

Using (4), (5) and (7) the permissible (i.e., satisfying conservation of mass) range of *E* for values of the other terms in the equations can be found. These are given in Table 4. For collections only by direct settling $Q = 0$ and, therefore, $E = 1$ in (5). In this case, (7) requires that $C_i W - \phi_b = C_o W$: if $C_i = C_o$ then $\phi_b = 0$ (A in Table 4); if $C_i \gtrless C_o$ then $\phi_b \lessgtr 0$ (C and D in Table 4). The latter cases are not easy to imagine since no dynamical mechanism, aside from buoyancy, is available to give a nonzero ϕ_b if $Q = 0$. Thus, generally, direct settling alone will result in unbiased trapping in cylinders.

When there is advection, if $\phi_b > 0$ and $C_i > C_o$, traps will be undercollectors ($E < 1$; E in Table 4); if $\phi_b < 0$ and $C_i < C_o$, traps will be overcollectors ($E > 1$; F in Table 4). Thus, cylinders will be unbiased collectors in advecting fluid only if there is no mechanism (e.g., no resuspension) generating the source/sink term which, in turn, is responsible for creating concentration differences between the fluid inside and outside the trap.

While concentration differences in an equal area cylinder can arise only when $\phi_b \neq 0$, in traps with $A_b \neq A_m$ concentration differences will result even when $\phi_b = 0$. However, in the absence of advection, the permissible concentration differences (see footnotes α and ϵ to Table 4) will not result in biased collections (G and M in Table 4). With advection and no source/sink term, a small-mouth, wide-body trap ($A_b > A_m$) will overcollect particles (H in Table 4) and a funnel-type trap will undercollect particles (N in Table 4). This results from our chosen definition of efficiency because collections are normalized to particle flux through the trap *mouth* area. If efficiency was defined so that collections were normalized to some other quantity (e.g., flux to the trap bottom area or flux through some average trap area), then the results of this mass balance analysis would be different.

As with cylinders, when there is no advection and a nonzero source/sink term, the noncylindrical traps will be unbiased collectors even though concentration differences exist (I, K, O, and Q in Table 4). As before, this situation may be physically unrealistic. When there is both advection and a nonzero souce/sink term, noncylindrical traps will be unbiased collectors only if $C_i = C_o$ (J and R in Table 4). Otherwise, the specific values of ϕ_b, C_o/C_i and A_m/A_b determine if the traps are undercollectors or overcollectors (J, L, P, and R in Table 4).

This kind of simple mass balance analysis can be extremely useful for interpreting trapping data (see 5.) and for designing unbiased collectors. For all traps, the only way

Table 4. Behavior of terms in Eqs. (3) and (4) in order to satisfy conservation of mass for our chosen definition of efficiency.

Area	Source/Sink	Advection	Concentration	Efficiency
Cylindrical traps				
A. $A_b = A_m$	$\phi_b = 0$	$Q = 0$	$C_i = C_o$	$E = 1$
B. $A_b = A_m$	$\phi_b = 0$	$Q > 0$	$C_i = C_o$	$E = 1$
C. $A_b = A_m$	$\phi_b > 0$	$Q = 0$	$C_i > C_o$	$E = 1$
D. $A_b = A_m$	$\phi_b < 0$	$Q = 0$	$C_i < C_o$	$E = 1$
E. $A_b = A_m$	$\phi_b > 0$	$Q > 0$	$C_i > C_o$	$E < 1$
F. $A_b = A_m$	$\phi_b < 0$	$Q > 0$	$C_i < C_o$	$E > 1$
Small-mouth, wide-body traps				
G. $A_b > A_m$	$\phi_b = 0$	$Q = 0$	$C_i < C_o^{\alpha}$	$E = 1$
H. $A_b > A_m$	$\phi_b = 0$	$Q > 0$	$C_i < C_o$	$E > 1$
I. $A_b > A_m$	$\phi_b > 0$	$Q = 0$	$C_i = C_o$	$E = 1$
			$C_i > C_o$	$E = 1$
			$C_i < C_o^{\beta}$	$E = 1$
J. $A_b > A_m$	$\phi_b > 0$	$Q > 0$	$C_i = C_o$	$E = 1$
			$C_i > C_o$	$E < 1$
			$C_i < C_o^{\delta}$	$E > 1$
K. $A_b > A_m$	$\phi_b < 0$	$Q = 0$	$C_i < C_o$	$E = 1$
L. $A_b > A_m$	$\phi_b < 0$	$Q > 0$	$C_i < C_o$	$E > 1$
Funnel-type traps				
M. $A_b < A_m$	$\phi_b = 0$	$Q = 0$	$C_i > C_o^{\epsilon}$	$E = 1$
N. $A_b < A_m$	$\phi_b = 0$	$Q > 0$	$C_i > C_o$	$E < 1$
O. $A_b < A_m$	$\phi_b > 0$	$Q = 0$	$C_i > C_o$	$E = 1$
P. $A_b < A_m$	$\phi_b > 0$	$Q > 0$	$C_i > C_o$	$E < 1$
Q. $A_b < A_m$	$\phi_b < 0$	$Q = 0$	$C_i = C_o$	$E = 1$
			$C_i < C_o$	$E = 1$
			$C_i > C_o^{\gamma}$	$E = 1$
R. $A_b < A_m$	$\phi_b < 0$	$Q > 0$	$C_i = C_o$	$E = 1$
			$C_i < C_o$	$E > 1$
			$C_i > C_o^{\lambda}$	$E < 1$

α. but $C_o/C_i = A_b/A_m$
β. but $C_o/C_i < A_b/A_m$
δ. but $C_o/C_i < W + Q/A_b/W A_m/A_b + Q/A_b$
ϵ. but $C_o/C_i = A_b/A_m$
γ. but $C_o/C_i > A_b/A_m$
λ. but $C_o/C_i > W + Q/A_b/W A_m/A_b + Q/A_b$

to achieve unbiased collections when $Q > 0$ is to create the situation where $C_i = C_o$, as was also shown by Hargrave and Burns (1979) and Bloesch and Burns (1980). For cylindrical traps, this requires elimination of any mechanism that produces a nonzero source/sink term. However, eliminating the source/sink term *results* in biased collections for noncylindrical traps collecting in advection.

c. Particle behavior in eddies. Most traps used in ocean environments collect particles in moving fluid so interactions between the trap and flow play a major role in trap collections, as has been pointed out in many studies, the landmark publication being Gardner (1980a). The interactions result in trap eddies with length scales of trap diameter or height and smaller. These eddies affect particle trapping directly, through the advection terms, C_oQ and C_iQ; for all cases studied to date, the advected fluid (Q) carrying particles into traps is in the form of eddies, whether or not the oncoming flow is turbulent. Eddies also affect particle trapping indirectly, through the source/sink term, $\phi_b A_b$. For example, turbulence generated in the trap interior by the eddy may cause sufficient shear stress to resuspend particles that have settled onto the trap bottom. Because of the importance of eddies to particle trapping, we briefly summarize several features of particle behavior in eddies relevant to trapping.

The presence of an eddy over the mouth of a trap or inside a trap placed in moving fluid is well-documented (e.g., Peck, 1972; Gardner, 1977, 1980a, 1985; Lau, 1979; Butman, 1986). No studies have addressed the quantitative aspects of these three-dimensional trap eddies, but simpler two-dimensional eddies have been studied. Both analytical and experimental studies have provided a reasonably complete picture of the behavior of a particle in an idealized, two-dimensional, solid body vortex so that, in theory, particle orbits and velocities can be calculated. An eddy is a unique accelerating flow region because the flow can travel through a complete circle. At some point the instantaneous fluid velocity of the eddy will operate in the same direction as the particle fall velocity, enhancing the vertical distance a particle falls per unit time. The eddy velocity also could directly oppose the particle fall velocity, causing the particle to stall or move up. Depending on the magnitude of the eddy and particle velocities, a particle potentially could "fall out" of an eddy or it could be entrained in the eddy. From experimental and theoretical studies viewing a two-dimensional eddy as a potential vortex, rotating as a solid body (Lamb, 1932; Dosanjh *et al.*, 1962), and on particle behavior within the core region of the eddy (Tooby *et al.*, 1977; Nielson, 1979, 1984) it can be concluded that most particles of interest in the ocean can be entrained in eddies that develop within a trap.

Tooby *et al.* (1977) carried out an experimental study of particles in a two-dimensional solid body vortex (the core region of an eddy). This study showed (refer to Fig. 9): (1) Particles initially present when the eddy forms can be retained in the eddy only if $\omega r > W$, where ω is the eddy angular velocity and r is the radial coordinate. (2) The point where the upward eddy velocity balances the particle fall velocity is defined by $\omega r_o = W$, where r_o is the distance from the center of the eddy to the center of the particle orbit. (3) Particles in eddies orbit around a point $r_o = W/\omega$, that lies on a horizontal plane through the center of the eddy, but upstream of the eddy center. Thus, particles entrained in an eddy tend to concentrate on the upstream side of the eddy. (4) Although, for the particles of interest here, the initial particle orbits are nearly closed, a finite inertial force causes the orbits to evolve in time and become unstable so

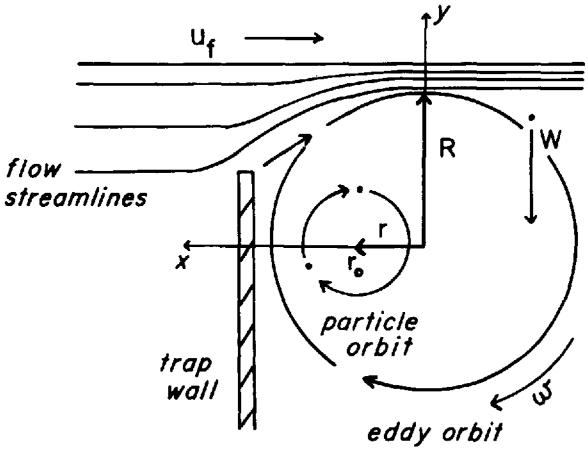

Figure 9. Diagram of particle behavior inside the solid body vortex region of an eddy from the study of Tooby *et al.* (1977); u_f = mean-stream flow velocity, ω = eddy angular velocity; R = radius of solid body vortex, W = particle fall velocity, r = radial coordinate, r_o = distance from center of eddy to center of particle orbit.

the particles spiral slowly outward. When particles leave an orbit, they do so on the side of an eddy with the highest opposed velocity, or the upstream side. Based on limited empirical data, eddies shed behind a vertical barrier are unsteady; at some frequency long, relative to the rotational frequency of the eddy (the limit frequency is $\omega = u_f/R$), eddies are shed and a new eddy is formed.

The eddy characteristics (intensity and shedding frequency) and the ability of an eddy to trap and retain particles depends both on characteristics of the flow regime and of the particles. Several of the dimensionless parameters identified in the similarity analysis affect or are affected by eddies. For example, as R_t increases, eddy intensity and shedding frequency will also increase. The effects of turbulent mixing by eddies inside traps on particles in the trap is virtually unexplored; such mixing could result in concentration gradients inside traps or above the trap mouths. Moreover, eddy formation is highly three-dimensional and unsteady. In summary, we know eddies are a pervasive feature of the trap flow environment, and based on the simple two-dimensional solid-core vortex studies and on qualitative observations (e.g., see 5.a.), we can identify specific effects of eddies on particle trapping. However, studies of the role of eddies and turbulence in particle trapping is embryonic and both theoretical and experimental research are needed for a thorough quantitative understanding of the dynamics of particle collections by traps.

5. Hypothesized biased trapping effects and some models

A set of working hypotheses regarding biased trapping effects are presented to: (1) help organize future research such that experiments can be designed to test specific mechanisms, (2) streamline the number of experiments that must be conducted, and (3) help insure that the proper variables will be measured in the experiments so that a definitive statement can be made regarding the feasibility of the hypothesis tested. To understand the complex process of trapping particles in marine environments, the system initially must be simplified so that specific mechanisms can be tested. Thus, the first three hypotheses presented here are for unbaffled, straight-sided cylindrical traps with equal mouth and bottom cross-sections. The other hypotheses concern the effects of unbaffled, noncylindrical trap geometries on particle trapping.

a. Hypothesis 1: For a given trap aspect ratio and particle size class, collection efficiency will decrease over some range of increasing trap Reynolds number. The dimensional analysis indicated that collection efficiency would be a function of R_t. Results from the laboratory studies of traps collecting particles (Peck, 1972; Tauber, 1974; Hargrave and Burns, 1979; Gardner, 1980a) revealed no consistent significant relationship between R_t and efficiency, but few parameter combinations were tested (see 3.a.). Lau's (1979) study of the water motion inside traps did show that for a given aspect ratio, water movement at the trap bottom increased with increasing R_t; thus, for example, if this motion is sufficient to resuspend settled particles, then depending on the trap aspect ratio and particles collected, efficiency may decrease with increasing R_t.

From the mass balance analysis we know that cylinders collecting particles where $Q > 0$ can have $E = 1$ only if $\phi_b = 0$ (B in Table 4). The cylinders will be undercollectors when $Q > 0$ and $\phi_b > 0$ (E in Table 4) and will be overcollectors when $Q > 0$ and $\phi_b < 0$ (F in Table 4). A nonzero ϕ_b results in $C_i \neq C_o$, so if we can identify probable R_t-dependent *mechanisms* that result in these concentration differences, we can then determine how such R_t-dependent changes in concentration would quantitatively affect efficiency.

We have stated that turbulent eddies are ubiquitous in the trap flow environment and eddy characteristics are expected to be R_t-dependent (e.g., see Table 2 in Gardner, 1980a). Thus, eddies are likely to be both directly and indirectly involved in the mechanism that produces R_t-dependent collection efficiencies. The direct influence of eddies on collection efficiency is through the trapping and retention of particles in eddies, which are then shed either into the trap interior or over the trap mouth. The indirect influence of eddies on collection efficiency is through other hydrodynamic processes (e.g., resuspension or trap-wall adhesion, discussed later) that are, themselves, affected by turbulence. Direct eddy effects are discussed first.

The intensities and frequencies of eddy shedding into the trap interior increase with increasing R_t. Because particle entrainment in eddies depends on the eddy angular velocity (ω) (as discussed in 4., see Fig. 9), as ω increases with increasing R_t, relatively more particles may be retained in eddies. Then, these particles enter the trap with the eddy. This results in a decrease in trapping efficiency with increasing R_t only if the flux out of the trap is greater than the flux back in (i.e., $QC_i \neq QC_o$). For such flux differences to exist, however, requires a gradient in particle concentration across the trap, either from above or below. At present, from arguments concerning the motion of a particle in a vortex alone, it is not possible to create such concentration differences even though particle retention by an eddy, and the time scale for this retention, are dependent on the values of both R_t and W relative to u_f. Thus, in order for this direct eddy mechanism to explain the observed dependence of collection efficiency on R_t in water, some other mechanism(s) must be responsible for $\phi_b \neq 0$ to get the required concentration changes.

Two mechanisms that result in $\phi_b \neq 0$ are resuspension of particles from the trap bottom and adhesion of particles to the trap wall. The former results in $\phi_b > 0$ so that $C_i > C_o$ and $E < 1$, while the latter results in $\phi_b < 0$ so that $C_i < C_o$ and $E > 1$. Both mechanisms are indirect effects of eddies, but resuspension also includes a direct effect through entrainment into the eddy. Entrainment of resuspended sediment into an eddy is well-studied for both steady and oscillatory flow and fits the models hypothesized here well (Nielsen, 1984). Resuspension and trap-wall adhesion are likely to be R_t-dependent because they involve turbulence.

If resuspension increases with increasing R_t, then ϕ_b also increases. For a fixed particle size and trap geometry, (3) shows that C_i must increase relative to C_o, but not as fast as ϕ_b, since Q also increases with R_t. Then, from (4), E must decrease, so the resuspension mechanism should produce decreasing E with increasing R_t. In this case, E may be expected to approach one from below (i.e., from $E < 1$) for the limit where u_f, and thus, R_t go to zero, since $E = 1$ for $Q = 0$ for cylinders.

For particles to be resuspended from the trap bottom, the shear stress at the trap bottom must exceed the critical shear stress for settled particles. Thus, the resuspension mechanism hypothesizes that for constant H/D, the shear stress at the trap bottom increases with increasing R_t. The range of R_t for which the critical value is exceeded depends on the particles collected by the trap and on the trap design. Lau's (1979) results indicate that water motion at the trap bottom increases with increasing R_t and decreases with increasing H/D. Since shear stress is related quadratically to water velocity, Lau's results suggest that particle resuspension would follow this same pattern, once an initial motion criterion (e.g., Shields' parameter, see below) is exceeded. Experiments that specifically quantify particle resuspension for realistic values of R_t and H/D are needed. In addition, a measure of the ratio of critical entrainment stress to resisting force, such as Shields' parameter for noncohesive particles (Shields, 1936), is required to determine the values of stress at the trap bottom for which particles of certain sizes and densities will be resuspended.

Concentration differences inside and outside of traps also may be caused by the adhesion of particles to the inside walls of a trap either by electrostatic forces or by chemical adhesion. Such adhesion would decrease the concentration of particles available to settle inside the trap (C_i). In this case, we rewrite the source/sink term as $\phi_w A_w$, where ϕ_w is mass flux to the interior trap *walls* per unit wall area and is negative, and A_w is the interior trap wall area; a "small" ϕ_w would approach zero, while a "large" ϕ_w would be a large negative number, so we refer to the $|\phi_w|$ when discussing the relative size of this term. From (4), when ϕ_w is negative, $E > 1$ and, from (5), $C_o > C_i$. If particle adhesion is effective only when trap-induced turbulence is low, then a relatively larger amount of material would adhere to the walls at low R_t than at high R_t. As R_t increases, higher turbulence may not permit adhesion and, in this case, $|\phi_w|$ would decrease with increasing R_t. If $\phi_w < 0$, and $|\phi_w|$ decreases with increasing R_t, C_i will relatively increase. Because $C_i < C_o$, when C_i increases, E will decrease. However, an increase in Q with increasing R_t would cause E to increase, so the relative changes in ϕ_w, C_i/C_o and Q are important here to predict specific effects. For trap-wall adhesion, the relationship between E and R_t as R_t approaches zero is difficult to predict and is only constrained by the fact that E must equal one when $u_f = 0$. The possibility of particle adhesion on trap walls has not been investigated experimentally and is likely to be a function of the particle type, the particle concentration and the material used to construct the traps, as well as of the flow parameters.

Thus far, we have discussed two eddy-dependent mechanisms, resuspension and trap-wall adhesion, which would result in $C_i \neq C_o$. In addition, there is an eddy-dependent mechanism that may enhance or diminish the relative differences between C_i and C_o; this is trap-induced particle aggregation or disaggregation and also is likely to be R_t-dependent.

Trap-induced turbulence and shear may either aggregate or disaggregate particles inside traps. If aggregated particles inside traps have higher fall velocities than individual particles outside traps, then relatively more mass can fall to the trap bottom than can fall an equivalent distance in the outside flow. Disaggregation would have the opposite effect. Aggregation depends on the rate at which particles collide and also on the probability that they adhere to one another. Collision rates depend on differential settling, fluid shear and the residence time of the flow in the trap. Cohesion between particles after collision depends on mineralogy, sizes and the quantity and type of cations present. The probability of cohesion can be quantified only through experiments. The disaggregation of particles depends on fluid shear and on collisions between particles with sufficient relative translation energy (Spielman, 1978). Gardner (1985) suggested that particle disaggregation is possible in the shear generated by the bluff-body effect of the trap on the flow.

A difference between particle-particle interactions in the fluid outside and inside a trap affects the distribution of mass concentration between particle fall velocity-classes. We can discuss only the qualitative implications of this because the mass balance presented here is for single fall velocity-classes of particles; to quantitatively assess aggregation effects requires a mass balance that sums effects for all fall velocity-classes of particles present in the flow. If aggregation occurs inside traps, then relative to the outside flow, more mass concentration occurs in the larger fall velocity-classes. Disaggregation inside traps would increase the mass concentration in the smaller fall velocity-classes relative to the outside flow. Aggregation or disaggregation may affect particle collection efficiency when $\phi_b \neq 0$ because the amount of mass concentration affected by either resuspension or trap-wall adhesion depends on the distribution of mass among fall velocity-classes; for example, for a given shear stress, particles with relatively small fall velocities will be resuspended from a particle mixture.

As shown earlier, for E to decrease with increasing R_t requires either $\phi_b > 0$ and ϕ_b increasing with increasing R_t or $\phi_w < 0$ and $|\phi_w|$ decreasing with increasing R_t. To amplify these changes in the source/sink term requires disaggregation in the first case and aggregation in the second. In the following we assume that trap-induced particle-particle interactions increase with increasing R_t since these are eddy-dependent effects.

If trap-induced turbulence disaggregates particles, then ϕ_b would relatively increase (compared with the no particle-interaction case) with increasing R_t and E would decrease. If trap-induced turbulence aggregates particles, then $|\phi_w|$ would relatively decrease with increasing R_t and E would decrease. Obviously, the magnitude of the changes in ϕ_b and ϕ_w depend on the shear stress of the flow at the trap bottom relative to the critical stress for the particles involved.

It also is possible that aggregation could occur over one range of R_t, while disaggregation would occur over another. For example, it has been experimentally demonstrated that particle aggregation increases with increasing shear stress only to a certain threshold value and then the shear stress acts to disaggregate particles (Spielman, 1978). The range of shear stress values that would enhance aggregation or disaggregate particles must be determined for the specific particle mixture in question.

In summary, the literature review indicated that, if anything, E may decrease over a certain range of R_t, depending on the type of particles collected. R_t-dependent particle collection efficiencies of traps are likely to result from mechanisms involving trap-induced turbulence because eddies are a dominant feature of the trapping environment and eddy characteristics are R_t-dependent. To satisfy conservation of mass for our chosen definition of efficiency, a difference in the mass concentration between the fluid outside and inside traps is required to obtain $E \neq 0$ for cylinders collecting in advecting fluid. Two R_t-dependent mechanisms are identified that result in $C_i \neq C_o$ and whereby E would decrease with increasing R_t. The resuspension mechanism results in traps that are undercollectors and resuspension must increase with increasing R_t for E to decrease. The trap-wall adhesion mechanism results in traps that are overcollectors and adhesion must decrease with increasing R_t for E to decrease. When resuspension or trap-wall adhesion occur, their effects on E may be amplified by trap-induced particle-particle interactions. Such particle-particle interactions would change the distribution of mass among fall velocity-classes of particles between the fluid inside and outside of traps. Specifically, trap-induced disaggregation of particles inside traps would augment the resuspension effect, while trap-induced aggregation of particles inside traps would augment the trap-wall adhesion effect. Currently, it is not possible to predict the range of R_t for which aggregation or disaggregation would occur.

b. Hypothesis 2: For a given trap aspect ratio and trap Reynolds number, collection efficiency will decrease over some range of decreasing particle fall velocity. A relationship between particle fall velocity and collection efficiency was suggested in the dimensional analysis through the parameter u_f/W. The ratio u_f/W indicates the magnitude of the horizontal component of fluid motion relative to vertical particle motion (gravitational fall velocity). These two terms determine particle trajectories if the particles accelerate nearly instantaneously with the flow, since $\mathbf{u}_p = \mathbf{u}_f - W\mathbf{k}$, where $\mathbf{u}_p$ = particle velocity and $\mathbf{k}$ = vertical vector component. For relatively large values of u_f/W, the flow can advect particles for large horizontal distances before the particles can fall any substantial vertical distance. For relatively low values of u_f/W, particles can fall through the flow with minimal horizontal displacement.

That a decrease in particle collection efficiency may occur over some range of decreasing particle diameter was suggested by the quantitative results of Peck (1972). Peck (1972) also suggested a relationship between particle characteristics, eddies and collection efficiency from observations of particle behavior in flows through traps. The field experiments of Blomqvist and Kofoed (1981) indicated that lighter and heavier particles are collected in different relative abundances depending on trap diameter, and thus, probably on eddy diameter. Finally, the experimental results of Tooby *et al.* (1977) showed that particle behavior in eddies depends on the particle fall velocity. Again, because eddies dominate the trap flow environment, it is likely that they play a role in the observed dependence between particle characteristics and collection efficiency of traps.

Tooby *et al.'s* (1977) laboratory experiments were modeled to assess the physical behavior of diatoms in ocean turbulence, so particle Reynolds numbers (Re_p) were about 10^2, well within Stokes' range; for comparison, $Re_p \sim 10^{-1}$ for a quartz silt-sized particle (63-μm diameter) and $Re_p \sim 10^{-5}$ for a quartz clay-sized particle falling in the ocean. The particle behavior in eddies quantified by Tooby *et al.* (1977) for Stokes' particles also was observed in preliminary experiments by them for larger Re_p (of 10^0 to 10^2 [Tooby *et al.*, 1977]). Tooby *et al.*'s (1977) experiments showed that particles are not retained in eddies unless $r\omega > W$ (see Fig. 9 and the more detailed discussion in 5.a.), so particles with smaller fall velocities are captured at lower flow velocities. Also, for some range of relatively fast-falling particles (where $W > r\omega$), eddies would not affect particle trajectories so the particles would fall through eddies. These experimental results suggest that fall velocity-dependent particle trapping may be possible through an eddy mechanism; particles retained in eddies can leave the trap when the eddy exits the trap (and thus, the particles are not collected by the trap) so that particles with relatively low fall velocities would be caught less efficiently by a trap than particles with relatively high fall velocities.

For the eddy mechanism to advect sorted particles out of the trap, an additional mechanism is needed to make particles initially available to be entrained in the eddy. Resuspension provides this additional mechanism, which is fall velocity-dependent (see 5.a.). As discussed earlier, the critical shear stress must be exceeded for particles to be resuspended from the trap bottom. For a given flow, the boundary shear stress is set by u_f and probably also by trap geometry. In a particle mixture, the critical stress may be exceeded for only a portion of the particles (those with relatively low fall velocities), and thus, only some particle size classes will be resuspended. Material resuspended from the trap bottom is not considered to be "collected" by the trap according to the efficiency definition in (4). Furthermore, previously (see 5.a.) we showed that, for cylinders collecting by advection, when $\phi_b > 0$ (e.g., due to resuspension) and ϕ_b is increasing, then $E < 1$ and E will be decreasing. If any particle mixture was separated into fall velocity-classes and ϕ_b was calculated for each class, we would see ϕ_b increase with decreasing W; thus, E would decrease.

Once particles are resuspended from the bottom, they must be retained in the trap eddy to be advected out. The trap eddy and resuspension mechanisms are both time- and space-dependent within the trap and are related to both the external flow and trap geometry. Not all resuspended particles can be initially entrained in the eddy, nor are all retained long enough to be advected out. Thus, a combination of resuspension and eddy entrainment provide feasible mechanisms for fall-velocity dependent trapping, but the quantitative aspects of this dependence are still obscure. However, if resuspension is involved in fall velocity-dependent collection efficiencies, then the traps would be undercollectors when resuspension and entrainment occur.

It is interesting that the trap-wall adhesion mechanism (see 5.a.), which may also preferentially affect particles with lower fall velocities (as they are more easily transported by the fluid), would result in E increasing with decreasing W. Because $\phi_w < 0$ for trap-wall adhesion, as ϕ_w increases, E also increases. If this situation occurred, the traps affected would be overcollectors. The reviewed data do not suggest an increase in E with decreasing W; however, the quantitative data are scant (see 3.b.).

c. Hypothesis 3: For a given trap Reynolds number and particle size class, collection efficiency will increase over some range of increasing trap aspect ratio. The relationship between particle collection efficiency and aspect ratio of straight-sided cylinders is suggested from dye studies of water movement through traps (e.g., see the photographs in Butman [1986]), from Lau's (1979) more detailed study of water motion in traps and from Gardner's (1980a) and Hargrave and Burns' (1979) quantitative results. All of the studies show that E should increase over some range of increasing H/W. Certainly this idea is not new; in fact, traps for field experiments often are designed with goals to eliminate this particular trap bias. As many others have proposed (e.g., Gardner 1980a,b; Hargrave and Burns, 1979; Lau, 1979; Bloesch and Burns, 1980), this trap bias probably results from resuspension of particles from the bottom of traps with relatively low H/W. However, it now appears that the required aspect ratio to eliminate resuspension is not a constant, but depends both on the flow regime (as suggested by Lau, 1979; Gardner, 1980b) and on the particles collected.

Butman's (1986) dye study of water movement through traps suggests that particles can be resuspended from the trap bottom by eddies (described in 4.) that circulate throughout the entire trap. The eddies enter the traps at the downstream edge and impinge all the way to the trap bottom before circulating back up to the trap opening. The cylinders tested all had aspect ratios of ~3.0, but they varied in mouth diameter so that R_t ranged from 1×10^3 to 1×10^4; eddies penetrated to the bottom of all the traps for a turbulent mean-stream flow speed of ~10 cm/sec. This suggested dependence of resuspension on eddies explains the R_t-dependence on water motion in traps of various aspect ratios, observed by Lau (1979) (see 3.a. and 3.c.). As before (see 5.a.), the resuspension mechanism results in $E < 1$, so traps with aspect ratios allowing resuspension will be undercollectors and, at a given R_t, as aspect ratio increases, E should asymptotically approach 1. Also, the ability of the eddy to remove particles depends on u_f/W, as discussed above.

Several authors (e.g., Soutar *et al.,* 1977; Hargrave and Burns 1979; Gardner 1980a; Honjo *et al.,* 1980) have suggested that inserting baffles into the mouth opening of traps would decrease the depth inside the trap for which significant water motion (and thus, resuspension) would occur. Baffling would supposedly offset resuspension effects so that baffled traps with relatively low aspect ratios would have collection efficiencies similar to unbaffled traps with aspect ratios at or greater than the asymptotic value of particle collection efficiency (of one, according to our physical analysis). Another requirement is that the aspect ratios of individual cells in the baffle must be within the range of aspect ratios at the asymptotic value of particle collection efficiency. The baffling hypothesis was tested in the laboratory on a cylinder once only: Hargrave and Burns (1979) baffled a cylinder (with R_t of 3×10^3) of aspect ratio ~4.0 and increased its collection efficiency, but not significantly. However, Gardner (1980a) found that baffled funnels had higher collection efficiencies than unbaffled funnels (see Fig. 4). More detailed studies of the effects of baffles on the collection efficiencies in controlled laboratory flows are needed.

The range of aspect ratios, for a given R_t and u_f/W, for which resuspension is negligible must be determined experimentally. As previously discussed (see 3.c.), data from the calibration studies to date are difficult to interpret because experiments to separate the effect of aspect ratio versus R_t and u_f/W on particle collection efficiency were not conducted and only a narrow range of H/W, R_t and u_f/W have been tested for sediment collectors. In addition, the importance of the particle mixture in determining the outcome has never been studied. Only empirical studies can provide the data needed because there is not enough information on trap turbulence and the time and space scales of eddy variability to model the complete system.

d. Hypothesis 4: For a given trap Reynolds number, trap aspect ratio and particle size class, small-mouth, wide-body traps generally will be overcollectors and funnel-type traps generally will be undercollectors, compared to cylinders with the same mouth diameter. Two significant effects of trap geometry on particle collection efficiency were demonstrated in the studies of Gardner (1980a) and Hargrave and Burns (1979); relative to cylinders with the same mouth diameter, (1) small-mouth, wide-body traps have higher collection efficiencies and (2) funnel-type traps have lower collection efficiencies (see Figs. 4 and 7). The conservation of mass arguments of both Hargrave and Burns (1979) and Bloesch and Burns (1980) predicted that when there is no resuspension and particle collection efficiencies are normalized by A_m, funnel-type traps would be undercollectors and small-mouth, wide-body traps would be overcollectors, because $C_i/C_o = A_m/A_b$. Also, they suggested that if traps were collecting in flows where there was no resuspension and where the entire trap contents are steadily flushed (by Q), then traps should be unbiased collectors if collections are normalized by A_b. However, in flows where conditions change between calm and turbulent, then the true trap collection area would be unknown.

The mass balance analysis given here indicates that collections by noncylindrical traps is complex (see Table 4). The predicted trap bias, in some cases, requires quantification of the specific terms involved so that, for example, the same trap collecting in advection and where $\phi_b \neq 0$ could be an undercollector, an overcollector, or an unbiased collector depending on the specific values of C_o/C_i, A_m/A_b, W, and Q/A_b (see J and Q in Table 4). In contrast to cylindrical traps, a nonzero ϕ_b term is *not* required to obtain concentration differences between the fluid outside and inside of noncylindrical traps, and thus, to obtain $E \neq 1$ (see H and N in Table 4). As stated earlier (see 4.), when $\phi_b = 0$ and $Q > 0$, the biased collections by noncylindrical traps result from the conservation of mass constraints on our definition of E in (4), because collections are normalized to the flux settling into the trap *mouth* area. However, we feel that the definition of E used in this paper is appropriate for the scientific questions that traps are used to ask (see 4.).

Conditions where small-mouth, wide-body or funnel-traps will be undercollectors or overcollectors are shown in Table 4. While laboratory studies indicate only overcollection by small-mouth, wide-body traps and undercollection by funnel-type traps, the converse theoretically is possible. Only a narrow range of parameter combinations have been tested thus far. Given this, blanket statements that small-mouth, wide-body traps always will be overcollectors and funnel-type traps always will be undercollectors in advecting flows *do not* follow from the physics. Quantification of, especially, ϕ_b and C_o/C_i for specific values of A_b/A_m is required to determine which of the cases predominates for particular noncylindrical trap designs. Simply normalizing the data by A_b, rather than by A_m may not result in $E = 1$ even when $\phi_b = 0$ and flows are steady, because the actual collecting surface still could be anything between A_m and A_b. The diameter of the collecting surface depends on eddy size and behavior in traps which, undoubtedly depends on the ratio A_m/A_b and on the dynamics of the oncoming flow. This may explain why the normalizations we applied to Gardner's (1980a) and Hargrave's and Burns' (1979) data were only partially effective (see Table 3), even though the studies were conducted in steady flume flows.

Finally, funnel-type trap collections may be complicated by a mechanism that is not addressed by our mass balance analysis. In contrast to a cylindrical trap opening, the flow tends to follow closely the funnel contours, dipping into the funnel at the downstream edge of the trap mouth and circulating through the funnel to the upstream edge (see Hannan, 1984). The funnel imparts drag to the flow and the velocity decreases as the flow passes across the funnel. Thus, the velocity near the funnel surface is smaller than in the external driving flow. As a result, it is possible that particles are retained on the funnel surface (see also Gardner, 1985). This retention may be intermittent, however, due to turbulent effects. In several studies (Gardner, 1980a; Hargrave and Burns, 1979; Butman, 1986) it was observed that 50 to 70% of the material collected in a funnel-type trap is collected on the funnel. In Butman's (1986) study, if this material was added to the total flux of particles into the body of a funnel-type trap, the trap had a similar collection efficiency to a cylinder. The behavior of the funnels with and without baffles suggests that resuspension of particles settling on the funnel surface may occur (e.g., Gardner, 1980a). The baffles may tend to damp the large energetic eddies, and therefore, reduce the potential for resuspension and transport of particles out of the trap.

6. Summary and conclusions

The physics of collecting particles in various designs of traps has been analyzed and summarized. A dimensional analysis of the variables relevant to the process of trapping particles indicated that particle collection efficiency is a function of six dimensionless parameters and of trap geometry. Since dimensional analysis cannot identify the nature of these functions, available data from the literature were analyzed toward this end. The specific relationship between particle collection efficiency and three of the dimensionless parameters, DV/ν (trap Reynolds number), u_f/W (the dimensionless velocity ratio), and D/H (trap aspect ratio), and trap geometry was addressed using data from the five published laboratory studies (Peck, 1972; Tauber, 1974; Gardner, 1980a; Hargrave and Burns, 1979; Lau, 1979) that investigated trap collection characteristics. From this summary of observed trap biases, three hypotheses were developed regarding biased particle collections by unbaffled cylinders: for fixed values of the other two parameters, the efficiencies will (1) decrease over some range of increasing R_t, (2) decrease over some range of decreasing u_f/W, and (3) increase over some range of increasing aspect ratio. Predictions of biased collections by unbaffled, noncylindrical traps were more complicated. For fixed values of R_t, H/D, and particle size class, small-mouth, wide-body traps will tend to be overcollectors, but undercollection also is theoretically possible for a narrow range of conditions; funnel-type traps will tend to be undercollectors, but they also can be overcollectors theoretically for a narrow range of conditions. All hypotheses were supported by simple fluid mechanical arguments or models to help guide future calibration studies of particle collecting traps.

A physical description of the process of tapping particles was provided, based on direct observations of flow through traps, the mass balance of particles entering and leaving traps, and a definition of particle collection efficiency. Particle trapping in moving fluid involves the constant exchange of water in the trap through turbulent eddies that develop at the trap mouth. The structure of turbulence inside a trap is likely to differ from that in the outside flow; turbulence, in general, is a function of the flow regime and we suggest that it also is a function of trap design. Because most particles of interest to trap-users in ocean environments tend to follow the flow, the physical mechanisms that result in biased trap collections are either directly or indirectly related to the turbulence in the flow. Resuspension of particles from the trap bottom, trap-induced particle-particle interactions and trap-wall adhesion are mechanisms provided to physically account for theoretical or observed trap biases.

Results of the mass balance analysis, coupled with models of physical mechanisms that affect the terms, point the way for future systematic studies of biased trapping effects. In particular, laboratory studies are needed where the vertical flux of particles in the external flow is carefully monitored, where mass concentration suspended inside traps can be separated from the mass settling onto the trap bottom, and where resuspension, trap-wall adhesion and particle-particle interactions can be quantified. In addition, these quantities must be measured as a function of R_t, u_f/W, D/H and trap geometry.

From this analysis it is clear that characteristics of particle collecting traps require thorough and careful investigation. The laboratory studies, to date, provide a valuable groundwork for future experiments but the results, thus far, raise more questions than they have answered. It is the conclusion of this analysis and literature review that the data to adequately evaluate trap biases of field-deployed traps do not exist for a wide range of conditions. Rigorous laboratory experiments are essential; future experiments might be fruitfully organized by testing the hypotheses suggested in this study. In addition, it is emphasized that laboratory experiments must be carefully designed especially so that competing physical effects are minimized (e.g., R_t must be constant when H/D and u_f/W effects are being tested), and so that dynamic and geometric similarity to the field is achieved (i.e., R_t and particle characteristics, especially W, must be matched).

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