# The FLIP Experiment: Testing the Relationship of Length of Upwelling Tubes to Maximize Upwelling Velocity

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## Introduction

The Hydrocratic Generator is a patented technology that captures the free energy of mixing along a salinity gradient. The device consists of an open vertical tube and a fresh water injection system at its base that induces upwelling. The resulting upwelled water can be used to drive a turbine/generator for power generation.

A recent review of developments in salinity gradient technology was published in 2003 (see Jones and Finley, 2003). A manuscript describing the earlier efforts on developing hydrocratic power is under review (Finley et al., 2004).

A series of upwelling experiments were conducted onboard the Research Platform FLIP off San Diego, California in May, 2004. The objective was to test the relationship between length of upwelling tube and seawater entrainment or upwelling velocity. Tubes with an internal diameter of 45 cm (18 in.) and lengths of 31 m (100 ft.) to 62 m (200 ft.) were attached to the hull of FLIP and suspended vertically in the water column after FLIP converted to it's vertical orientation. Freshwater was injected into the base of the vertical tubes at rates varying from $3.2 \times 10^{-2}$ $m^3/s$ (500 gpm) to $6.3 \times 10^{-2}$ $m^3/s$ (1000 gpm).

A "hydrocratic" effect was observed with a strong linear response to freshwater input. However, no difference in upwelling velocity was observed directly among the three tube lengths. A lower entrainment for the longest tube (200-ft) was inferred from salinity-derived calculations of the velocity.

## *Research Platform FLIP*

The Floating Instrument Platform, FLIP, is a 355-ft non-propelled research platform, owned by the U.S. Navy and operated by the Marine Physical Laboratory of Scripps Institution of Oceanography. It is a highly stable platform, having the unique ability to flip from the horizontal position to the vertical position while at sea. This science platform was selected as a practical means to deploy three upwelling tubes of varying lengths. More details on the FLIP are available at the Scripps web site (www-mpl.ucsd.edu/resources/flip.intro.html).

# Methods

## *Equipment Description*

Three upwelling tubes (45 cm; 18” i.d.) were attached to the submersible section of *FLIP*, such that the tubes would be aligned vertically when the platform was in the “flipped” vertical position. The lengths of the three tubes were 100 ft. (31 m), 160 ft. (49 m), and 200 ft. (62 m). The tops of all three tubes were located 75 ft. (23 m) below the lower deck of *FLIP*, which positioned them 55 ft. (17 m) below the waterline when the platform was in the vertical orientation (Figure 1). Structural support for the upwelling tubes was provided by three steel cables running flush along the inner walls of each tube and secured under tension to a tripod at either end.

At the top of each upwelling tube, a temperature-salinity probe (YSI 30M Temperature-Salinity Meter) was installed 8” (20 cm) below the end of the tube. General Oceanics digital flow meters (Model 2135) were positioned 24” ( 60 cm) below the top end of the tubes (Figure 2). An internally-logging Conductivity-Temperature-Depth instrument (CTD, AML STD12+) was attached to *FLIP*’s hull, such that the sensors were aligned 3 ft. (~ 1 m) above the bottom end of the 200 ft. (62 m) upwelling tube in approximately 78 m ( 256 ft. ) water depth (see Figure 3).

A down tube (PVC, 10 cm; 4” i.d.) was installed alongside each of the upwelling tubes. Each of the down tubes ran through a 180° bend at the bottom of its respective upwelling tube, terminating in an injector that directed the outflow from the down tube directly into the entrance of the upwelling tube (Figures 1-2). The distance between the injectors and the bottom end of the upwelling tubes was 21” (± 1”) (~ 53 cm). Flexible hoses connected the tops of each of the down tubes to a manifold located on *FLIP’s* lower deck, and an externally-mounted ultrasonic flow meter (EASZ-10FP) was installed to measure the flow delivered to the manifold.

## *Experimental Procedure*

*FLIP* and a support barge equipped with four 19,000-gal (72 $m^3$) freshwater storage tanks were towed to a position roughly 8.5 miles (13.7 km) off the coast to the north of San Diego (32° 52' N, 117° 27' W). The FLIP operated in free drifting mode, drifting south-southeast over the course of the experiment.

Prior to flipping, the CTD was turned on to start logging data. After the platform reached its vertical “flipped” position, the manifold was connected to a hose running from a pump on the support barge that could deliver either fresh water contained in the storage tanks or surface seawater to the manifold.

The valves on the manifold were manipulated to direct the flow from the barge pump to the down tube for the 100 ft. upwelling tube while sealing off the other two down tubes. The pump speed was adjusted to produce flow through the down tube at

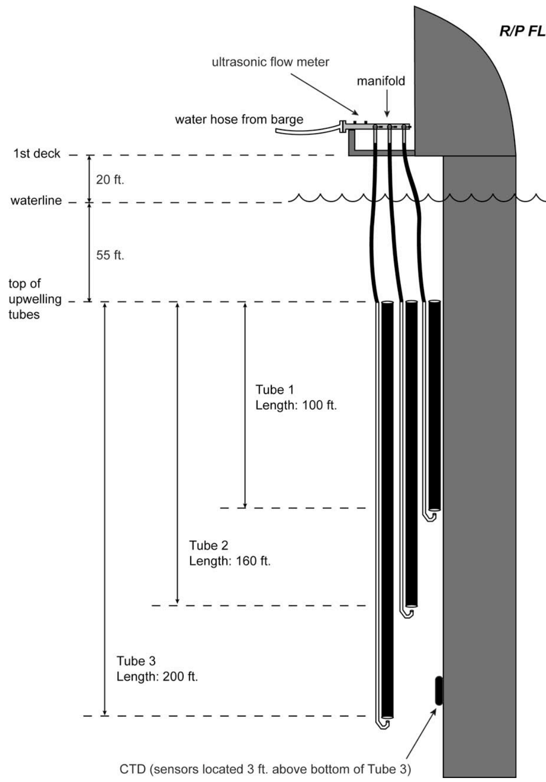


Figure 1. Arrangement of upwelling tubes on FLIP.

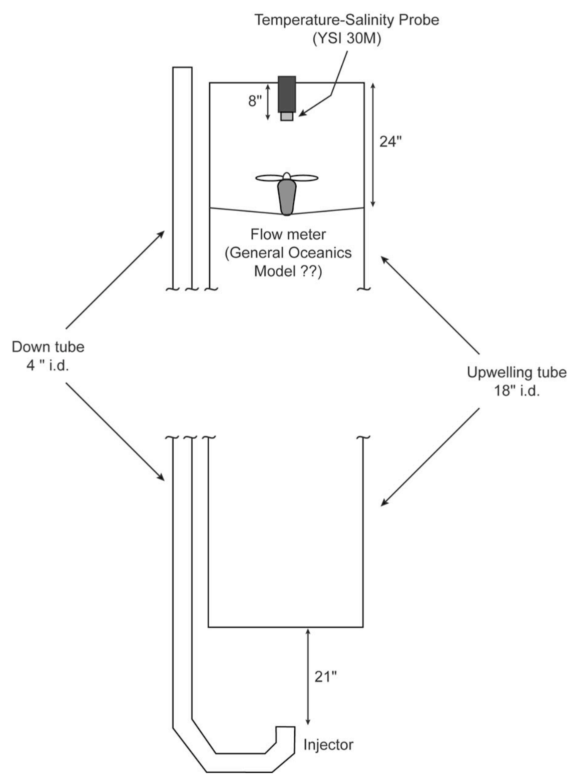


Figure 2. Schematic illustration of injector and instrumentation.

rates of 500 – 1,000 gallons-per-minute (gpm). At each of the flow rates for the down tube, several readings of temperature, salinity, and flow velocity were made at the top of the upwelling tube. This procedure was repeated for the 160 ft. and 200 ft. upwelling tubes.

After all of the freshwater runs were completed, the pump intake was switched to surface seawater. The manifold valves were adjusted to deliver the pump outflow to the down tube of the 100 ft. upwelling tube, and the pump speed was adjusted to produce a range of flows as was done in the fresh water runs. At each of the flow rates for the down tube, several readings of temperature, salinity, and flow velocity were made at the top of the upwelling tube. This procedure was repeated for the 160 ft. and 200 ft. upwelling tubes. After completing all of the seawater runs, the barge pump hose was disconnected from the manifold and *FLIP* was returned to the horizontal "tow" position. The CTD was switched off upon return to the dock.

# Results

Field measurements from the FLIP experiment are tabulated in Appendix A. Two approaches were conceived to analyze the upwelling velocity. First, the linear velocity was measured directly with a digital flow meter as described above. Second, the temperature and salinity of the out flowing water was recorded to indirectly calculate the flow rates assuming conservation of salt.

## *Direct Flow Rate Measurements*

Freshwater (and seawater as a control) was injected into the base of the vertical upwelling tubes at rates varying from 500 gpm ( $3.2 \times 10^{-2}$ $m^3/s$ ) to 1000 gpm ( $6.3 \times 10^{-2}$ $m^3/s$ ). The direct measurement of linear velocity of water exiting the top of the tubes ranged from 2.95 mph to 4.95 mph with an average velocity of 4.13 $\pm$ 0.54 mph. This is equivalent to a volumetric flow in the range of from 3,441 gpm to 5,776 gpm, given the diameter of the upwelling tube. The average exit flow rate was 4,821 $\pm$ 635 gpm. Data are presented graphically in Figure 3 below.

In examining the difference between the tube lengths, over the range of conditions tested in the FLIP experiment, there was no significant difference in the response of the three lengths of upwelling tubes. A strong linear response to the injection of freshwater was observed in all three cases (see Table 1).

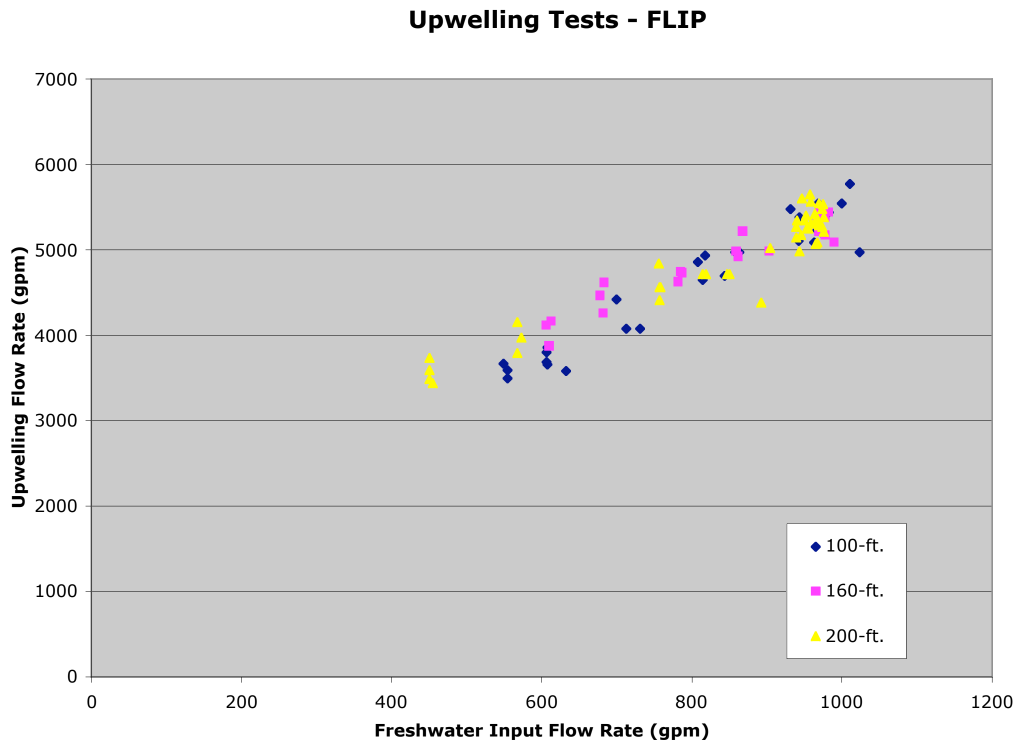


Figure 3. Relationship of freshwater flow rate to upwelling flow rate for three tube lengths.

Table 1.
Analysis of linear relationship between freshwater injected and upwelled seawater.

| Length of Upwelling Tube (ft.) | Slope (β) | Correlation Coefficient | Count |
|---|---|---|---|
| 100 | 4.30 | 0.9608 | 29 |
| 160 | 3.29 | 0.9587 | 22 |
| 200 | 3.45 | 0.9528 | 42 |

Note: In linear regression, a mathematical relationship is established to fit the equation $y = \alpha + \beta x$, where $\beta$ is the slope of the line and $\alpha$ is the y-axis intercept.

In the linear regression, the $\beta$ coefficient (or slope) is a measure of the seawater entrainment. Regression coefficients approaching 1.00 are perfectly linear.

**Seawater Controls**

Surface seawater was used as an experimental control to account for pumping of water from the barge up to the elevated platform on FLIP. The surface seawater was slightly less dense than the water at the bottom of the upwelling tubes (see Table 2).

Table 2.
Density of seawater

| Water Depth (ft.) | Temperature (°C) | Salinity (psu) | Density ($g/cm^3$) |
|---|---|---|---|
| Surface | 19.2 | 34.91 | 1.0249 |
| 155 | 12.2 | 35.75 | 1.0273 |
| 215 | 9.8 | 35.37 | 1.0276 |
| 255 | 9.6 | 35.46 | 1.0273 |

Note: Practical Salinity Units or PSU are equivalent to parts per thousand.

Since there is no statistical difference between the length of upwelling tube on the upwelling velocity, we can pool the experimental results from the freshwater tests and examine the introduction of surface seawater into the Hydrocratic System. In comparing the input of freshwater versus seawater, there is an obvious "hydrocratic" effect as shown in the shift in the trend lines as seen in Figure 4.

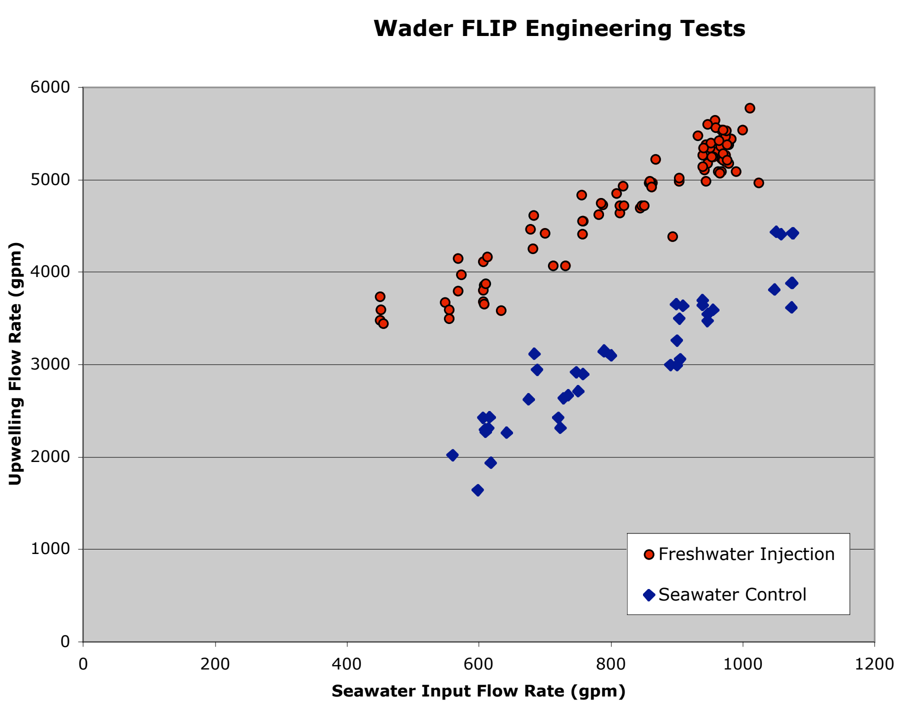


Figure 4. Pooled results of freshwater injections compared with seawater injection.

## *Indirect Flow Rate Measurements*

In our second approach, the velocity of water exiting the upwelling tubes was determined algebraically assuming conservation of salt (see Appendix B). Salinity was measured at the top of each vertical tube and ambient seawater conditions were recorded on the CTD during descent and ascent. Vertical profiles acquired during "flipping" are similar to archival data for off San Diego (Jones 2001, unpublished report).

Presented below are the results of the calculation for volumetric flow rate exiting the top of the upwelling tube based primarily on salinity (Figure 5). The longer tube had a calculated lower upwelling flow rate than the other two tubes. Several assumptions are incorporated in these calculations including utilizing the density and salinity for the upwelled water from values identified in Table 2 above. We also assume that the density of the freshwater pumped into the system was at or near 1.000 $g/cm^{3}$.

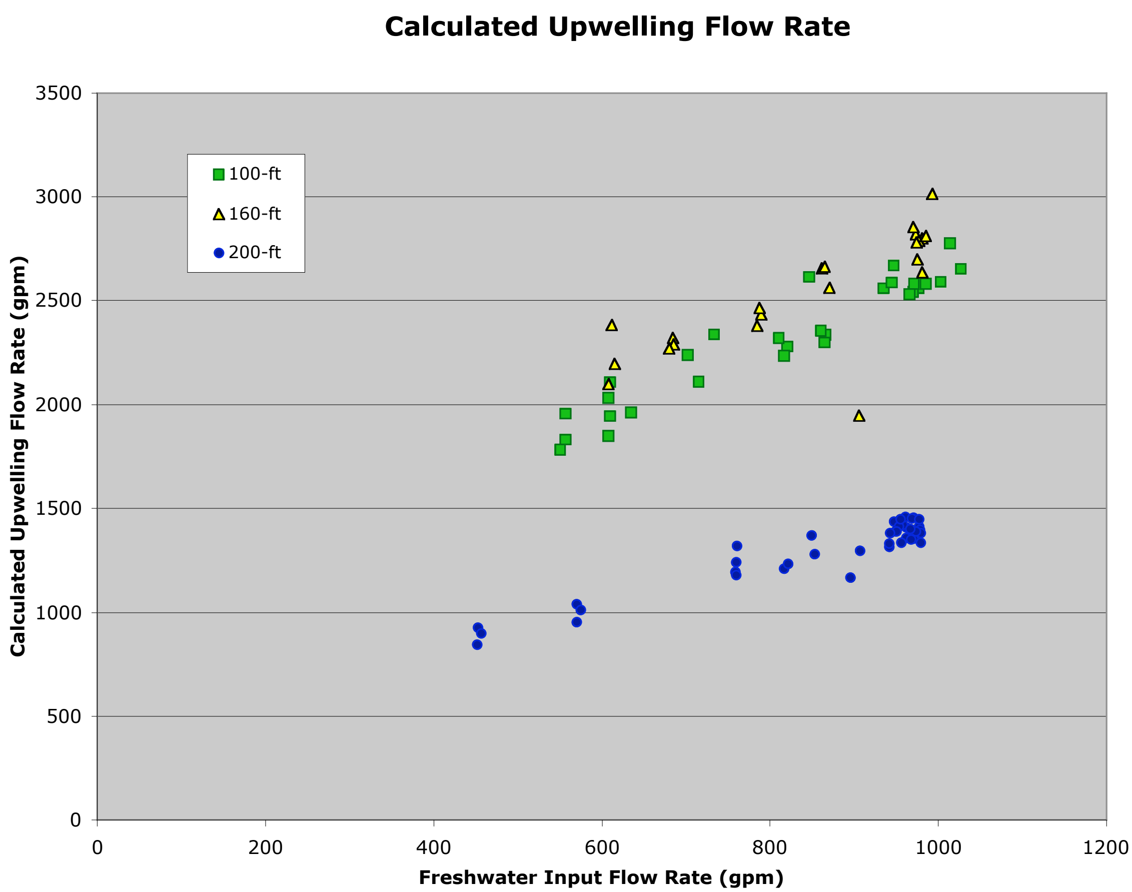


Figure 5. Calculated flow rate exiting the upwelling tube based on salinity values.

The linear relationship between freshwater injected into the system and the upwelled water still holds. However, the slope of the relationship is less. In comparing the direct measured flow rates with the calculated flow rates, either the direct flow reading over estimate the velocity or the calculated flow rates underestimate the actual upwelled flow. A graph illustrating this point is presented below (Figure 6). At higher input flow rates, the calculated upwelling flow rates appear to flatten, indicating that not enough time for complete mixing has occurred or that not enough seawater could enter the system at the bottom of the upwelling tube.

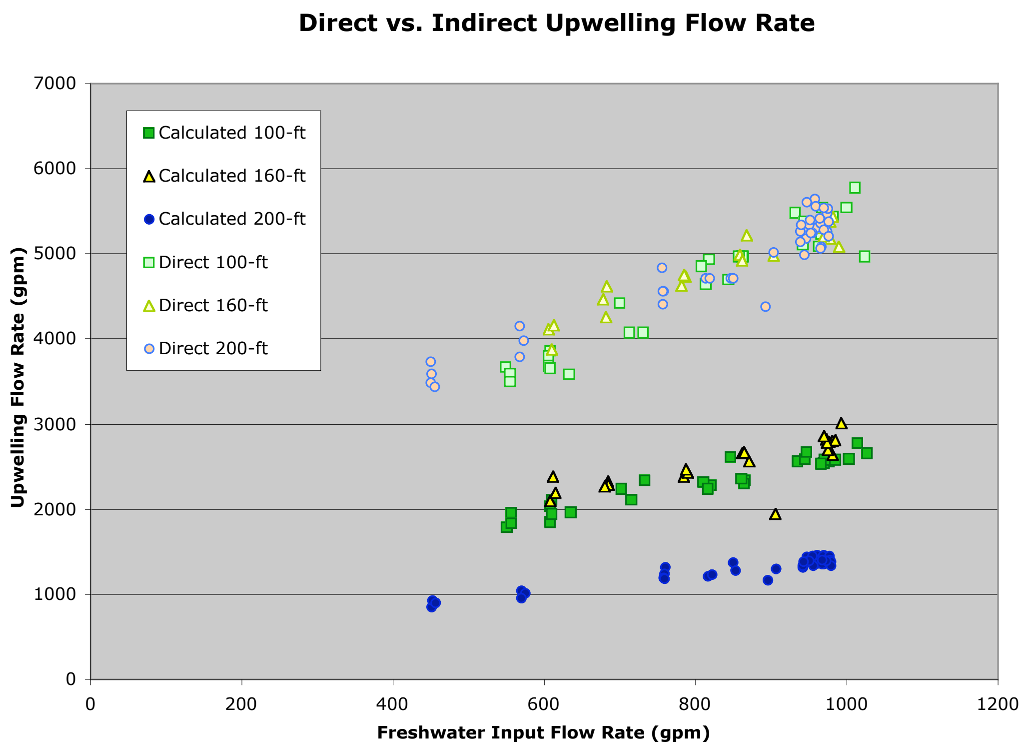


Figure 6. Direct and calculated volumetric upwelling rates for three tube lengths.

# Acknowledgements


We thank Dr. Freita of ONR for authorizing a 1-day FLIP cruise. We also thank Bill Gaines, Tom Golfinos and George Trekas of MPL/FLIP.

# References

Finley, W., E. Pscheidt, and A.T. Jones (2004). Hydrocratic Generator: A Technology for Capturing Energy from Salinity Gradients. (Manuscript in review).

Jones, A.T. and W. Finley (2003). Recent Developments in Salinity Gradient Power. OCEANS 2003, pp. 2284- 2287.

# Appendices

Appendix A. Measured Field Data from May 20, 2004

Appendix B. Calculation of Velocity Exiting Vertical Tube.

Appendix A. Measured Values for the FLIP Experiment, 20 May 2004.

| **UpTube Length** □ | | **Source Water** | | **Upwelling** | | |
|---|---|---|---|---|---|---|
| □ | | Flow | Pressure | Linear Velocity | Salinity | Temp. |
| (ft) | Time | (gpm) | (psi) | (m/s) | (ppt) | (°C) |
| □ | | **Freshwater** | | □ | | □ |
| 100 | 14:11:00 | 1000 | 35 | 2.124 | 26.1 | 14.0 |
| 100 | 14:12:00 | 1011 | □ | 2.214 | 26.5 | 13.9 |
| 100 | 14:13:00 | 1024 | □ | 1.905 | 26.1 | 14.1 |
| 100 | 14:13:30 | 863 | □ | 1.905 | 26.4 | 13.7 |
| 100 | 14:14:00 | 844 | 20 | 1.800 | 27.3 | 13.6 |
| 100 | 14:15:00 | 713 | <5 | 1.561 | 27.0 | 13.7 |
| 100 | 14:15:30 | 731 | <5 | 1.561 | 27.5 | 13.5 |
| 100 | 14:17:00 | 700 | □ | 1.695 | 27.5 | 13.5 |
| 100 | 14:18:00 | 549 | ~0 | 1.407 | 27.6 | 13.4 |
| 100 | 14:18:30 | 555 | ~0 | 1.377 | 28.1 | 13.2 |
| 100 | 14:19:00 | 555 | ~0 | 1.341 | 27.7 | 13.4 |
| 100 | 14:19:30 | 608 | ~0 | 1.480 | 28.0 | 13.3 |
| 100 | 14:21:00 | 606 | □ | 1.411 | 27.2 | 13.5 |
| 100 | 14:21:45 | 606 | □ | 1.457 | 27.8 | 13.3 |
| 100 | 14:22:15 | 608 | □ | 1.400 | 27.5 | 13.4 |
| 100 | 14:24:00 | 633 | | 1.373 | 27.3 | 13.5 |
| 100 | 14:42:00 | 818 | ~19 | 1.892 | 26.6 | 13.7 |
| 100 | 14:42:30 | 808 | ~15 | 1.861 | 26.8 | 13.6 |
| 100 | 14:43:00 | 814 | ~15 | 1.780 | 26.5 | 13.6 |
| 100 | 14:44:00 | 862 | ~23 | 1.905 | 26.3 | 13.9 |
| 100 | 14:44:30 | 858 | 20 - 25 | 1.905 | 26.5 | 13.8 |
| 100 | 14:45:30 | 932 | □ | 2.101 | 26.5 | 13.8 |
| 100 | 14:46:00 | 942 | □ | 1.957 | 26.5 | 13.8 |
| 100 | 14:46:30 | 944 | □ | 2.063 | 26.7 | 13.8 |
| 100 | 14:47:46 | 974 | 35 | 1.991 | 26.2 | 13.9 |
| 100 | 14:47:50 | 982 | 35 | 2.085 | 26.2 | 13.9 |
| 100 | 14:48:30 | 967 | □ | 2.005 | 26.2 | 13.9 |
| 100 | 14:49:00 | 968 | □ | 2.124 | 26.3 | 13.9 |
| 100 | 14:49:15 | 963 | □ | 1.950 | 26.2 | 13.9 |
| 160 | 14:51:30 | 903 | 25 - 50 | 1.910 | 24.5 | 13.0 |
| 160 | 14:56:30 | 606 | □ | 1.578 | 27.7 | 12.8 |
| 160 | 14:57:00 | 610 | □ | 1.484 | 28.4 | 12.6 |
| 160 | 14:57:30 | 613 | □ | 1.596 | 27.9 | 12.6 |
| 160 | 14:58:00 | 682 | □ | 1.632 | 27.6 | 12.8 |
| 160 | 14:58:30 | 683 | □ | 1.769 | 27.5 | 12.9 |
| 160 | 14:58:45 | 678 | □ | 1.711 | 27.5 | 12.9 |
| 160 | 14:59:30 | 782 | □ | 1.774 | 26.9 | 13.2 |
| 160 | 15:00:00 | 787 | □ | 1.814 | 27.0 | 13.1 |
| 160 | 15:00:30 | 785 | □ | 1.820 | 27.1 | 13.1 |
| 160 | 15:01:00 | 859 | □ | 1.911 | 27.0 | 13.4 |
| 160 | 15:01:30 | 862 | □ | 1.886 | 27.0 | 13.2 |

Appendix A. Measured Values for the FLIP Experiment, 20 May 2004 (continued).

| UpTube Length | □ | Source Water | | Upwelling | | |
|---|---|---|---|---|---|---|
| □ | | Flow | Pressure | Linear Velocity | Salinity | Temp. |
| (ft) | Time | (gpm) | (psi) | (m/s) | (ppt) | (°C) |
| 160 | 15:01:45 | 868 | □ | 2.001 | 26.7 | 13.3 |
| 160 | 15:02:30 | 990 | 40 - 45 | 1.950 | 26.9 | 13.2 |
| 160 | 15:02:45 | 978 | " | 1.984 | 26.5 | 13.4 |
| 160 | 15:03:00 | 970 | " | 1.998 | 26.6 | 13.4 |
| 160 | 15:03:15 | 974 | " | 2.063 | 26.5 | 13.4 |
| 160 | 15:03:30 | 978 | □ | 2.063 | 26.1 | 13.5 |
| 160 | 15:03:45 | 972 | □ | 2.085 | 26.3 | 13.5 |
| 160 | 15:04:00 | 982 | □ | 2.085 | 26.5 | 13.4 |
| 160 | 15:04:15 | 971 | □ | 2.104 | 26.5 | 13.4 |
| 160 | 15:04:18 | 967 | □ | 2.033 | 26.7 | 13.3 |
| 200 | 15:12:30 | 450 | □ | 1.335 | 30.5 | 10.0 |
| 200 | 15:13:20 | 450 | □ | 1.432 | 23.5 | 12.3 |
| 200 | 15:13:45 | 451 | □ | 1.377 | 24.2 | 11.9 |
| 200 | 15:14:00 | 455 | □ | 1.319 | 23.9 | 11.9 |
| 200 | 15:14:45 | 568 | □ | 1.454 | 23.3 | 12.3 |
| 200 | 15:15:00 | 573 | □ | 1.524 | 23.0 | 12.5 |
| 200 | 15:15:30 | 568 | □ | 1.591 | 22.6 | 12.6 |
| 200 | 15:16:15 | 758 | □ | 1.747 | 22.9 | 12.5 |
| 200 | 15:16:30 | 757 | □ | 1.690 | 22.4 | 13.0 |
| 200 | 15:16:40 | 756 | □ | 1.855 | 22.1 | 13.0 |
| 200 | 15:17:00 | 757 | □ | 1.747 | 22.0 | 13.0 |
| 200 | 15:17:30 | 847 | □ | 1.808 | 22.3 | 13.1 |
| 200 | 15:17:55 | 814 | □ | 1.808 | 21.6 | 13.2 |
| 200 | 15:18:15 | 819 | □ | 1.808 | 21.7 | 13.2 |
| 200 | 15:18:30 | 850 | □ | 1.808 | 21.7 | 13.2 |
| 200 | 15:19:00 | 944 | □ | 1.911 | 21.8 | 13.1 |
| 200 | 15:19:15 | 974 | □ | 2.098 | 21.4 | 13.3 |
| 200 | 15:19:30 | 967 | □ | 2.041 | 21.7 | 13.1 |
| 200 | 15:19:45 | 959 | □ | 2.033 | 21.5 | 13.3 |
| 200 | 15:19:50 | 955 | □ | 2.012 | 21.6 | 13.2 |
| 200 | 15:20:00 | 958 | □ | 2.164 | 21.8 | 13.1 |
| 200 | 15:20:15 | 950 | □ | 2.048 | 21.6 | 13.2 |
| 200 | 15:20:22 | 946 | □ | 1.984 | 21.5 | 13.3 |
| 200 | 15:20:35 | 952 | □ | 2.070 | 21.8 | 13.1 |
| 200 | 15:20:45 | 966 | □ | 2.055 | 21.7 | 13.2 |
| 200 | 15:21:00 | 974 | □ | 2.019 | 21.6 | 13.2 |
| 200 | 15:21:15 | 959 | □ | 2.132 | 21.2 | 13.2 |
| 200 | 15:21:25 | 970 | □ | 2.026 | 21.3 | 13.2 |
| 200 | 15:21:45 | 967 | □ | 1.950 | 21.1 | 13.2 |
| 200 | 15:22:00 | 965 | □ | 1.943 | 21.1 | 13.3 |
| 200 | 15:22:30 | 975 | □ | 2.121 | 21.3 | 13.3 |
| 200 | 15:22:40 | 976 | | 2.063 | 21.2 | 13.3 |
| 200 | 15:22:50 | 976 | □ | 1.998 | 20.9 | 13.4 |

Appendix A. Measured Values for the FLIP Experiment, 20 May 2004 (continued).

| **UpTube Length** □ | | **Source Water** | | **Upwelling** | | |
|---|---|---|---|---|---|---|
| □ | | Flow | Pressure | Linear Velocity | Salinity | Temp. |
| (ft) | Time | (gpm) | (psi) | (m/s) | (ppt) | (°C) |
| □ | | **Freshwater** | | □ | | □ |
| 200 | 15:23:00 | 970 | □ | 2.124 | 21.3 | 13.2 |
| 200 | 15:23:15 | 964 | □ | 2.078 | 21.4 | 13.3 |
| 200 | 15:23:25 | 953 | □ | 2.012 | 21.1 | 13.3 |
| 200 | 15:23:35 | 947 | □ | 2.148 | 21.5 | 13.1 |
| 200 | 15:23:45 | 939 | | 1.970 | 21.1 | 13.3 |
| 200 | 15:24:00 | 939 | □ | 2.019 | 21.2 | 13.2 |
| 200 | 15:24:10 | 940 | | 2.048 | 21.5 | 13.1 |
| 200 | 15:24:20 | 904 | □ | 1.924 | 21.3 | 13.1 |
| 200 | 15:24:40 | 893 | | 1.680 | 20.5 | 13.2 |
| □ | | **Seawater** | | □ | | □ |
| 100 | 15:58:20 | 1050 | ~35 | 1.700 | 33.6 | 13.4 |
| 100 | 15:58:45 | 1048 | □ | 1.461 | 33.6 | 13.6 |
| 100 | 15:59:00 | 1058 | □ | 1.690 | 33.5 | 13.3 |
| 100 | 16:01:00 | 909 | ~18 | 1.393 | 33.6 | 13.5 |
| 100 | 16:01:30 | 904 | □ | 1.341 | 33.5 | 13.2 |
| 100 | 16:02:00 | 899 | □ | 1.400 | 33.6 | 13.4 |
| 100 | 16:02:45 | 790 | ~8 | 1.208 | 33.6 | 13.4 |
| 100 | 16:03:00 | 800 | □ | 1.188 | 33.6 | 13.3 |
| 100 | 16:03:15 | 789 | □ | 1.205 | 33.6 | 13.3 |
| 100 | 16:04:30 | 688 | "0" | 1.129 | 33.6 | 13.2 |
| 100 | 16:04:45 | 684 | □ | 1.195 | 33.6 | 13.2 |
| 100 | 16:05:00 | 675 | □ | 1.006 | 33.5 | 13.2 |
| 100 | 16:06:00 | 642 | □ | 0.868 | 33.6 | 13.4 |
| 100 | 16:06:10 | 614 | □ | 0.886 | 33.5 | 13.2 |
| 100 | 16:06:20 | 598 | □ | 0.630 | 33.5 | 12.9 |
| 100 | 16:06:30 | 560 | □ | 0.775 | 33.6 | 13.1 |
| 160 | 16:14:50 | 947 | □ | 1.360 | 31.7 | 13.3 |
| 160 | 16:15:00 | 955 | □ | 1.377 | 31.7 | 13.1 |
| 160 | 16:15:20 | 946 | □ | 1.332 | 31.7 | 13.1 |
| 160 | 16:15:30 | 939 | □ | 1.418 | 31.7 | 13.1 |
| 160 | 16:15:45 | 939 | □ | 1.397 | 31.7 | 13.1 |
| 200 | 16:16:55 | 905 | ~30 | 1.173 | 31.4 | 10.2 |
| 200 | 16:17:10 | 900 | □ | 1.250 | 31.4 | 10.0 |
| 200 | 16:17:25 | 900 | □ | 1.147 | 31.8 | |
| 200 | 16:17:35 | 890 | □ | 1.149 | 31.1 | 14.0 |
| 200 | 16:24:30 | 720 | □ | 0.930 | 32.9 | 13.0 |
| 200 | 16:25:00 | 723 | □ | 0.887 | 32.9 | 13.1 |
| 200 | 16:25:10 | 735 | | 1.022 | 33.0 | 13.0 |
| 200 | 16:25:30 | 728 | □ | 1.011 | 32.9 | 13.0 |
| 200 | 16:26:30 | 610 | □ | 0.871 | 32.9 | 12.9 |
| 200 | 16:26:50 | 606 | | 0.930 | 33.0 | 13.0 |
| 200 | 16:27:00 | 609 | □ | 0.880 | 32.9 | 13.0 |

Appendix A. Measured Values for the FLIP Experiment, 20 May 2004 (continued).

| **UpTube Length** □<br>□<br>(ft) | Time | **Source Water**<br>Flow<br>(gpm) | <br>Pressure<br>(psi) | **Upwelling**<br>Linear Velocity<br>(m/s) | <br>Salinity<br>(ppt) | <br>Temp.<br>(°C) |
|---|---|---|---|---|---|---|
| □ | | **Seawater** | | □ | | □ |
| 200 | 16:27:15 | 618 | □ | 0.743 | 33.0 | 13.0 |
| 200 | 16:27:30 | 616 | □ | 0.932 | 32.9 | 12.8 |
| 160 | 16:29:00 | 1074 | ~45 | 1.488 | 33.1 | 10.8 |
| 160 | 16:29:15 | 1075 | □ | 1.488 | 33.0 | 14.6 |
| 160 | 16:29:30 | 1074 | □ | 1.387 | 33.2 | 13.4 |
| 160 | 16:29:40 | 1076 | □ | 1.695 | 33.1 | 13.1 |
| 160 | 16:30:00 | 1075 | □ | 1.695 | 33.1 | 13.1 |
| 160 | 16:31:00 | 755 | ~11 | 2.066 | 33.4 | 13.1 |
| 160 | 16:31:10 | 753 | □ | 1.666 | 33.2 | 12.6 |
| 160 | 16:31:20 | 758 | □ | 1.111 | 33.1 | 12.8 |
| 160 | 16:31:35 | 750 | □ | 1.039 | 33.2 | 12.9 |
| 160 | 16:31:45 | 747 | □ | 1.118 | 33.1 | 13.0 |

Appendix B.

## Calculation of Velocity Exiting Vertical Tube

In order to derive the flow rates and kinetic power exiting the upwelling tubes, we utilized the following logic. The points referred to in the following discussion are indicated on Figure B-1. Since there was a continuous tube from Point 1 to Point 3, their salinity and flow rates are identical. Since the only inlets to the vertical tube are from Point 3 and Point 4, the flow rate at Point 2 equals the sum of the flow rates from Point 3 and Point 4.

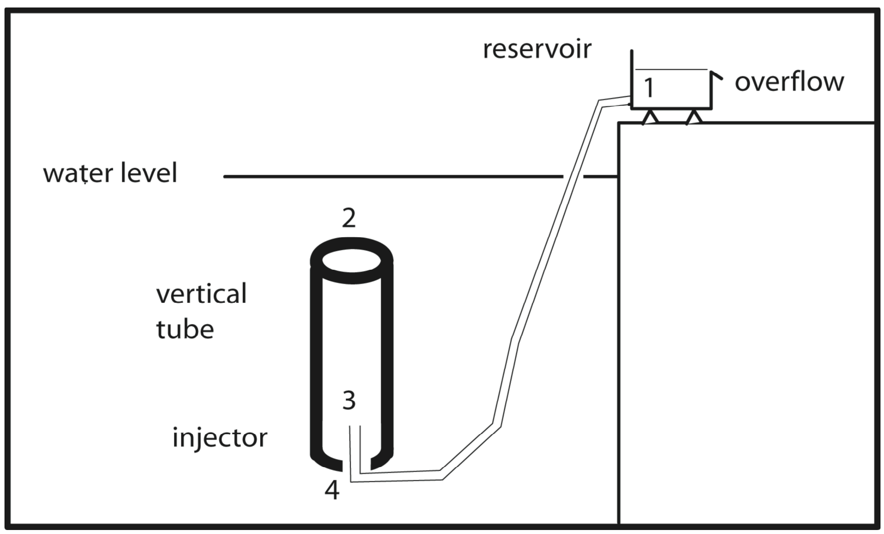


Figure B-1. Diagram of the test configuration.

The equation for the flow rate Point 4 is derived from:
If:

$$Q_i = \textit{Volumetric flow rate at point } i$$
$$= W_T / \rho \textit{ per second} \quad (1)$$
$$S_i = \textit{Salinity at point } i$$
$$= (W_S / W_T) \quad (2)$$
$$W_S = \textit{Weight of Salt in a Solution}$$
$$W_T = \textit{Total Weight of Solution}$$

Then:

$$S_2 = W_{S2} / W_{T2} \quad (3)$$

And since the flow past Point 2 comes from either Point 3 or Point 4:

$$S_2 = (W_{S3} + W_{S4}) / (W_{T3} + W_{T4}) \quad (4)$$

Substituting in:

$$W_S = S\, W_T \quad (5)$$

Results in:

$$S_2 = (S_3 W_{T3} + S_4 W_{T4}) / (W_{T3} + W_{T4}) \quad (6)$$

Substituting in:

$$W_T = Q \rho \ seconds \quad (7)$$

Results in:

$$S_2 = (S_3 Q_3 \rho_3 + S_4 Q_4 \rho_4) / (Q_3 \rho_3 + Q_4 \rho_4) \quad (8)$$

Which gives an equation that has one unknown variable (Q4).

$$Q_4 = Q_3 (\rho_3 / \rho_4) (S_2 - S_3) / (S_4 - S_2) \quad (9)$$

It can be assumed, within the accuracy of this experiment, that:

$$S_3 = 0 \quad (10)$$

and

$$\rho_3 = \rho_4 \quad (11)$$

Which leaves:

$$Q_4 = Q_3 S_2 / (S_4 - S_2) \quad (12)$$

The power values are derived from:
If:

$$A = Cross\ Sectional\ Area$$
$$= \pi d^2 / 4 \quad (13)$$
$$d = Tube\ Diameter$$
$$M_q = Mass\ Flow$$
$$= \rho \times Q \quad (14)$$
$$\rho = 1 + (S_i / 1000) \quad (15)$$
$$v = Fluid\ Velocity$$
$$= Q / A \quad (16)$$

Then:

$$P_k = Power\ from\ Kinetic\ Energy$$
$$= 0.5 M_q v^2 \quad (17)$$
$$= 0.5 (\rho Q)(16 Q^2 / \pi^2 d^4) \quad (18)$$
$$= 8 Q^3 \rho / \pi^2 d^4 \quad (19)$$