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Author
Harms, V.W.

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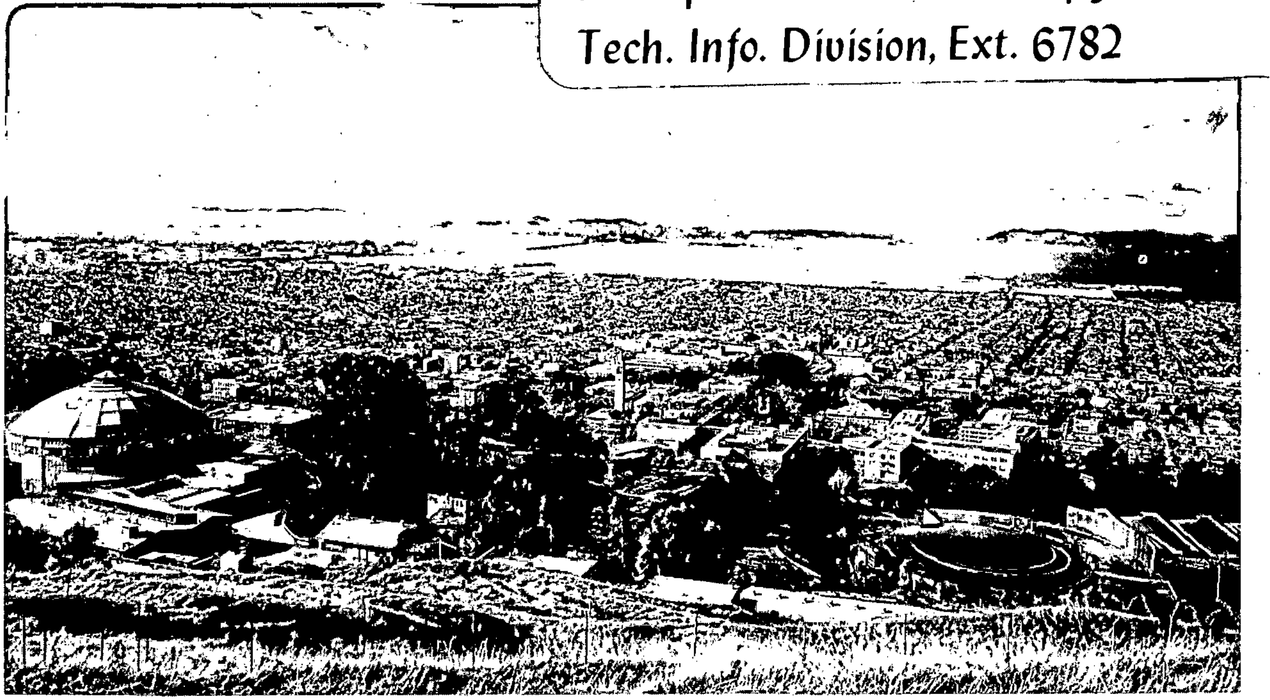

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CURRENT MEASUREMENTS OFF KEAHOLE POINT HAWAII APPLICATION TO OTEC-1 OCEAN TEST PLATFORM

Volker W. Harms

Earth Sciences Division
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

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This work was prepared for the Assistant Secretary for Conservation and Renewable Energy, Office of Solar Power Applications, Division of Ocean Energy Systems, of the U.S. Department of Energy under Contract W-7405-ENG-48.

CURRENT MEASUREMENTS OFF KEAHOLE POINT HAWAII APPLICATION TO OTEC-1 OCEAN TEST PLATFORM

Volker W. Harms

Lawrence Berkeley Laboratory
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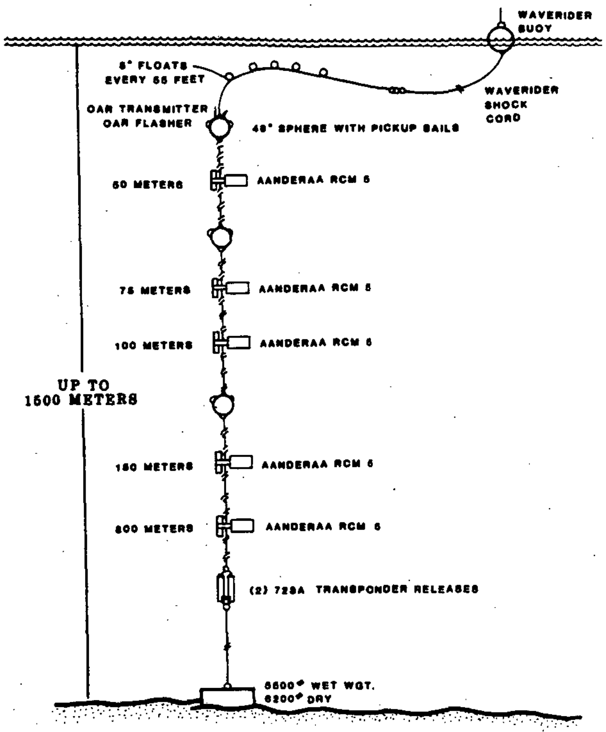
The importance of detailed current measurements at sites of major ocean engineering projects such as OTEC (Ocean Thermal Energy Conversion), is generally well recognized. The relevance of such measurements to at-sea OTEC operations, and engineering design, can be vividly demonstrated and more fully appreciated by analyzing time-series data records from recent deployment of the OTEC-1 ocean test platform (October 1980-April 1981). Data from the OTEC-1 vessel, a converted T-2 tanker that was renamed "Ocean Energy Converter", is presently becoming available and permits a preliminary analysis to be made of current-induced hydrodynamic loads on the cold water pipe (CWP) and hydrodynamic mixing along the trajectory of the mixed sea-water plume (1)(2)(3)(4), and is the subject of this paper.

It should be noted that some of the force data acquired via the OTEC-1 onboard data acquisition system is suspect (possibly influenced by errors in calibration procedure zero shift, etc.) and has only been utilized when cross-verification among several parameters was possible. Therefore, in view of this and the simplifying assumptions used in the pipe-drag analysis, the findings of this paper should be treated as preliminary. An in-depth report of OTEC-1 test results is to follow after the final data products have been received and analyzed (3). A summary of current conditions at the OTEC-1 site (Hawaii OTEC) and the Punta Tuna site (Puerto Rico OTEC) may be found elsewhere in these proceedings.

Two major episodes of strong near-surface currents were recorded at the OTEC-1 site off Keahole Point Hawaii, using taut moored current meter arrays located in 1346 m of water, just outside the OTEC-1 drift circle and approximately 4 km from the location of the OTEC-1 mass anchor (Figure 1) A typical array is shown in Figure 2 and consists of five Aandera RCM-5 current meters, a wave-recording surface buoy, three buoyancy spheres, dual acoustically-triggered releases and a mass anchor. Currents at the OTEC-1 site were measured from 26 June 1980 to 14 April 1981. This represents four separate deployments; retrieval and redeployment of the array was accomplished on 20 July, 19 September and 20 December 1980. The first, and most severe of the high-speed events, occurred during the month of September when the upper current meter at a depth of 56 m registered current speeds in excess of 103 cm/sec (2.0 knots) for 14 consecutive days starting 5 September 1980,



MOORING DESIGN FOR OTEC-1
PRIMARY CURRENT METER MOORING

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Figure 1.

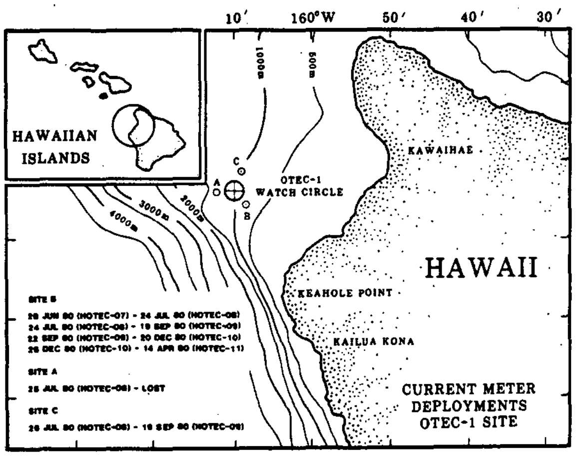

Figure 2.

and reached a maximum of 152 cm/sec (3.0 knots) on 7 September 1980. In retrospect, one must be thankful for the delay that prevented the OTEC-1 vessel from being on-station in September. The vessel was finally deployed during the last week of October, a time that very benign current conditions once more prevailed and the earlier ocean "storm" had been completely, and fortuitously, avoided. During the second high-current episode this was not so because the platform was on station and operating in the OTEC mode. But fortunately this event (February-March 1981) was also of lesser intensity: daily current-speed maxima larger than 51 cm/sec (1.0 knots) were registered for 15 consecutive days (starting 24 February 1981) but did not exceed 92 cm/sec (1.8 knots). The strongest surface current during this episode was experienced on 4 March 1981 and is shown in Figures 3 and 4. Although a 1.8-knot surface current appears rather mild compared to the earlier 3-knot event, hydrodynamic loads on the CWP were sufficiently large to demand drastic action by the ship's operators (ETEC, Tracor) in order to prevent structural failure of the pipe. The gimbal attaching the CWP to the OTEC-1 hull permits a maximum deflection of 30°, in either port-starboard or fore-aft direction as shown in Figure 5. This limit was being approached on 4 March 1981 and, with increasing current-induced forces on the pipe, it had to be anticipated that excessive bending and strain near the gimbal end would make failure of the CWP imminent. During this critical period the OTEC-1 vessel was at a stable position downstream of the moor, well aligned with and heading into the current. Gimbal deflections therefore took place predominantly in the fore-aft vertical plane, as shown in the schematic of Figure 6 where β designates this angle and is referred to as the gimbal pitch angle, i.e., the pipe trailed aft with only negligible port-starboard deflections.

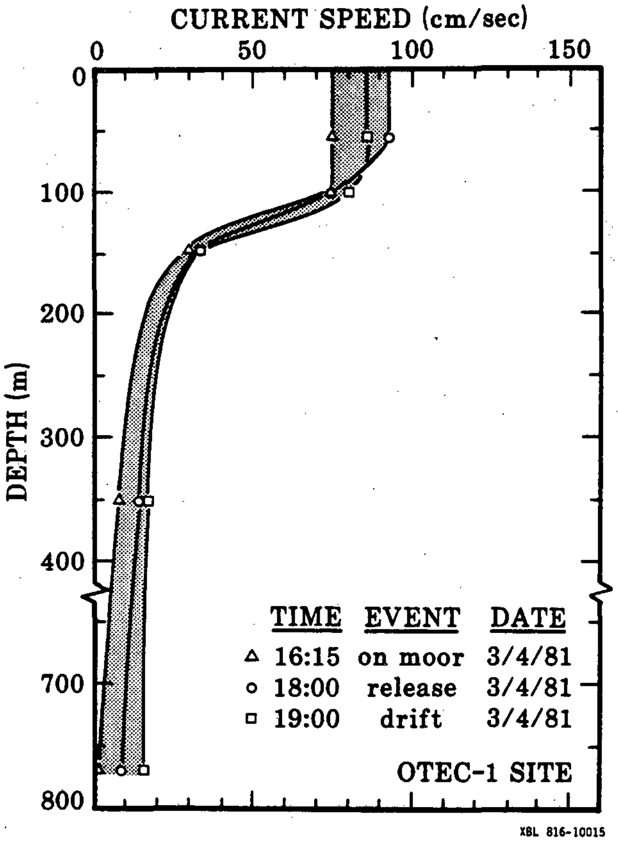

Figure 3.

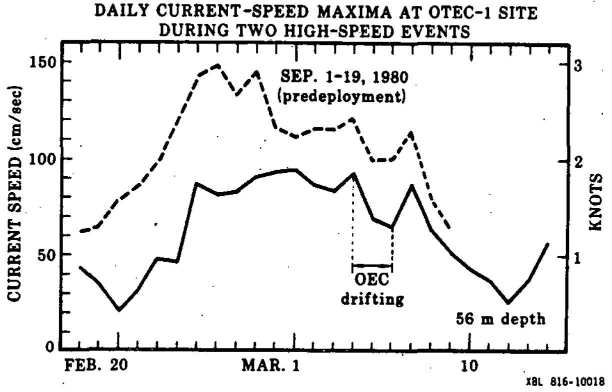

Figure 4.

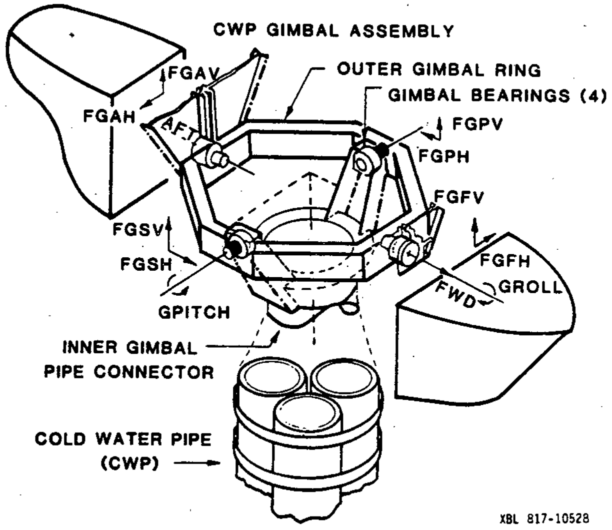

Figure 5.

Gimbal pitch angles reached critical levels around 18 00 hours on March 4 when the pipe actually came in contact with the gimbal stops. Under the circumstances it was decided to separate from the moor and let the OTEC-1 test platform, with pipe attached, drift in the northerly flowing current; this reduces hydrodynamic loads on the CWP very substantially because it lowers the relative velocity between cold-water pipe and the surrounding water mass. The mooring line release mechanism was tripped at 18:05 hours and the OTEC-1 vessel, with CWP attached and sea-water pumps operating, proceeded to drift in a northerly direction. The position of the "grazing" OTEC-1 vessel was monitored using the onboard range-range electronic position-locating system (with shore stations installed near Kawaihae on the island of Hawaii) Ship logs indicate that the vessel drifted in a northerly direction at a rate of 45 21 and 21 cm/sec for the first, second and third hour after release, respectively, and more slowly thereafter. By 12 00 hours of the next day the vessel was 5 3 miles north of the moor, its farthest excursion, and currents had decreased substantially. It was therefore decided to return to the moor under "dead slow" marine power. This was accomplished by "driving" the vessel south against the current at a speed that would produce a gimbal angle just less than the maximum allowable; this turned out to be approximately 14 cm/sec (0.3 knots) relative to land, and 70 cm/sec (1.4 knots) with respect to the surface current flowing north.

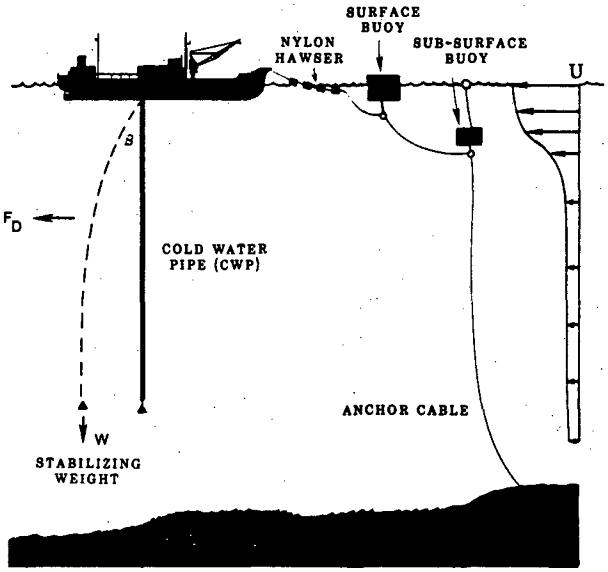

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Figure 6.

In Figure 7, the current profile responsible for the above described sequence of events is compared to the 3 knot predeployment episode of September 1981. Inspection of this figure indicates that nature was really rather kind to us in March of 1980. Not only were surface speeds substantially higher during the September event, but greater depth penetration of the high-speed layer is also evident. In either case we note that the speed decreases to approximately one half as the depth is increased from 50m to 140m.

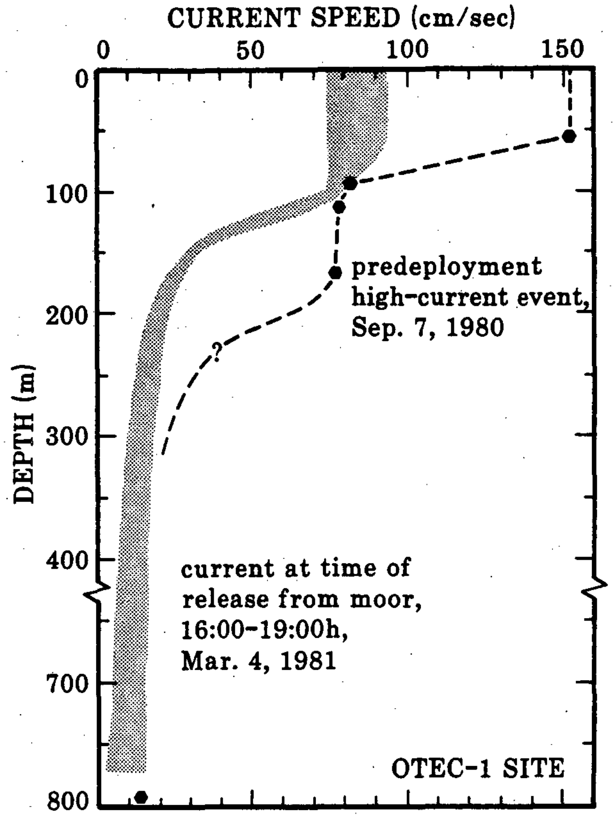

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Figure 7.

The variation of surface currents with time, over some 30 days centered around the drifting event, is shown in Figure 8 alongside vessel heading, gimbal pitch angle and mooring line tension. The indicated levels of mooring line tension (uncorrected output from the onboard data acquisition system) are probably too large by a factor of 2.5, based upon instrument readings of 80,000 pounds made and recollected by several members of

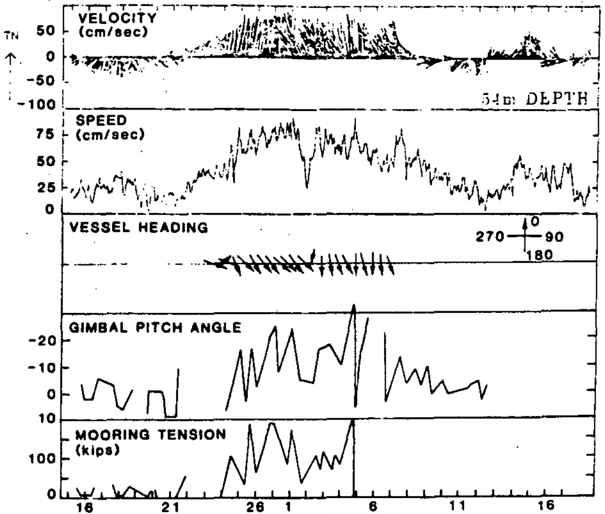

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Figure 8.

the OTEC-1 technical staff at the time of release (4). The variation in gimbal pitch angle, as well as time histories of current speed and direction and vessel heading, are shown in greater detail in Figure 9 for the 50 hours preceding release. Interpretation of this data, and the underlying cause-effect relationship between ocean currents and vessel/CWP response, is made easier because of the following circumstances prevailing on 4 March 1981:

(1) Currents were flowing essentially from S to N and the OTEC-1 vessel was well aligned with this current, heading S;

(2) Low wind speeds (less than 5 knots) and mild seas (less than 2m) prevailed;

(3) Current direction did not change appreciably with depth (range: 328°-024° over depth of 800m);

(4) The CWP was streaming aft with only negligible deflections in roll.

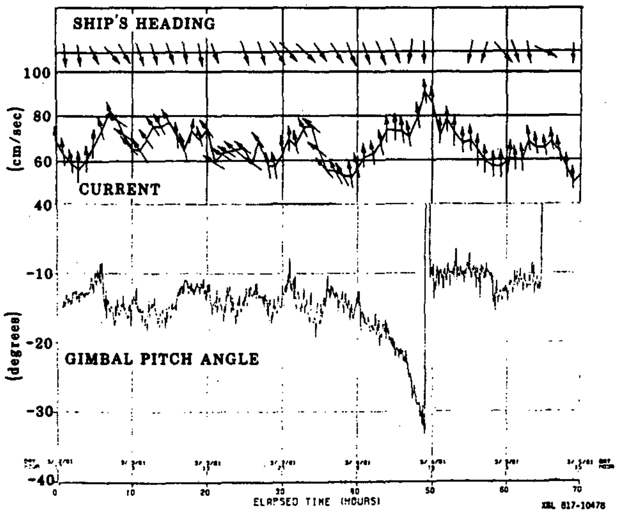

Figure 9.

However, at the same time, interpretation and reconciliation of onboard-data records is presently still complicated by factors such as (1) lack of information on the use of the vessels two 1000 hp rotatable propeller thrusters. With an estimated combined thrust of 50,000 pounds, these could produce substantial ship motions and would alter forces acting on the CWP, OTEC-1 hull and the mooring line; (2) force-transducer output signals that are inconsistent, cannot be reconciled between themselves, or are not physically reasonable, e.g., some gimbal-force components and the mooring tension signal. The source of many of these problems can probably be isolated and corrected with even a moderate data-reduction and verification effort (which has not been possible to date); (3) a variety of ship maneuvers while on the moor, as for example, ballasting the vessel to produce a list of 18° (in roll) during the February-March high current event.

Nevertheless, by detailed inspection of the available time-series data records, it was possible to select time periods during which a number of important parameters give every indication of being reliable and consistent and are, at the same time, amenable to analysis and interpretation. An example of this is the "calm event" of 19 February 1981, which is listed as Event 1 in Table 1. This "calm" condition was sought in order to verify that the output from gimbal force and deflection transducers was, in fact, physically credible, i.e., in the absence of wind, waves and ocean currents the CWP pipe should hang vertically ($\beta = 0$) and horizontal forces on the gimbal should vanish. Event 1 of Table 1 approaches the ideal zero-load reference condition for the CWP and gimbal: currents were very low at 6 cm/sec (0.1 knot), wind speed did not exceed 3 knots and the significant wave height was less than 1.5 meters. The following parameters were generally scrutinized and correlated in order to select "favorable events" such as those listed in Table 1: gimbal vertical load (forward, aft, port, starboard), gimbal horizontal load (forward, aft, port starboard) gimbal pitch angle, gimbal roll angle, ship's pitch angle, ship's roll angle, mooring line tension, wind speed and direction, ship's heading, wave height, displacement and bearing of CWP end. Inspection of Event 1 in Table 1 indicates that gimbal pitch and roll angles are very reasonable, and probably would have been within a degree of zero if there had been less wave action; more than anything else, the values shown reflect pitching and rolling of the vessel about a stationary vertical CWP (with wave-induced rolling typically exceeding pitch, as is the case here). The horizontal forces registered on the port and starboard gimbal pins, on the other hand, are certainly in error: residuals of 13 and 26 kips represent either a hefty zero shift or spurious output from a faulty instrument (kips = kilo pounds = 1000 pounds). The forward and aft pins are fortunately more reliable, at least in the horizontal direction, approaching the expected zero reference level to within 0.5 and 1.5 kips, respectively. Note that for all events listed in Table 1, except the first, the surface current is flowing towards the north (ranging from 326°-010° True) and the vessel points south (162°-185° true). Furthermore, the events have been arranged in order of increasing ocean-current severity, with the CWP trailing aft at increasingly larger angles, i.e., gimbal pitch angles of 0°, -10°, -11°, -16°, -24° and -30° (the negative sign indicating that the CWP is streaming aft, not forward). Event 6 is the "release event", i.e., conditions during the last hour before release of the moor on 4 March 1981. Event 3 is the drifting episode and covers the first three hours after dropping the mooring line. Event 5 corresponds to the time that the vessel was returning to the moor under "dead slow" marine power.

The fact that the OTEC-1 vessel was forced into "drifting-mode" operation because of large

			(1)		(2)	(2)	(3)		(7)	(2)	(5)				(4)	(5)	(6)
Event No.	Date 1981	Time (hours)	Surface Current (cm/sec)	(°True)	Wind (knts)	Vessel Headg (°True)	Gimbal Angle Pitch (deg)	Roll (deg)	Line Tension (kips)*	Wind From (°True)	Horizontal Gimbal Loads PORT (kips)	STBD (kips)	FWD (kips)	AFT (kips)	Pipe Drag Wtanβ (kips)	FWD+AFT (kips)	Equ.(4) (kips)
1	2/19	14-16	6	180±70	1±2	325	0±1	-4±1	20±5	200	13±1	-26±1	-0.5	1.5	±2	0	—
2	2/25	15-18	74	010	5	165	-10^{+2}_{-1}	-3±1	70±10	120±50	12±1	-26±1	1±3	2±5	18	∿1	11
3	3/4	19-21	77	340	2±1	179	-11±2	1±2	—	≈190	11±1	-26±1	-7^{+3}_{-4}	10^{+6}_{-4}	20	∿17	—
4	3/3	06-08	76	326	6±2	162	-16±1	0±3	90±20	100±10	11±1	-26±1	-4±3	6±7	30	∿10	12
5	3/5	12-14	55	350	4±2	185	-24±1	(10±2)	—	280	15±2	-31±2	-14±6	20±12	47	∿34	13
6	3/4	18:00	93	347	5	179	-30±2	(18)	180±10	199	16±1	-30±4	-22±4	30±5	61	∿52	14

Legand/Data Source: (1) From moored current-meter array, 54 m depth; flow towards direction shown. (2) From OTEC-1 Onboard Environmental Data Log; wind direction is "from". (3) From preliminary time-series plots provided by ETEC. Negative pitch angle implies pipe trailing aft. (4) From measured values of pitch angle (β), wet pipe weight (W) of 105 kips and Drag - Wtanβ. (5) From output of gimbal horizontal load cells (precision and reliability questionable). (6) Pipe drag based on measured current profile (current meters at 54, 100, 147, 350 and 771 m), with D = 2.4 m and assuming C_d = 0.5 in Equation (4). (7) Most probably exaggerated by a factor of 2.5 (for Event 6, a tension of 80 kips was logged on the bridge).

*1 kip = 1000 pounds

Table 1. OTEC-1 Response to Ocean Currents

CWP hydrodynamic loads, and this during current conditions not unusual for the site is sufficiently serious to warrant investigation (even at a preliminary level) of drag forces actually experienced by the pipe during this event and others. In particular, measured pipe drag forces and measured ocean current profiles must still be determined to substantiate the design assumption that "Above Reynold's Number of 0.6×10^6, the drag coefficient was estimated to be 0.5 or less" (6). An approximate value for the total horizontal force acting on the CWP was obtained by applying the equations of static equilibrium to the CWP and gimbal, using the following assumptions in this elementary analysis: (1) The flow is steady, and static conditions prevail for the OTEC-1 vessel and the CWP. (2) The CWP, which is actually a cluster of three 4′-diameter polyethylene pipes, may be treated as a single 8′-diameter uniform slender member of negligible stiffness, i.e., similar to a rope. (3) The total wet weight of the CWP assembly (net negative buoyancy) is 105 kips and is concentrated at the location of the stabilizing weight. The actual wet weight of the stabilizing weight was 132 kips, with lift from the buoyancy collar and polethelene pipes making up the difference. (4) The CWP trails aft with gimbal pitch angle β, and negligible roll angle.

Under these conditions, a simple force balance of the CWP indicates that the drag force, F_D, is related to gimbal pitch angle β, and stabilizing weight, W, (both measured values) by

$$F_D = W \tan \beta \qquad (1)$$

This relationship was evaluated for the cases given in Table 1 (using W = 105 kips), with results shown in the second to last column of that table. Pipe drag forces calculated in this manner have been found to be somewhat lower than those obtained through application of more precise stepped-beam structural models such as the HULL-GM finite-difference computer code (7); the values of W tan β in Table 1 should therefore normally err on the low side

Although based upon measurements, the above technique for evaluating pipe drag forces involves assumptions and errors that can be avoided if drag forces are measured directly as, in the case of OTEC-1, by strain-gauge force transducers mounted on the gimbal. Pipe drag forces registered by these load cells are listed in Table 1 under the heading "Horizontal Gimbal Loads", and refer to the four gimbal pins shown in Figure 5. Since these strain-gauge load cells were designed to respond only to bending of the pins, not compression, it follows that the port and starboard pins are the ones that should measure CWP drag when the pipe is streaming aft. Inspection of Table 1 indicates that this is not the case. In fact, horizontal loads on the starboard pin effectively do not change as the gimbal pitch angle increases from 0° to 30°, and neither the port nor starboard horizontal loads show credible trends or magnitudes. In addition to evident zero shifts (13 and 26 kips, respectively), it would have to be concluded that both instruments were actually malfunctioning and that their outputs should be discarded, unless one admits to the possibility of a switch in port-starboard and fore-aft signals. Just such a reversal appears to be indicated by the horizontal loads registered on forward and aft gimbal pins: they should remain near zero but, instead, increase substantially with gimbal pitch angle as one would expect of the drag force. It will therefore be assumed that a mix-up of signals actually did take place. CWP drag forces should consequently be sought under the heading of FWD and AFT under Pipe Drag in Table 1 their sum, the total CWP drag load, is listed in the next to last column Although it was at times difficult to obtain precise values from the FWD and AFT analog force records, it can be seen that the total drag force based on these readings (next to last column of Table 1) agrees at least in trend with those obtained from Equation (1) and, for the largest gimbal angle, is even reasonable in magnitude (52 versus 61 kips).

Drag forces on the CWP may also be calculated from the classical steady-state drag formula for immersed bodies,

$$F = C_d \cdot 1/2\rho V^2 \cdot A \qquad (2)$$

where C_d is the drag coefficient that must generally be determined experimentally, $1/2\ V^2$ is the dynamic pressure and A is the frontal area of the immersed object. Assuming for the moment that C_d is known and does not change with distance along the pipe (i.e., as current speed and Reynold′s number change), then Equation (2) can be used to calculate the total drag force, F, because both ocean current profile and pipe frontal area are known. Since five current meters were used to define the current profile (at depths of 56 100, 147, 350 and 771 m), it was also convenient to treat the pipe in five segments: starting from the OTEC-1 hull, their lengths are 49, 44, 47, 203 and 343 m, and with each we associate a single velocity, the average current speed over that segment Accordingly, we may write Equation (2) as

$$F_D = C_d \cdot 1/2\rho D \cdot \sum_{i=1}^{5} l_i V_i^2 \qquad (3)$$

where, is the seawater density, D the effective diameter of CWP, V_i the current speed for pipe segment number i, l_i the length of CWP segment i and, C_d the drag coefficient which is assumed independent of Reynold′s number over the range encountered. Using a value of D = 2.44 m, = 1033 kg/m^3 and C_d = 0 5 as recommended for flow at right angles to one of the sides of the pipe triad (the only hydrodynamically stable orientation) (6), the drag force (in kg-force) becomes

$$F_D = 63.2 \sum l_i V_i^2 \qquad (4)$$

Table 2. Depth-Averaged Dynamic Pressure on CWP
(18:00 hours, 4 March 1981)

Current Meter No.	CWP Segment No.	Ocean Current (cm/sec)	(°True)	Length L_i (m)	Speed V_i (cm/sec)	Re# 10^5	$L_i V_i^2$ (m^3/sec^2)
0		--	--				
	1			49	93.0	24	42.4
1		93.0	347				
	2			44	84.0	22	31.0
2		75.0	345				
	3			47	53.9	14	13.7
3		32.7	328				
	4			203	23.6	6	11.3
4		14.6	339				
	5			343	11.9	3	4.9
5		9.2	024				
							Σ = 103.2

Evaluation of the $l_i V_i^2$-terms is demonstrated in Table 2 for the release event of 4 March 1981. It should be noted that a unidirectional current, unchanging with depth, has been assumed in the analysis, and is well justified since current direction only varied from 328° to 024° over a depth of 800m. The variation of drag force with depth is indicated by the value of $L_i V_i^2$ for each segment. For the case of Table 2, for example, 41% of the total drag load originated in the upper 49m segment, and 71% of the total can be attributed to the upper two segments with combined length of 93 m. The value of 103.2 m^3/sec^2 in Table 2 is a measure of the depth-averaged dynamic pressure on the CWP for the current profile prevailing at the time (Figure 3). Using this value in Equation (4), and a drag coefficient of 0.5, one obtains the CWP drag force that this current should generate: this turns out to be 6,500 kg or 14 kips, and has been entered as Event 6 in the last column of Table 1. The same procedure was followed for the other cases, except that an additional uniform flow had to be imposed on the ocean-current profile of Event 5 in order to correct for the speed of the vessel during its return to the moor on 5 March (approximately 14 cm/sec, relative to land). The sequence of drag forces shown in the last column, although substantially lower than those listed in the other two columns, particularly at large gimbal angles, is a useful indicator of the range of ocean-current strengths encountered (since everything but the current remained constant in Equation (4)): a drag-force increase of 30%, from 11 kips for Event 2 to 14 kips for Event 6, indicates that the strength of the ocean flow field also did not increase by much more than 30% during this period. The gimbal pitch angle, on the other hand, increased three fold during the same period, from 10° to 30°, and horizontal gimbal loads more than that! From this and what follows, it becomes clear that the use of a single C_d-value in Equation (4) is inconsistent with the measured drag forces of Table 1 because (1) If a sufficiently large value of C_d is chosen to provide reasonable agreement for the strongest current case (Event 6 with $\beta = 30°$), then the drag force for the weakest current (Event 2, $\beta = 10°$) would be unrealistically large at approximately 44 kips. (2) If C_d is evaluated at the low-current end (Event 2), then the drag prediction for the high-speed case (Event 6) will be so low as to be inconsistent with $\beta = 30°$. (3) If the measured drag force $F_D = W \tan \beta$ is used in Equation (3), then the required C_D-values for Events 2, 4, 5 and 6 turn out to be C_d = 0.8 1.2, 1.7 and 2.1; with weighed, representative Reynold′s numbers of 14, 14, 13 and 19 x 10^5, respectively.

In view of the above, and inspection of the pipe-drag data in Table 1, it is concluded that actual CWP drag coefficients must have been substantially higher than 0.5 (the value apparently used for CWP design purposes). What is this to be attributed to? Our first choice would probably be "an error in current measurments" since this would restore our desire for harmony most rapidly and easily. Alas, there are no grounds for doing so; the same current meters have performed reliably for nearly a year during four separate deployments at the OTEC-1 site and additionally, the uppermost meter of the array was checked against the OTEC-1 onboard current meter (Neil-Brown Instruments) and found to be in good agreement. It should be noted that current-speed estimates made by tracking object is floating near the OTEC-1 hull are generally unreliable and deceptive, and can be far larger than actual because they tend to measure the vessel-induced flow field and not the freestream current. The problem is compounded if the vessel is yawed with respect to the oncoming current and if thrusters are operating at the same time. If the ocean-current data is accepted as being accurate then the reason for excessive CWP hydrodynamic loads can only lie within the CWP-assembly itself. Under the circumstances, it is relatively safe to speculate about potential causes since the CWP was monitored only with respect to (a) angles and forces at the top end and (b) horizontal displacement of the bottom end, and little is known in between. The following should be seriously considered as potential contributors to the problem:

(1) Pipe Flaring
Loose nylon straps allow the pipe cluster to flare into a 3-pipe arc with larger frontal area and drag coefficient than the original pipe cluster. CWP flaring would probably vary with speed (continuously or abruptly) and position along the pipe.

(2) Reynold's Number Influence
Drag coefficients for a 3-pipe cluster were apparently determined in the laboratory up to a Reynold's number of 6×10^5 (6). The OTEC-1 field data applies to a loosely-strapped cluster and lies at higher Reynold's numbers, effectively between 14 and 19×10^5. It is not known what C_d to expect in that range particularly if motion between pipes is substantial.

(3) Stabilizing Weight
If portions of the stabilizing weight were lost, then the CWP would respond to a given current with far larger gimbal angles than anticipated. This should not affect horizontal gimbal loads (next to last column in Table 1).

(4) Vortex-Induced Oscillations
Vortex shedding can excite the CWP into transverse oscillations and thereby increase steady-state drag forces substantially.

(5) Vessel Drift
The action of aerodynamic forces and two rotatable propeller thrusters can cause the vessel to drift about the moor, thereby generating an additional current with respect to the pipe Although this current is probably small (say less than 15 cm/sec) it extends over the whole length of the pipe. It is estimated that a 30-knot wind would generate a drag force of 9,000 lbs if blowing in the fore-aft direction and 54 000 lbs if blowing broadside. Frictional drag on the wetted hull is comparatively small for our cases with the vessel aligned with the current: less than 4,000 lbs. for a 3-knot current.

Based on the preliminary data presented, it is concluded that cold-water-pipe drag forces attained levels of at least 50 000 to 60 000 pounds on 4 March 1981 when surface currents reached 1.8 knots and pipe deflections at the gimbal reached 30°. Such drag forces are consistent with mooring-line tensions of approximately 80 000 pounds reported during that time, i.e., the sum of CWP drag force and OTEC-1 extraneous loads (hull frictional drag, thruster action, etc.) should approximately equal the mooring-line load. Steady-state drag formula indicate that CWP drag coefficients must have been far larger than 0.5 in order to generate such large loads. Currents with surface speeds of 3 knots should be expected at least annually at the OTEC-1 site: hydrodynamic loads on the CWP would then be two or three times larger than those experienced during the 1.8-knot mooring-release event of 4 March 1981.

The Lawrence Berkeley Laboratory (LBL) carries out shipboard measurement programs to provide baseline physical, chemical and biological oceanographic data at potential OTEC sites. One of the goals of this program is the assessment of environmental effects associated with the OTEC-1 mixed-sea-water discharge which consists of approximately equal portions of nutrient-rich cold water (5°C) and warm surface water (25°C), and was intermittently chlorinated to control biofouling within the heat exchangers. A plume survey was undertaken for LBL by the University of Hawaii during 11-12 April 1981, in order to (a) see if the thermal plume could be found and tracked, (b) determine dilution rates along the plume trajectory and, if possible, map the physical extent of the plume, and (c) carry out a biological and water-quality sampling program both within and outside of the seawater plume. This difficult effort was largely successful a detailed description of the field program and results are given by Noda (2). It is here only intended to compare mixing rates and plume equilibrium levels as obtained from buoyant-jet analytical models and actual field measurements.

The OTEC-1 vessel and sea water system are shown in Figure 10; the vessel is 160 m long with a beam of 21 m and draft of about 8 m. Warm water is drawn in at the bottom of the hull and cold water from a depth of approximately 693 m by the cold water pipe. After flowing through the OTEC evaporator and condenser, respectively, they pass into the mixed-water discharge sump and are then normally ejected via the vertical discharge pipe (up to 70 m in length). Structural failures of the flexible discharge pipe had necessitated aban-

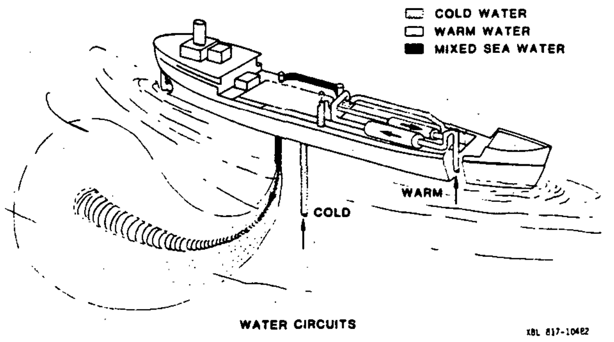

Figure 10.

donment of that concept and, instead, the mixed seawater was now discharged vertically downward from a 1.8 m diameter round port at the bottom of the hull. Typical discharge rates were about 9.8 m^3/sec during the plume survey, with exit velocity of about 3.7 m/sec and exit temperature approximately 7°C lower than ambient for the case here considered. The use of expendable bathythermographs (XBT's) for plume detection was not successful due to the small temperature signal involved, but did indicate unusual near-surface temperature distributions (no mixed layer, or very thin) as shown in Figure 11. Ocean currents were recorded throughout the plume study with the OTEC-1 onboard current meter (Neil-Brown acoustic) lowered to a depth of 30 m; currents were relatively low with an average speed of approximately 30 cm/sec, as shown in Figure 12. Predicted plume trajectory and dilution-along-trajectory are shown in the left-hand portion of Figure 13 for the case corresponding most nearly to conditions around noon of 11 April 1981, i.e., mixed-layer depth of 30 m and uniform current 30 cm/sec. The analytical model used to predict the behavior of the negatively buoyant sea-water jet was provided by B. Safaie (State University of New York, Buffalo, New York) and is based upon the work of Hirst (8). It is a three-dimensional model in which the equations of motion are solved using similarity and entrainment assumptions and the integral approach, and is applicable to the near-field region where jet momentum dominates the dynamics of the flow. Inspection of Figure 13 indicates that the jet would be expected to descend very rapidly, reaching its 30m equilibrium depth at a horizontal distance of only 10 m from the discharge and attaining a center-line dilution ratio of between 10 and 15 at that point. The dilution ratios are shown in circles (those along the trajectory are theoretical and those to the right are measured) and represent the ratio of dye concentration at the discharge to maximum dye concentration at the location under consideration. Rhodamine WT dye was used as the tracer and detection was accomplished with a Turner Model 3 fluorometer with continuous flow attachment (and a submerged seawater pump). Once the sea water plume reaches its equilibrium depth it has lost all characteristics of a jet since its momentum now differs little from the surrounding waters. It is now conceptually more helpful to think of a cloud of dyed water being convected by the current and undergoing mixing at a rate governed by the prevailing ocean turbulence, which is generally very small compared to the mixing accomplished during the jet phase. The measured dilution ratios of Figure 13 and their locations indicate very reasonable agreement with predicted values. Note that meas-

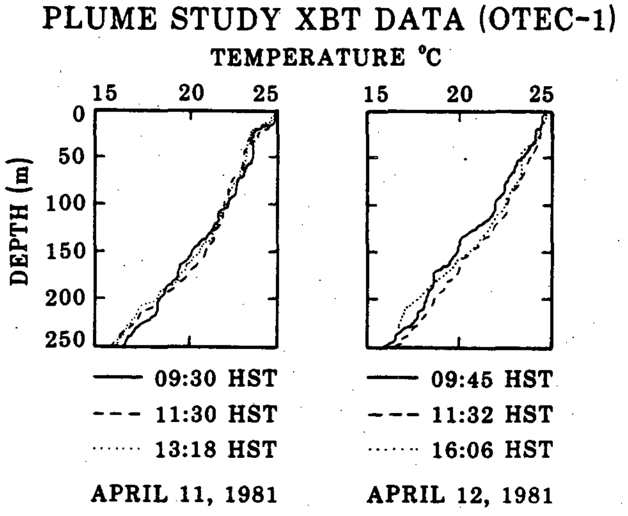

Figure 11.

XBL 817-10480

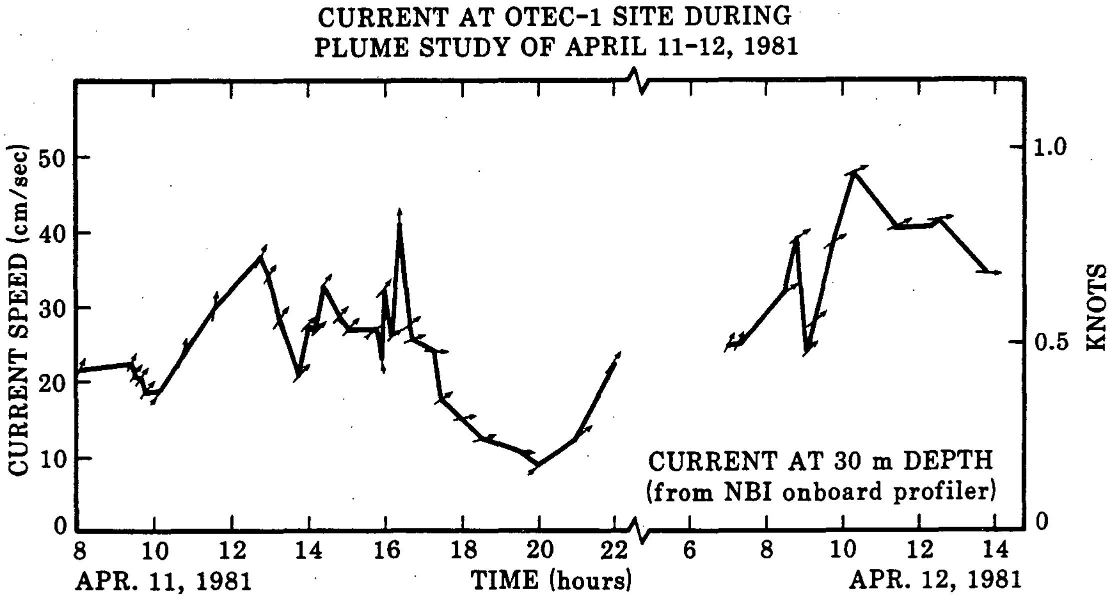

Figure 12.

XBL 816-10019

ured dilutions are always based upon maximum dye concentrations at a given location, and may therefore be compared to the theoretical center-line dilution ratios shown along the trajectory. The following observations summarize our findings:

(1) The measured equilibrium depth of the OTEC-1 sea water plume agrees well with that predicted by the plume model, and occurs near the base of the ocean mixed layer.

(2) Dilution ratios of between 10 and 12 were measured within a horizontal distance of 50 m from the discharge (depth 23-45 m) and agree reasonable with predicted values of 10 to 15.

(3) Dilutions of 14 to 17 were measured at horizontal distances of 75-140 m from the discharge, and indicates that ocean turbulence has provided some additional mixing.

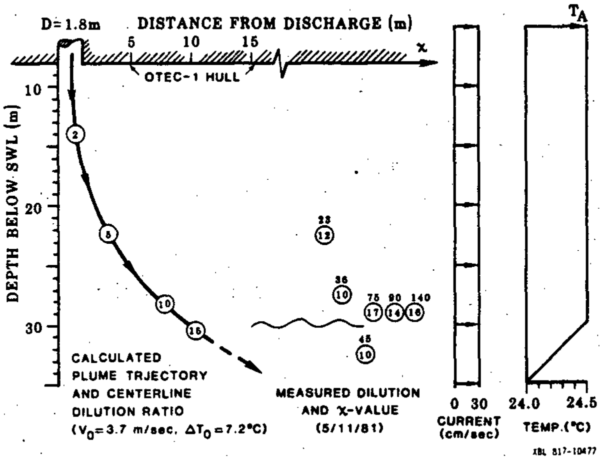

Figure 13.

ACKNOWLEDGEMENT

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LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720