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Woods Hole Oceanographic Institution

A Benthic Chamber with Electric Stirrer Mixing

by

Wayne Dickinson and F.L. Sayles

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Technical Report

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Geoffrey Thompson, Chairman
Department of Chemistry

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Abstract

Benthic chambers incorporating electric stirrer mixing have been designed and tested and have proven reliable during seven 18-31 day, 4300m ocean deployments. The chambers are 21 cm diameter by 31 cm long acrylic tubes sealed with pvc lids. A stepper motor and pressure tolerant electronics contained within the lids are magnetically coupled to stirring paddles to provide mixing within the chambers. The stirrers exhibit stable mixing rates and uniform speeds between chambers, require less than 1/3 watt of power, and are maintenance free. Laboratory calibration of stirring and mixing charactersitics demonstrate that areal averaged equivalent seawater-sediment boundary layer thickness can be set to agree with in situ measured values.

Introduction

Benthic chambers, used to isolate and measure chemical exchange across small areas of water-sediment interface, are increasingly common (Smith and Teal 1973; Smith et al. 1979; Berelson et al. 1986; Devol 1987). The chambers generally incorporate a means to mix the isolated overlying water so that hydrodynamics within the chamber simulate those of the external seafloor (Smith et al. 1979; Santschi et al. 1984; Berelson et al. 1986; Devol 1987; Buchholtz-Ten Brink et al. 1989). Methods of mixing have included circulating water from an impeller (Smith et al. 1979; Santschi et al. 1983; James, 1974) and use of rotating paddles or rods commonly driven by an electric motor (Berelson et al. 1986; Devol 1987; Buchholtz-Ten Brink et al. 1989; Cahoon 1988). Studies have shown that the rate of oxygen consumption within the chambers increases with increased stirring speed (Boynton et al. 1981; James, 1974) and that higher rates of consumption occur in stirred chambers as compared to unstirred ones (Hargrave, 1969). The exchange of oxygen and other substances across the seawater-sediment interface is influenced by the rate of diffusively mediated transport across the thin stagnant boundary layer, the "diffusive sublayer", separating the seawater and sediment. (Santschi et al. 1983; Devol 1987). In order to obtain accurate measurements of fluxes influenced by the diffusive sublayer, water within the chamber must be circulated at a velocity adequate to produce a sublayer thickness similar to that outside the chamber. This velocity is dependent on rotation rate of the stirring paddles for a given geometry, and as a consequence, the rotation rate must be known and constant. Difficulties in achieving constant stirring rates in some stirrer designs have been noted (Santschi et al. 1984; Buchholtz-Ten Brink et al. 1989). As part of the development of a benthic flux instrument, we have designed and built chambers incorporating electric stirrers that exhibit stable mixing rates adequate to produce equivalent diffusive sublayer thicknesses in agreement with reported in situ values.

Materials and methods

The benthic chambers are 31 cm lengths of 20.8 cm i.d. x 3 mm wall cast acrylic tube. Acrylic is inexpensive, transparent, permiting inspection of recovered sediments and is of low O_2 permeability. Lids housing the stirrer and sampling and chemical injection ports, are made of two PVC plates. A flat perforated baffle is secured ~4cm below the lid to break up and shed the central stirring vortex. In operation, the plates are forced together by a spring to provide an o-ring seal once the chamber has been implanted into the sediment. The lower plate forms an o-ring seal with the acrylic tube. (Fig. 1)

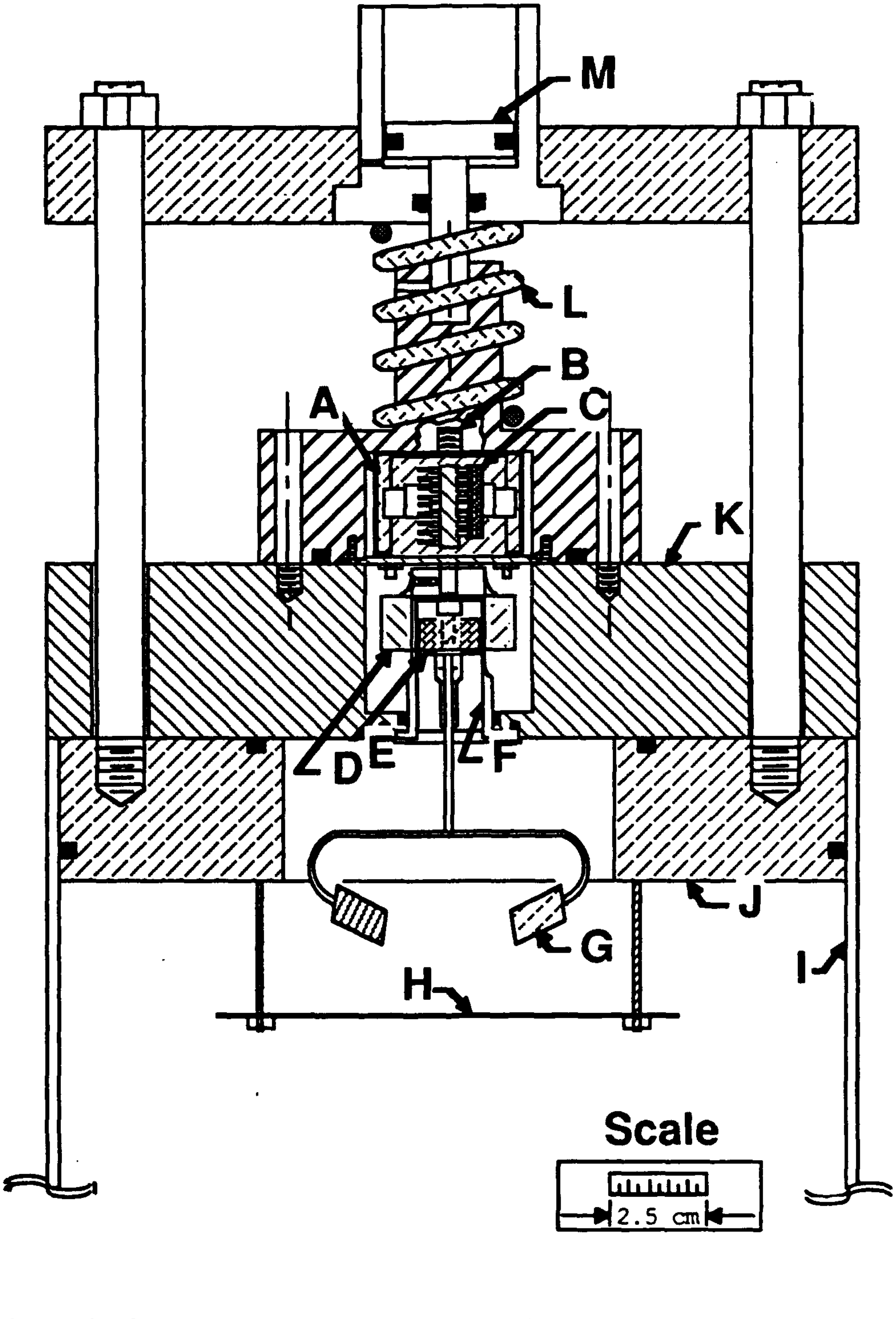
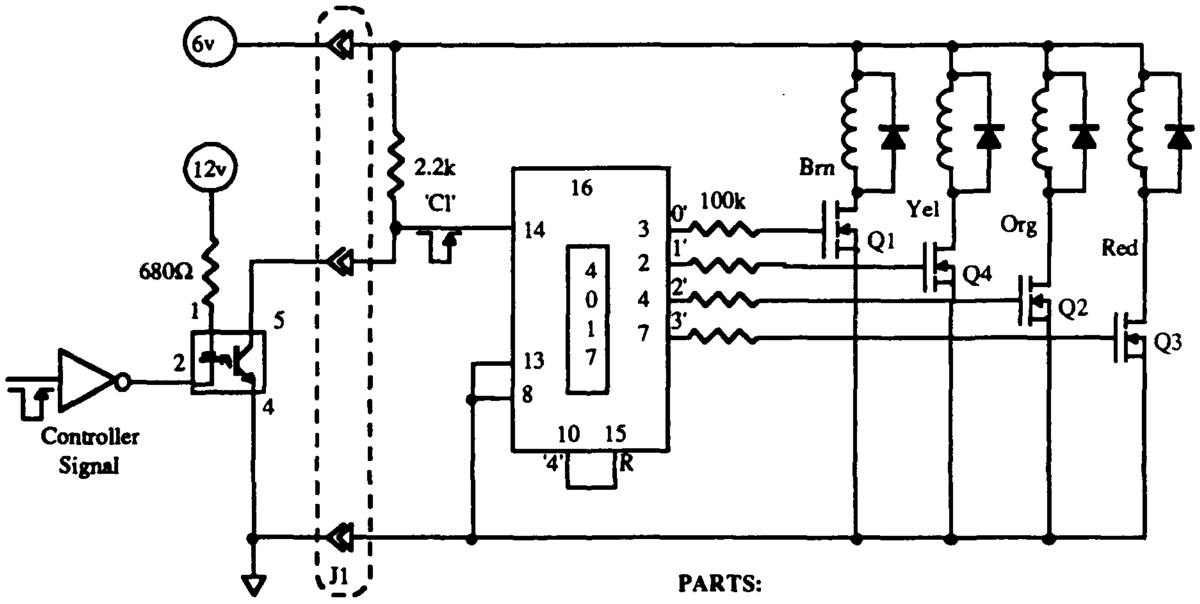


Fig. 1. Schematic of chamber assembly. A-Stepper motor. B-Fluid volume compensation port. C-18 pin DIP socket with 4017 IC and resistors. D-Drive magnet. E-Driven magnet. F-PVC cup. G-Stirring paddles. H-Baffle. I-Acrylic barrel. J-PVC chamber plate. K-PVC lid plate. L-Lid closure spring. M-Lid closure piston.

The stirrer is a unipolar stepper motor (Warner Electric, S. Benoit, IL) magnetically coupled to 2.5 cm square PVC paddles fixed at a compound angle 45 degrees from the vertical to the ends of a PVC tee. The motor is driven by a single integrated circuit counter and 4 field effect transistors (Fig. 2). that fit onto two 18 pin dip sockets cemented directly to the motor. Wells in the two portions of the upper lid plate form the housing for the motor, drive circuit and driving portion of the magnetic coupling. An o-ring sealed pvc cup isolates the motor from benthic chamber solution and provides a mount for the paddles and driven portion of the magnetic coupling. A 50cc hospital solution bag filled with Flourinert FC-40 (3M Co.) is attached to the fluid filled housing to provide volume compensation for the pressure tolerant system. A 3 conductor cable connects the housing to an external battery and clock pulse. Figure 3 includes a photograph and schematic showing the motor, drive circuit, pvc housing and stirring paddles.



PARTS:

Q1-Q4: BS170
Diodes: 1n4002
Resistors: 1/4w carbon composition
Motor: Warner Electric Model 13 Hybrid Stepper
Opto isolater: 4N32

Fig. 2. Circuit diagram of stepper motor drive electronics

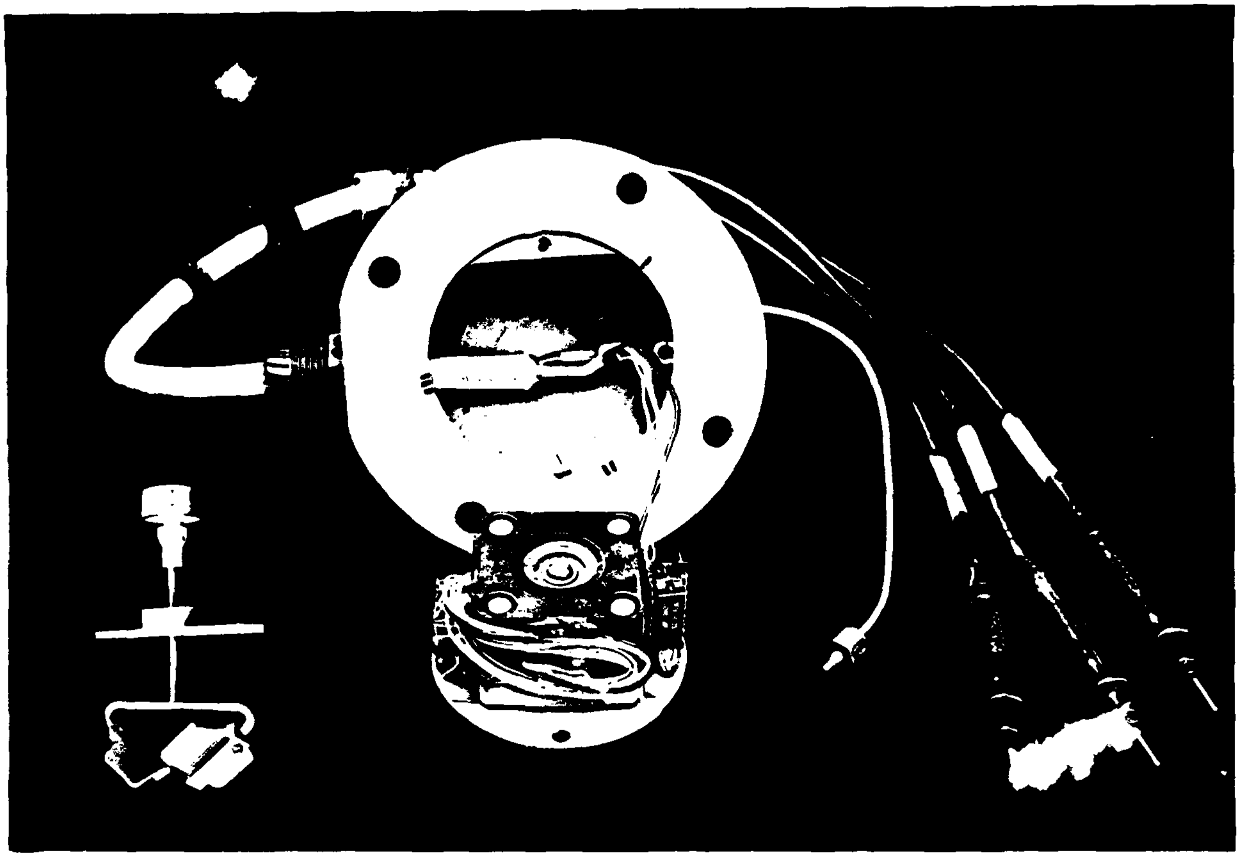


Fig. 3a. Photograph of stepping motor, drive, housing and stirring paddles.

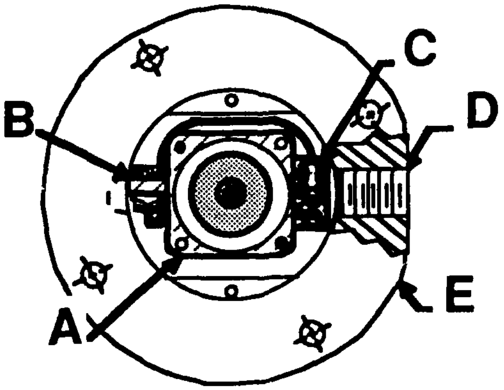


Fig. 3b. Schematic of stepper motor, drive circuit, and housing viewing motor face. A-Stepper motor. B-18 pin DIP socket with 4017 IC and resistors. C-18 pin DIP socket with FET's and diodes. D-Compression fitting port for electrical cable. E-PVC motor enclosure

There are several points worth noting about the motor and drive circuit design. To achieve the mixing requirements of benthic chambers deployed in stable flow regimes, the stirrers must rotate at slow stable speeds for periods up to many weeks. In cases where the height of enclosed water may vary on different deployments, the stirring speed must be adjustable to achieve the desired boundary layer thickness. In addition, to extend the duration of deployment to periods adequate for flux determinations in many parts of the deep ocean, power required to drive the motor and electronics must be minimized. These requirements are difficult to meet with some motors commonly used for under-sea work.

The brush commutated dc permanent magnet motor has been used in submersible pumps, winches and propulsion systems (Fugitt 1975; Heckman and McCracken 1979) but is troublesome to use in oil filled pressure compensated systems requiring steady speeds. Variable terminal resistance caused by commutator brushes arcing in the oil medium and 'hydroplaning' over the commutator cause the motor speed to vary. For slow speeds (10-100 rpm) used in benthic chambers, most inexpensive motors are operating near stall. In this condition, speed is very sensitive to changes in supply voltage and load torque as well as brush resistance, all of which may vary during the deployment. Gear motors commonly used to provide slow speed, operate at high armature speed, making them susceptible to brush hydroplaning and power losses due to the windage of armature rotation in fluid. Although low speed 'torque' motors are available, we found the price ranged from $700-$1000/ea for small quantities. The stepper motor used in the present design avoids these difficulties. It is brushless, operates at slow stable rotation speeds as low as 1 rpm for periods of at least several weeks and is inexpensive ($30).

The specification of low power consumption applies to both the motor and drive electronics. The stepper motor draws between 40 and 80 mA at 6v over its speed range of 1-90 rpm (Fig. 4). The drive circuit is CMOS technology and requires less than 20 uA at 6V. Exclusive use of solid electronic components i.e. integrated circuits, transistors, resistors, permits the circuit to operate in fluid at ambient deep ocean pressure without the need for pressure resistant housings or expensive undersea connectors.

The motor drive circuit operates by advancing the counter to energize successive motor windings upon receipt of an external clock pulse. The motor speed is then proportional to and has the same stability as the clock frequency. In our design, the clock pulses are sent from a computer present on the benthic chamber platform, but the pulses could easily be generated by a single integrated circuit such as the CMOS 4047. In the latter case, motor speed could be controlled by a single potentiometer adjustment. Motor speeds over the useable range of 1 to 90 rpm correspond to clock frequencies between approximately 3-300 Hz.

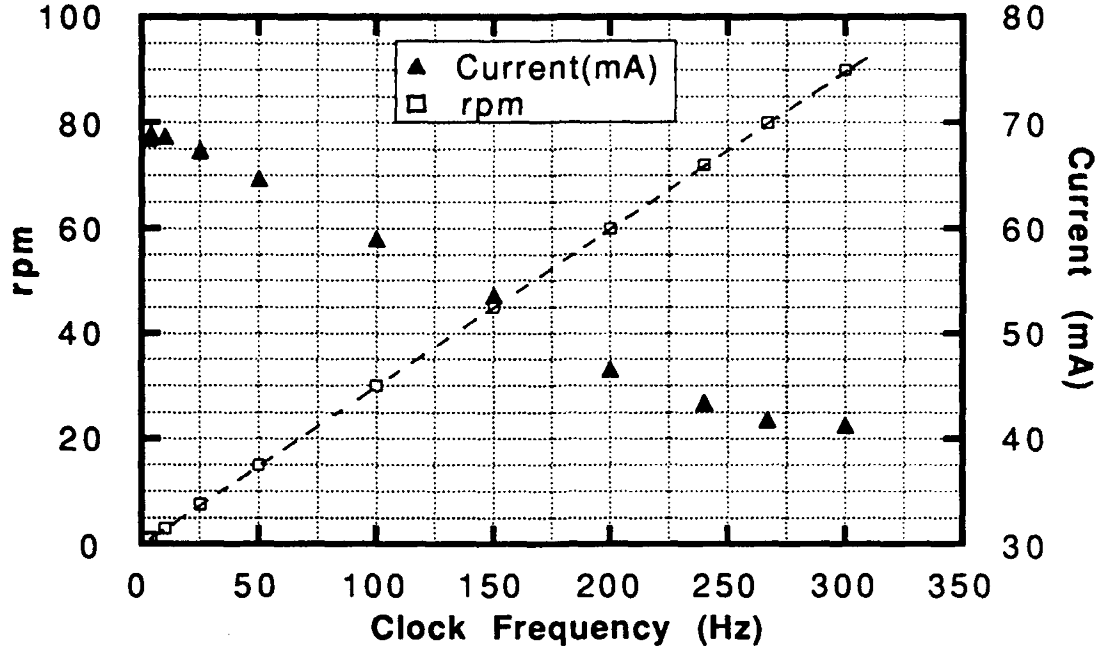


Fig. 4. Motor current and stirrer rpm at stepping rates from 3-300 Hz. with 5.96 volt supply. Stirrer was operated at 5.2 x 10^4 KPa and 2^o C. in a laboratory pressure vessel. Voltage and clock signals were supplied from sources external to tank. RPM was measured using an electronic counter to count pulses from a 4 slot encoder. The encoder generated 4 counts per revolution of the motor shaft. For speeds of 3 rpm and less, pulses were counted 3 times for 5 minute periods and counts for each period divided by 20 to give rpm. For other speeds, pulses were counted 7 times for 1 minute periods and counts for each period divided by 4 to give rpm. Current was measured with a digital volt meter connected between the voltage supply and the motor circuit. Symbol size exceeds 1 sd of average rpm.

Results and discussion

As the stirring mechanism is central to performance of the benthic chamber, several characteristics of the stirrer were investigated. We measured power requirements, available torque, and speed stability of the stirrer. We also tested the effectiveness of stirring by determining the equivalent boundary layer thickness at the water-solid phase interface within the chamber.

The stirrers were tested at 5.2 x 10^4 KPa pressure and 2^o C. in a laboratory pressure vessel. A slotted disk was fixed to the stirrer shaft as part of an optical shaft encoder to provide a pulse frequency proportional to shaft rpm. External clock pulses were sent to the assembly and current and rpm for each clock frequency were recorded. The results, shown in figure 4, indicate that the device provides stable rotation speeds over the range 1-90 rpm under deep sea conditions of temperature and pressure. To test the effect of varying voltage on stirrer speed, the stirrer was connected to a variable voltage source, and clocked at 200 Hz. The stirrer was able to start up and rotate at 60 rpm when operated at voltages ranging from 4.4-6.5 volts.

Torque characteristics of the motor were investigated using a simple dynamometer consisting of an elastic band, calibrated for its spring constant, having one end attached to a pulley on the motor shaft and the other end fixed. The motor was allowed to turn until it began to miss steps. Transition from smooth motor operation to missing steps, to stalling occurred within approximately 3 mm of elastic band travel, corresponding to a small, (~.35 mN-m), uncertainty in the torque determinations. Motor speed was calculated from drive pulse frequency and the step size of 1.8°. The results are shown in figure 5. The maximum stirrer speed is about 90 rpm indicating that the torque required to drive the stirrer is about one-tenth mN-m.

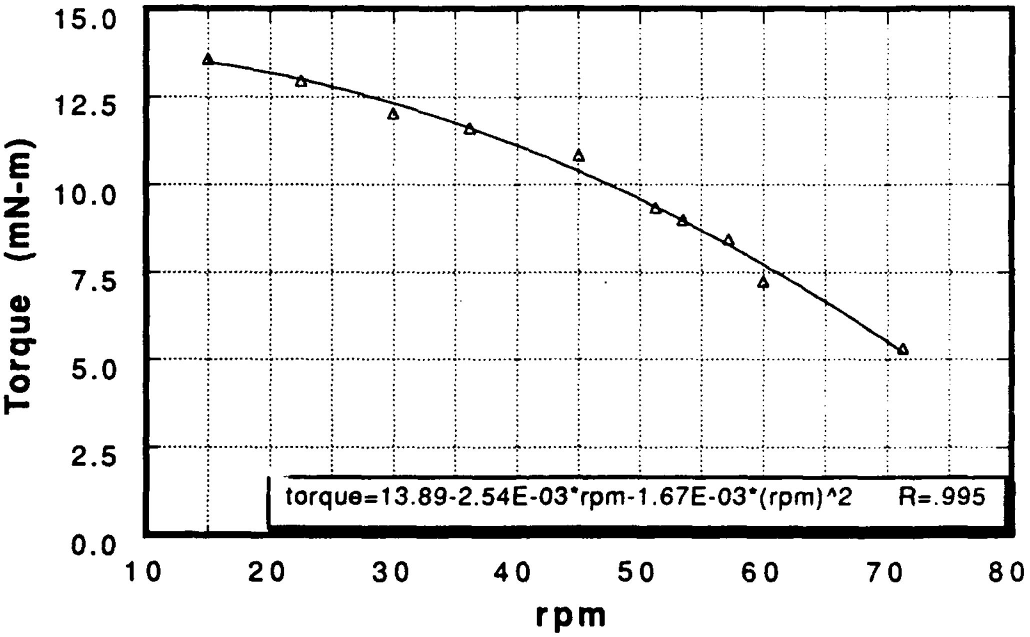


Fig. 5. Motor torque at speeds from 15 to 72 rpm. The motor was operated 'wave drive' from a 6.25 volt supply. Torque was measured using a simple dynamometer consisting of an elastic band calibrated for its force at various displacements. One end of the elastic band was held stationary and the other attached to line connected to a pulley on the motor shaft. At each speed, the motor was driven until it began to miss steps, then stall. Displacement of the elastic band was measured and converted to force, which applied at the radius of the pulley allowed calculation of torque. Displacement of the elastic band at stall ranged from 3.5 cm at 72 rpm to 27.6 cm at 15 rpm. Transition from smooth motor operation to missing steps to stalling occurred within approximately 3 mm of elastic band travel, introducing less than 0.3 mN-m uncertainty in the torque values.

To test the effectiveness of stirring, experiments were performed to determine the equivalent diffusive sublayer thickness within the chamber. The thickness, z, was derived from the rate of dissolved Cs transport between the stirred chamber solution and an underlying stationary bed of molecular sieve, in a fashion similar to the radiotracer technique of Santschi (1983). When the rate of transport across the diffusive sublayer is much slower than sorption processes in the stationary bed, the rate of transport is described by:

$$dC_t/dt=(C_t-C_{rl})*D/zH \qquad (1)$$
$$\{C_t\,(t=0) = C_o\}$$

where D is the molecular diffusivity of Cs^{2+}, C_t is the concentration of Cs^{2+} in the chamber at time t, C_o is the initial Cs^{2+} concentration, C_{rl} is the solution Cs^{2+} concentration in the stationary bed layer, and H is the height of the column of stirred chamber solution. C_{rl} is related to the change in Cs^{2+} concentration in the stirred chamber solution by: $C_{rl}=(C_o - C_t) * b$ where: $b = M_{ch}/((K_D * M_r) + M_s)$, K_D is the molecular sieve distribution coefficient, M_{ch} is the mass of stirred chamber solution, and M_r and M_s are masses of the molecular sieve and solution in the stationary bed layer, respectively. Substituting for C_{rl} and integrating yields:

$$Dt/zH = 1/(1+b)*\ln[((1+b)*C_t - b*C_o)/C_o] \qquad (2)$$

In cases where b << 1, equation 2 reduces to:

$$Dt/zH = \ln\,(C_t/C_o) \qquad (3)$$

The equivalent thickness, z, can be calculated from the slope of a plot of $1/(1+b)*\ln[((1+b)*C_t - b*C_o)/C_o]$ vs. t (Fig. 6).

The magnitude of z gives the area weighted average of sublayer thicknesses over the entire chamber floor. It does not provide information about the sublayer thickness or overlying water velocity at any specific site. It should be emphasized that in utilization of the chamber it is the average value that is of prime interest in the evaluation of fluxes. We confirmed that fluid velocity near the chamber floor was fairly homogeneous by visually following the movement of injected dye. Small upward velocity components were present and a 2-3 cm^2 patch of low velocity existed near the chamber center, but flow was generally rotationally uniform over the chamber floor.

The experiments were carried out in one of the benthic chambers cemented to an acrylic base. Approximately 50g (70 cm^3) 4A 100/120 mesh molecular sieve (Alltech Associates) was placed in the chamber, the barrel was filled with .005N NaHCO3 to stabilize pH, and the benthic chamber lid closure was fitted onto the barrel. The stirrer was turned on and the solution allowed to circulate and equilibrate overnight. The assembly enclosed a volume of 3282 cc, with an 8.7 cm column of water overlying a 2 mm thick bed layer of molecular sieve. A 7 ml volume of 75.1 m$\underline{M}$ $CsCl_2$ was added to the circulating solution to give 16.0 u$\underline{M}$ initial Cs^{2+} concentration. Aliquots were withdrawn at intervals over a 2-3 hour period for Cs analysis by flame atomic absorption.

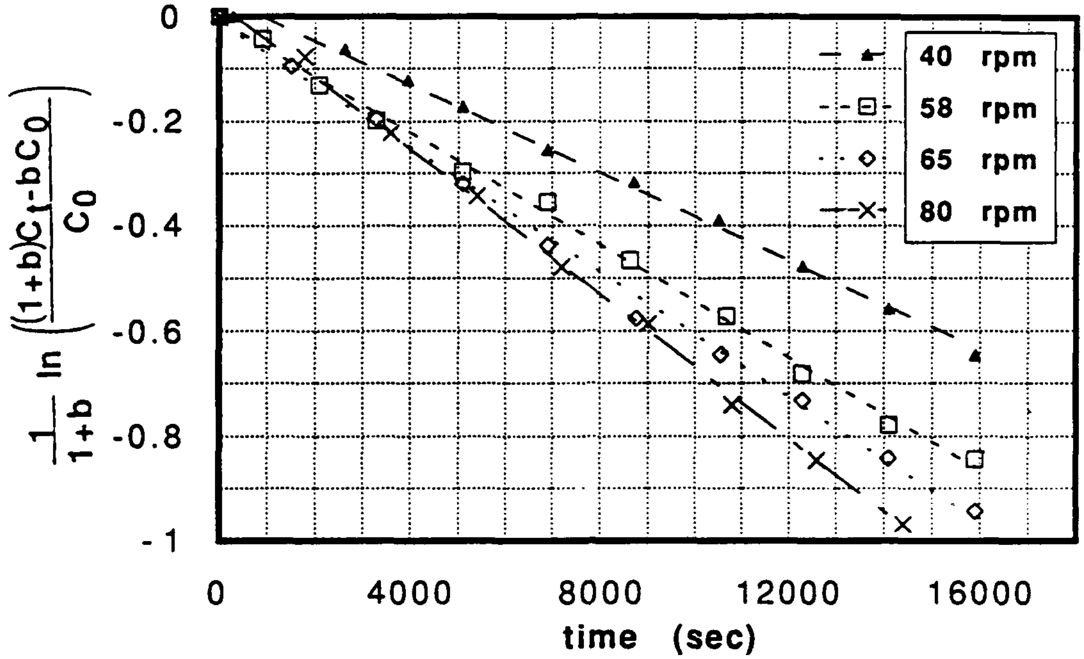


Fig. 6. Modelling of the Cs^{2+} concentrations for the chamber uptake experiments used to estimate diffusive sublayer thickness. The slope of the plots are proportional to equivalent boundary layer thickness. Shown are data from several of the experimental runs.

Separate experiments were conducted at 8 stirring speeds in the range 40-80 rpm. The rates of Cs^{2+} removal from the stirred chamber solution were at least 60 to 100 times lower than rates measured in well shaken batch experiments, indicating the sorption rate is rapid compared to transport across the diffusive sublayer. The value of b (eq. 2) was small and corresponded to a maximum C_{rl}/C_t value of .06 or less throughout all experiments. Figure 7 summarizes the effect of stirrer speed on diffusive sublayer thickness. The minimum thickness practical for the geometry we use is approximately 300um (i.e. stirring at 80-90 rpm). This permits us to extend our coverage beyond the range reported for the oceans of roughly 500 to 1500um (Santschi et al. 1983; Anderson et al. 1989). There is about a 5 percent change in diffusive layer thickness per 10 percent change in stirring speed at 60 rpm. Since variation in stirring speed is less than 2 percent (Figure 4), errors in flux estimates resulting from uncertainities in stirring speed contribute very little to reported flux uncertainities of 15-20 percent (Bender et al.,1989; Berelson et al., 1987; Devol, 1987).

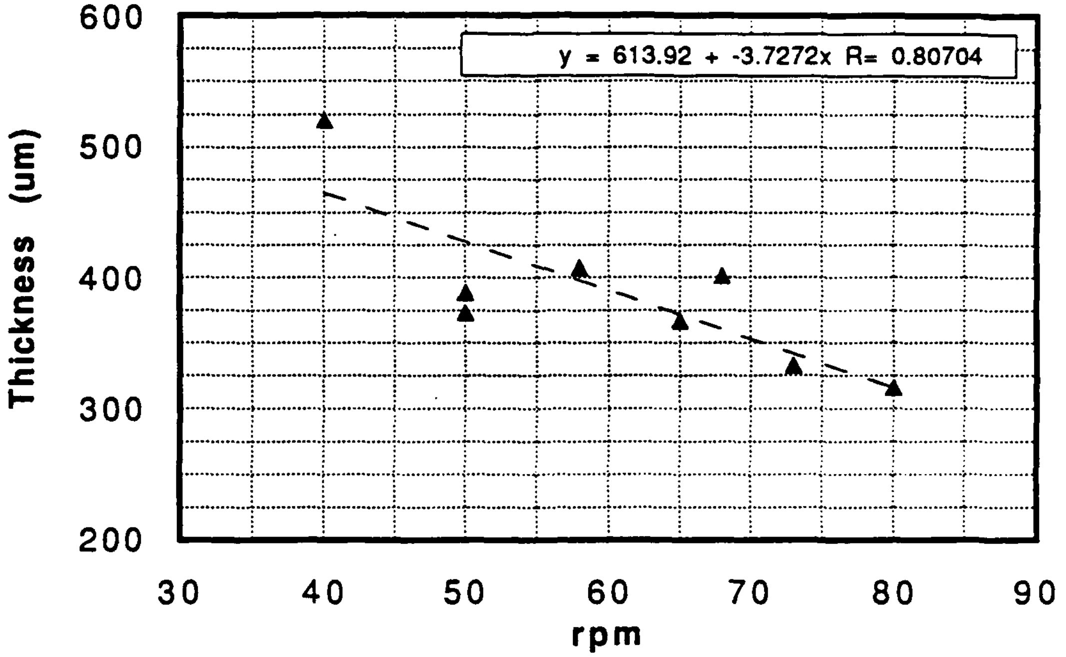


Fig. 7. The effect of stirring speed on equivalent diffusive sublayer thickness.

The real test of chamber operation has come from deployment for extended periods in the deep sea. Three of the chambers have been built and installed as part of our free vehicle benthic lander. The lander has been deployed 7 times at a depth of 4300 meters, each time for a period of 18 to 31 days. In all but one case, the stirrers in all chambers have been operating prior to and following the deployments. On the 31 day deployment, one stirrer was not stirring on recovery due to low battery voltage.

Consumed capacity during a deployment was evaluated for several stirrer batteries to estimate the average current drawn by the stirrers during the deployment and thereby the average stirring speed (Fig. 4). We measured the amp-hrs required to fully recharge the batteries following the deployments and found that a capacity equivalent to 50-54 mA for the duration of deployment had been consumed from each battery. While the consumed battery capacity represents only the integrated current over the duration of deployment, it is consistent with the measured current of 53 mA (6.2V, 2 degrees C., 5.2 x 10^4 KPa) corresponding to the set speed of 60 rpm.

Conclusion

We feel the chamber design is a versatile solution to many problems encountered in benthic chamber operation. It exhibits mixing rates adequate to establish an equivalent diffusive sublayer thickness that lies within the range of reported ocean values. The speed stability and low power requirements of the stirring mechanism will maintain stable mixing rates over deployments up to 1 month. Simple speed control allows the rate of mixing to be adapted to chambers of different volumes. A single clock can be used to drive several stirrers thereby assuring uniform speeds in each chamber. The small size and pressure balanced design allow the stirring mechanism to be integrated within the chamber lid and avoids the need for expensive pressure cases and undersea connectors. Magnetic coupling to the stirring paddles prevents leakage of electronic fluid into the chamber and avoids torque loss from bushing type shaft seals. Four 'D' cell alkaline batteries will furnish sufficient power for short chamber incubation periods up to a week, common for deployments in coastal waters. Finally, the chambers have proven very durable. No damage to the acrylic tube or lids has occurred in seven deployments and inspection of the stirrers after 75 days of operation revealed no wear, fluid decomposition, or seawater leakage. Routine maintenance consists solely of rinsing the chamber and exposed stirring paddles and coupling magnet with fresh water following recovery.

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16. Abstract (Limit: 200 words)

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submersible motors
boundary layer

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c. COSATI Field/Group

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