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STUDIES OF BIOFOULING IN OCEAN THERMAL ENERGY CONVERSION PLANTS *

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ABSTRACT

Ocean Thermal Energy Conversion (OTEC) plants will require large heat exchangers carrying immense quantities of seawater. The inevitable biofouling of the heat transfer surfaces will rapidly reduce the efficiency of such plants below acceptable levels unless suitable measures are taken. A group at Carnegie-Mellon University, in collaboration with one at the University of Hawaii, has begun a study, in the waters off Keahole Point, on the Big Island of Hawaii, of the problem of biofouling in simulated heat exchanger tubes under OTEC conditions.

One series of experiments was conducted with the apparatus mounted on a moored boat in the interval July-September 1976. In these experiments, water was pumped up to the apparatus from a depth of 20 feet. The tube was 1" ID aluminum, 8-1/2 feet long. Studies were conducted at nominal flow velocities of 3 and 6 feet per second.

At present a second series of experiments is underway. In these, the apparatus is mounted on a submarine buoy at a depth of about 50 feet. Three experiments are in progress. Two of these nominally duplicate the conditions described above. In the third, a similar titanium tube is being used at a velocity of about 6 feet per second.

In this paper we briefly describe the apparatus and methods being used, and discuss in detail the conditions of the experiments. The results of the analysis of the first series of experiments are also presented and discussed. All available preliminary results from the second series are also presented.

I. Introduction

There exists little data which is relevant to the problem of the effects of biofouling on the heat-transfer characteristics in OTEC heat exchangers. We are concerned here with the regime of "Microfouling"; a slime layer only a few thousandths of an inch thick could reduce the heat transfer rates to unbearably low values. Fouling rates are expected to depend on a number of variables: surface material, surface condition, flow velocity, depth, temperature, time of year, location, as well as other details of the system configuration. The economically efficient design of a plant will depend critically on the ability to predict the effects of biofouling on its operation.

For all of these reasons, it is necessary to study biofouling as nearly as possible under OTEC operating conditions. These conditions are not yet well-defined (e.g., what is the optimum velocity?), and indeed will in part be determined by the results of these studies. It is necessary, therefore, to make measurements under a wide range of conditions.

A system has been developed (1) specifically to facilitate the necessary measurements. The system was designed to provide high flexibility in fixing operating conditions, and to have high precision in sensing changes in heat transfer rates due to fouling (better than 1% sensitivity limited by flow velocity determination; potential to go to 0.1% to 0.2% sensitivity under controlled conditions). That these design goals have been met has been confirmed now by extensive laboratory tests, by field tests, and now by over four months of field operation.

The details of the method and the theory of operation have been extensively covered in previous reports and publications (1,2), and we will therefore only briefly discuss these here.

The main parts of the system are shown semi-schematically in Fig. 1. The 1 in. PIPE carries the seawater at a selected velocity which is measured by the FLOWMETER. Not shown is a thermistor, attached to the 1 in. PIPE, to measure the seawater temperature. The heat transfer coefficient, h, from the metal pipe wall to the seawater is measured in the following way. A small amount of heat is applied to the outer surface of the Cu BLOCK raising its temperature an amount ΔT above that of the water. When the heat is turned off, ΔT is observed (after a brief transient) to decay exponentially to zero with a time constant which is approximately inversely proportional to h. The value of ΔT is measured directly by the output of a thermopile whose measuring junctions are embedded in the Cu BLOCK, and whose reference junctions are embedded in the Cu REFERENCE BLOCK which is at seawater temperature. In this way h is determined by measuring the time constant of the thermal decay.

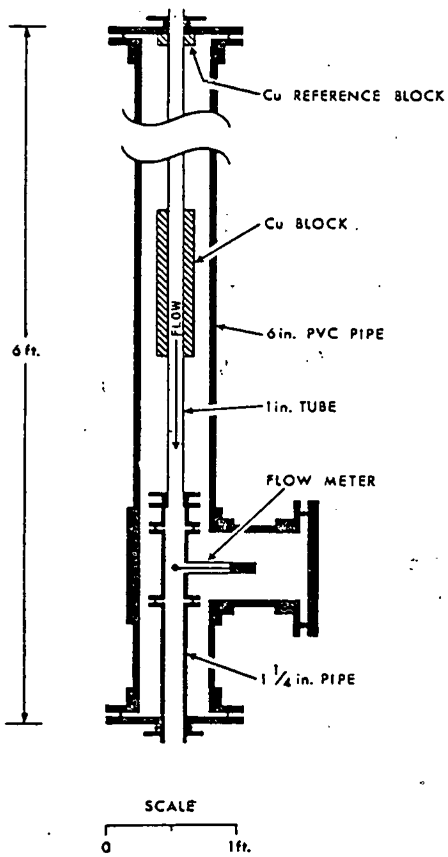


Fig. 1. Biofouling Measurement System

This rather unorthodox method of measuring h has two significant advantages. First, it has inherently high precision for two reasons: the direct measurement of ΔT is done by means of a thermopile, and the other critical aspect of the measurement is time which can be determined to extraordinary precision using quartz clocks. Second, it is insensitive to variations in calibration of all but the flowmeter (which is what at present limits precision).

In the geometry of our system, a power input of 100 watts produces a ΔT of 1°F at a flow velocity of 6 ft/sec (clean tube). Without significant degradation in precision, ΔT may be lowered to 0.1°F with a power input of 10 watts. If desired, ΔT could also be increased.

The system (Fig. 1) is contained in a water-tight PVC housing which helps to prevent variations in ambient conditions (wind, sunlight) from affecting the critical ΔT measurements when the system is operated above surface. The housing is designed also to allow submerged operation at depths to at least 100 feet.

Figure 2 shows how the system of Fig. 1 would be connected to a pump in typical submerged operation. The Throttle Valve is adjusted to achieve the desired flow velocity. Figure 3 and 4 depict a system under test in the laboratory, without the PVC housing.

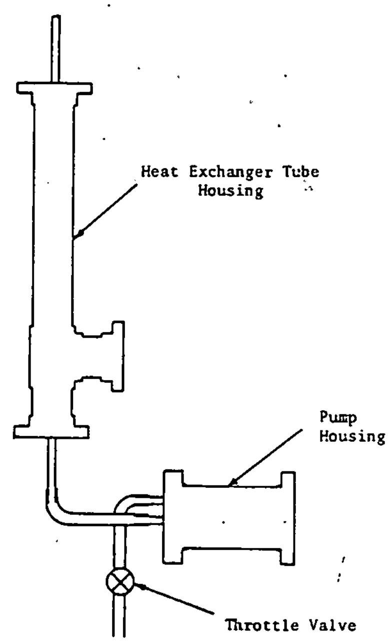
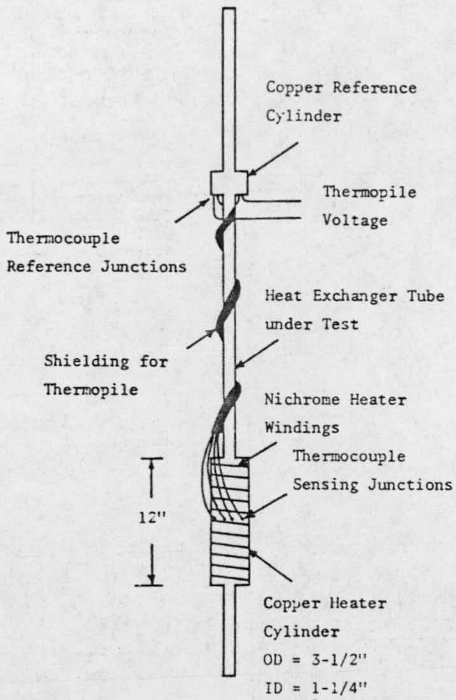


Fig. 2. System Plumbing



Tube with Instrumentation.

Fig. 3. Instrumented Tube

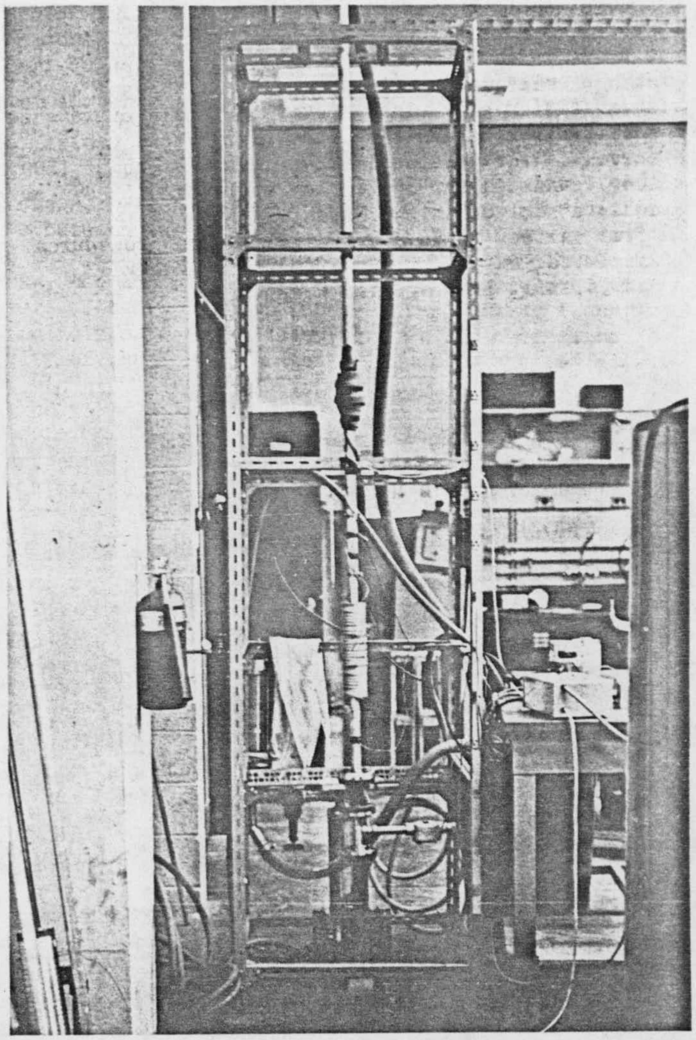


Fig. 4. Laboratory Setup

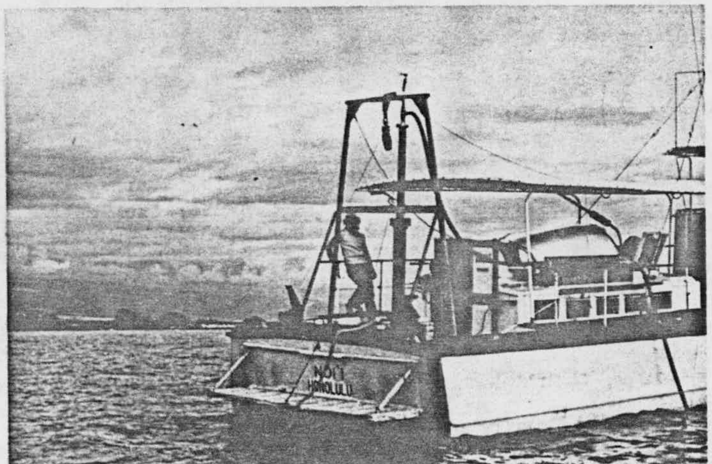


Fig. 5. 3ft/sec Experiment Mounted on NOI'I

II. Field Setup

Two field setups have so far been in operation. In the first, two units (as shown in Fig. 1) were mounted on the deck of a boat (RV NOI'I, U. of Hawaii). Each unit was connected to a pump on the downstream side. The seawater was brought to the system, through approximately 40 feet of 2 in. reinforced plastic hose, from a depth of 20 feet.

Figure 5 shows the NOI'I with one of the two units mounted on the stern. The data acquisition electronics (not visible) is housed in the aft cabin. This system was used for taking data from mid July through September 1976.

In January 1977, a second submerged system was put in place, at about the same location as the first. In this system, up to six units may be mounted on a submarine buoy: Fig. 6 is an underwater photograph of the buoy with 3 units in operation. Figure 7 shows the mooring system in preliminary form. The main difference from reality is that now the electromechanical cable also serves as the mooring line. The cable (about 1500 feet long) connects the system to an electronics system located in a shelter on the beach.

After various tests and initialization procedures were completed, data taking started on February 12, 1977 and is still in progress.

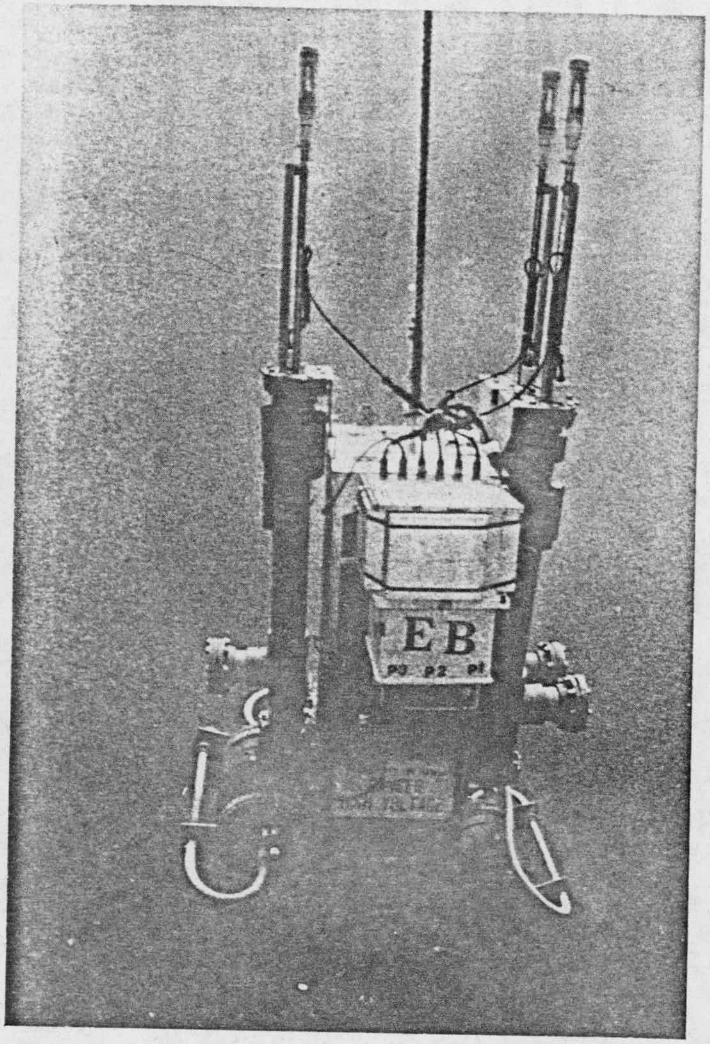


Fig. 6. Keahole Buoy in Operation Feb. 1977

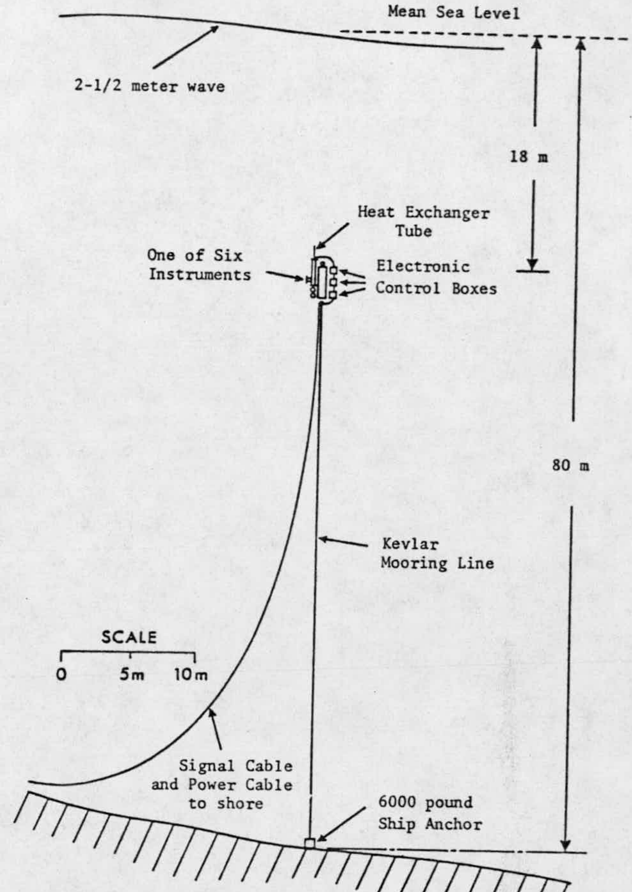


Fig. 7. Buoy Mooring System

III. Data

To date, this system has been used to obtain data using freshwater in the laboratory, seawater from dockside, seawater from the deck of a boat (NOI'I), and seawater using a submerged system. Various checks have been made to ensure that the system operates as it should. Some of these have been described in detail elsewhere (2). Here we mention only the most important.

If, for a clean, smooth tube, h is measured over a range of v, then 1/h should be related to $v^{-0.8}$ as follows

$$1/h = (3.44 \times 10^{-3})/v^{0.8}$$

(with h in BTU/hr ft^{2}°F and v in ft/sec) for fresh water and

$$1/h = (3.64 \times 10^{-3})/v^{0.8}$$

for seawater. We have confirmed, by measurements, that the system yields a linear relationship to high precision. Furthermore, the slope of the line has been shown quantitatively to agree with the semi-empirical theoretical expectation, as shown in Table 1.

TABLE 1

Comparison of slope of 1/h vs. $v^{-0.8}$ for different conditions

Material	Conditions	Slope $\frac{\text{hr ft}^2\,{}^\circ\text{F}(\text{ft/sec})^{0.8}}{\text{BTU}} \times 10^3$
Al	lab	3.44±0.03
90 Cu 10 Ni	lab	3.47±0.01
Ti*	lab	3.45±0.02
Al**	on NOI'I	3.50±0.2
Handbook value (3)		3.44

* Thermal grease used between Cu cylinders and Ti tube.

** Data taken with ocean water. Value quoted is corrected to fresh water properties using h(ocean water) = 0.945±0.008 h(fresh water). See (1).

On board the NOI'I, two units were run. Both used Al 6061-T6 alloy pipes, one at nominal 3 ft/sec velocity (actual 2.9 ft/sec) and the other at nominal 6 ft/sec (actual 5.5 ft/sec). In taking data, the water temperature was found to vary slightly from time-to-time. For tabulation and plotting purposes, the data points are normalized to the same temperature (70°F) using the relation (3),

$$h_{T_o} = h_{T_w} \frac{1+.012\ T_o}{1+.012\ T_w}$$

where T_o is the standard temperature in °F and T_w is the water temperature. Similarly, the water velocity varies slightly. The 1/h vs. $v^{-0.8}$ relation (above) is used to normalize each datum to the nominal velocity.

The NOI'I results are tabulated in Tables 2 and 3. As shown, h is measured at various times. The difference between the value of 1/h measured at any given time and that measured initially (t=0; clean tube) is equated to R_f, the thermal resistance of the accumulated fouling layer. The average thickness of the fouling layer, t_f, is calculated from R_f assuming that the thermal conductivity of the fouling layer is equal to that of seawater.

In Fig. 8, R_f is plotted vs. time for the two units on the NOI'I.

In our more recent setup on the submerged buoy, we started three experiments on February 12, 1977, which are still in progress. Two of these duplicate the NOI'I experiments (Al 6061-T6 at 3 ft/sec and 6 ft/sec nominal velocities). The third involves a titanium pipe at 6 ft/sec nominal.

The data, treated as described above, are tabulated in Tables 4, 5 and 6, and R_f for each case is plotted in Figs. 9 and 10.

TABLE 2

Nominal Flow Velocity: 3 ft/sec

Material: Al 6061-T6 (Tube No. 1)

Date	$\langle h \rangle$ $\left(\frac{\text{BTU}}{\text{Hr Ft}^2\,{}^\circ\text{F}}\right)$	$\langle 1/h \rangle$ $\left(\frac{\text{Hr Ft}^2\,{}^\circ\text{F}}{\text{BTU}}\right) \times 10^5$	$\Delta\langle(\frac{1}{h})\rangle = R_f$ $\left(\frac{\text{Hr Ft}^2\,{}^\circ\text{F}}{\text{BTU}}\right) \times 10^5$	$\frac{d}{dt}(R_f)$ $\left(\frac{\text{Hr Ft}^2\,{}^\circ\text{F}}{\text{BTU Week}}\right) \times 10^5$	t_f (mils)
July 13...17, 1976	627.2±8.0	159.4±2.0	0.0	---	0.0
Aug. 10, 1976	608.8±7.5	164.3±2.0	4.9±2.8	1.23±0.7	0.21±0.12
Aug. 31, 1976	551.6±4.3	181.3±1.4	21.9±2.4	5.67±1.2	0.92±0.10
Sept. 15, 1976	478.8±3.3	208.9±1.4	49.5±2.4	13.14±1.62	2.08±0.10
Sept. 22, 1976	435.4±3.7	229.6±2.0	70.2±2.8	20.70±3.69	2.95±0.12

TABLE 3

Nominal Flow Velocity: 6 ft./sec.

Material: Al 6061-T6 (Tube No. 2)

Date	⟨h⟩ $\left(\frac{BTU}{Hr\ Ft^2\ °F}\right)$	⟨1/h⟩ $\left(\frac{Hr\ Ft^2\ °F}{BTU}\right) \times 10^5$	$\Delta\langle\frac{1}{h}\rangle = R_f$ $\left(\frac{Hr\ Ft^2\ °F}{BTU}\right) \times 10^5$	$\frac{d}{dt}(R_f)$ $\left(\frac{Hr\ Ft^2\ °F}{BTU\ Week}\right) \times 10^5$	t_f (mils)
Aug. 19, 1976	1083.9±30.0	92.3±2.6	0.0	---	0.0
Aug. 30, 1976	1079.0±12.9	92.7±1.1	0.4±2.8	0.25±1.78	0.02±0.12
Sept. 13, 1976	963.1±11.1	103.8±1.2	11.5±2.9	5.55±2.02	0.48±0.12
Sept. 18, 1976	946.6±24.6	105.6±2.7	13.3±3.7	2.50±6.53	0.56±0.16
Sept. 26, 1976	848.0±14.9	117.9±2.1	25.6±3.3	10.79±4.35	1.08±0.14

TABLE 4

SUMMARY OF DATA FROM SUBMERGED BUOY AT KEAHOLE POINT, HAWAII

Nominal Flow Velocity: 3.0 ft/sec
Material: Aluminum (6061-T6)

Date	⟨h⟩ $\left(\frac{BTU}{hr\ ft^2\ °F}\right)$	⟨1/h⟩ $\left(\frac{hr\ ft^2\ °F}{BTU}\right) \times 10^5$	$\Delta\langle 1/h\rangle \equiv R_f$ $\left(\frac{hr\ ft^2\ °F}{BTU}\right) \times 10^5$	t_f (mils)
Feb. 14, 1977	680 ± 7 [5]	147 ± 1.5	0.0	0.0
Feb. 21, 1977	671 ± 7 [1]	149 ± 1.5	2.0 ± 2.1	0.08 ± 0.09
Feb. 25, 1977	673 ± 7 [4]	149 ± 1.5	1.6 ± 2.1	0.07 ± 0.09
Mar. 7, 1977	661 ± 7 [1]	151 ± 1.5	4.1 ± 2.1	0.17 ± 0.09
Mar. 14, 1977	670 ± 7 [3]	149 ± 1.5	2.3 ± 2.1	0.10 ± 0.09
Mar. 21, 1977	662 ± 7 [1]	151 ± 1.5	3.9 ± 2.1	0.16 ± 0.09
Mar. 28, 1977	654 ± 7 [2]	153 ± 1.5	5.8 ± 2.1	0.24 ± 0.09

TABLE 5

SUMMARY OF DATA FROM SUBMERGED BUOY AT KEAHOLE POINT, HAWAII

Nominal Flow Velocity: 6.0 ft/sec
Material: Aluminum (6061-T6)

Date	⟨h⟩ $\left(\frac{BTU}{hr\ ft^2\ °F}\right)$	⟨1/h⟩ $\left(\frac{hr\ ft^2\ °F}{BTU}\right) \times 10^5$	$\Delta\langle 1/h\rangle \equiv R_f$ $\left(\frac{hr\ ft^2\ °F}{BTU}\right) \times 10^5$	t_f (mils)
Feb. 15, 1977	1155 ± 12 [2]	86.6 ± 0.9	0.0	0.0
Feb. 22, 1977	1129 ± 11 [1]	88.6 ± 0.9	2.0 ± 1.3	0.08 ± .05
Mar. 6, 1977	1115 ± 11 [1]	89.7 ± 0.9	3.1 ± 1.3	0.13 ± .05
Mar. 6, 1977	1120 ± 11 [1]	89.3 ± 0.9	2.7 ± 1.3	0.11 ± .05
Mar. 16, 1977	1117 ± 11 [2]	89.6 ± 0.9	3.0 ± 1.3	0.13 ± .05
Mar. 22, 1977	1073 ± 11 [3]	93.2 ± 0.9	6.6 ± 1.3	0.28 ± .05
Mar. 29, 1977	1041 ± 10 [1]	96.1 ± 1.0	9.5 ± 1.3	0.40 ± 0.05

TABLE 6

SUMMARY OF DATA FROM SUBMERGED BUOY AT KEAHOLE POINT, HAWAII

Nominal Flow Velocity: 6.0 ft/sec
Material: Titanium (B337-76)

Date	<h> $\left(\frac{BTU}{hr\ ft^2\ {}^oF}\right)$	<1/h> $\left(\frac{hr\ ft^2\ {}^oF}{BTU}\right) \times 10^5$	Δ<1/h> ≡ R_f $\left(\frac{hr\ ft^2\ {}^oF}{BTU}\right) \times 10^5$	t_f (mils)
Feb. 16, 1977	1116 ± 11 (2)	89.6 ± 0.9	0.0	0.0
Feb. 23, 1977	1102 ± 11 (4)	90.7 ± 0.9	1.1 ± 1.3	0.05 ± 0.05
Mar. 7, 1977	1055 ± 11 (2)	94.8 ± 0.9	5.2 ± 1.3	0.22 ± 0.05
Mar. 9, 1977	1061 ± 11 (3)	94.2 ± 0.9	4.6 ± 1.3	0.19 ± 0.05
Mar. 17, 1977	1047 ± 10 (1)	95.5 ± 0.9	5.9 ± 1.3	0.25 ± 0.05
Mar. 23, 1977	1012 ± 10 (2)	98.8 ± 1.0	9.2 ± 1.3	0.39 ± 0.05
Mar. 30, 1977	966 ± 10 (1)	103.5 ± 1.0	13.9 ± 1.3	0.58 ± 0.05

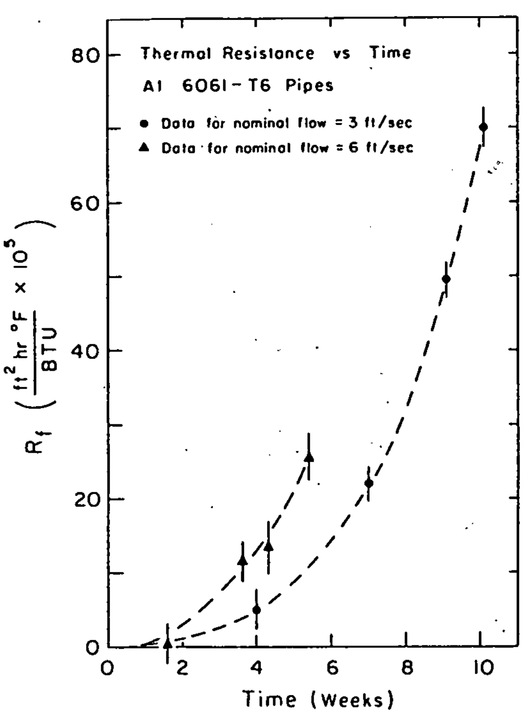


Fig. 8. NOI'I Data Al Pipes

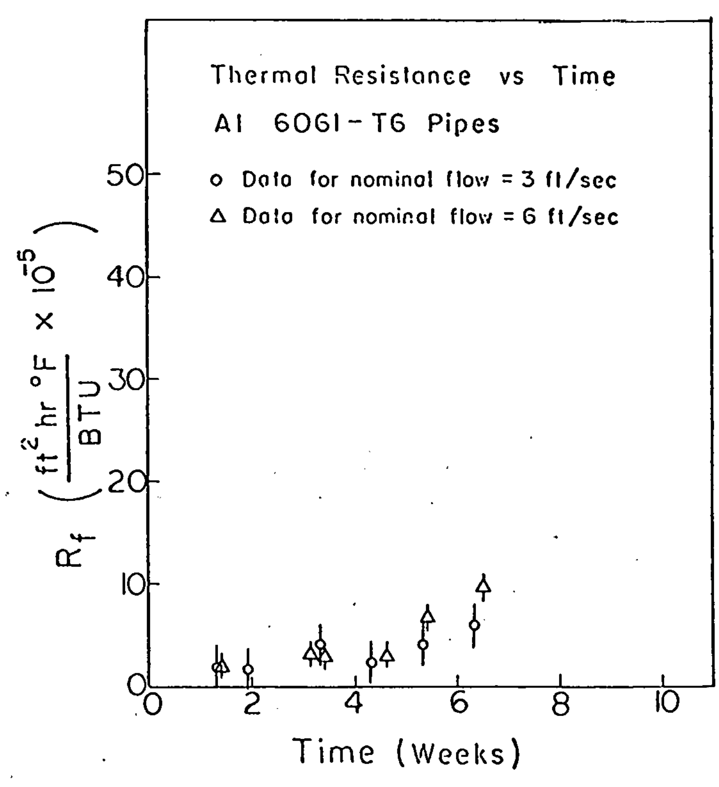


Fig. 9. Buoy Data Al Pipes

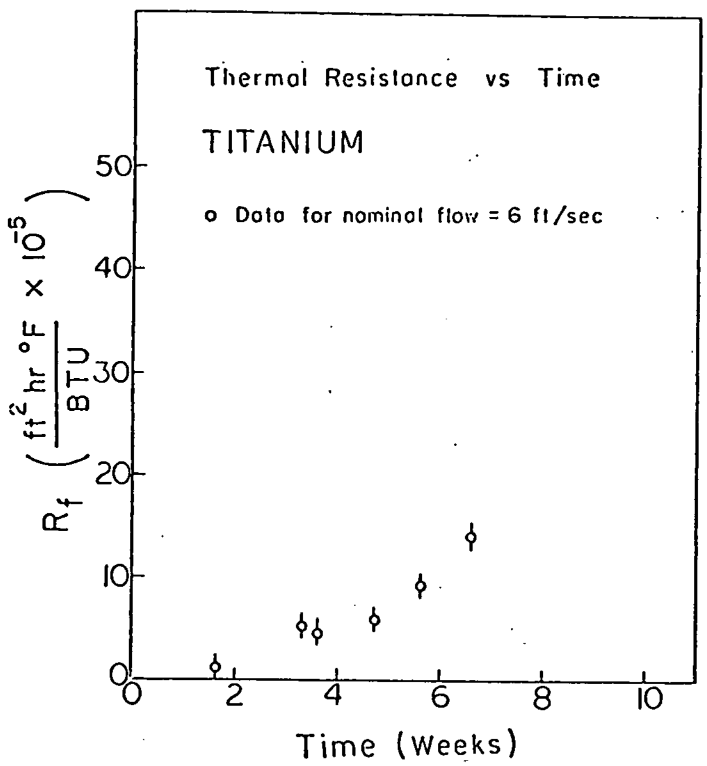


Fig. 10. Buoy Data Ti Pipe

IV. Discussion

The system which was used to obtain the data described here was specifically designed for OTEC biofouling studies. It is quite a general system which is now being used to study warm-water biofouling in 1 inch smooth tubes. However it is easily modified for other purposes or conditions. For example, it could be used for studies of biofouling in cold, deep water (or non-biological fouling), it could be used with other tube diameters or geometries (i.e., enhanced surfaces), it could be used with any desired temperature difference (in the OTEC range) between the tube wall and the seawater ($\Delta T=0$ in current experiments).

This is the first time a system of this sort has been developed or used. In order to ensure successful operation, the system was overdesigned in some ways. There are various modifications and improvements which could be impelemented to make the system simpler to use or to produce (1). So far, the urgent press for data has left us little time to implement these obvious improvements. However, as discussed earlier in this paper, the system has worked well beyond initial expectations.

The trends in our preliminary results are seen most clearly in Figs. 8, 9 and 10. In Fig. 8, the thermal resistance of the fouling layer is plotted vs. time for the two units run above the surface on board the NOI'I. These runs are now complete. There are two features of the data which are of obvious significance. First for each flow velocity, we find nearly zero slope at t=0, with the buildup accelerating with time (over the intervals covered). Secondly, we find that the biofouling rate is greater at the higher velocity.

The fact that the fouling rate is so slow at early times (it takes 2 to 4 weeks for the fouling resistance to reach 0.00005) is, in a sense heartening. It probably means (since the corresponding fouling layer averages less than 1/4 mil in thickness) that the fouling will be easier to remove at that stage than many had expected.

That the fouling rate is higher at the higher velocity will come as a surprise to some. In fact we must be careful about drawing premature conclusions about this, since there were some other differences between the two cases in addition to velocity. In particular there are two other possible sources of this difference which must be investigated.

One is that the two sets of data were not taken at the same time (the two experiments ended, rather than started, simultaneously). If the general biological activity in the area changed in the meantime, this could conceivably account for the difference. However, such a large change in so short a time seems unlikely in these waters.

A possible second difference between the two experiments is in the surface roughness. Although the two tubes were essentially identical as received from the supplier, they were cleaned differently. The one used at six feet per second merely had the surface film (oil, dirt, etc.) removed by swabbing with solvents. The one used at three feet per second, on the other hand, was in addition partially polished using an abrasive (cleaner) and a bristle brush. It is possible that the lower surface roughness of one tube led to a correspondingly lower fouling rate.

As a partial check on these questions, when the next set of experiments was started, this time using units operating in a submerged mode (mounted on a subsurface buoy at a depth of about 50 feet), all three experiments were started simultaneously, and all three tubes received the same treatment (including the partial polishing).

So far, we have analyzed data from six weeks of running (the experiments are being continued). The results for fouling resistance vs. time are shown in Fig. 9 for the two aluminum tubes at nominal flow velocities of 3 and 6 ft/sec, and in Fig. 10 for the Titanium tube at a nominal flow velocity of 6 ft/sec.

In the early stages of the experiments (t<5 weeks) the fouling buildup is so slow that the data points differ little from zero and from each other (relative to the experimental erros shown by the vertical bars), and few conclusions can be drawn. However, as we look at the last two sets of data points, we see again the beginning of a trend indicating that the 6 ft/sec Aluminum fouling rate is greater than the 3 ft/sec Aluminum rate. In this case, the difference cannot be ascribed to different treatment of the tubes or to different starting times of the experiments. It would seem to be an actual velocity effect. However, considering the experimental errors, it is evident that after only 6.5 weeks of running no firm conclusions can yet be drawn. More data are required (and are being obtained) on this point.

Comparing Figs. 9 and 10 we see another interesting effect. The fouling rate at 6 ft/sec in the Titanium tube is greater than that at 6 ft/sec in the Aluminum tube. It is possible that this may be a surface roughness effect, and that rougher surfaces foul more rapidly than smoother ones. This possibility suggests itself for two reasons. First, Titanium, being harder than Aluminum will be less affected by the polishing which is done (100 strokes of the bristle brush through the tube). Second, although no quantitative measurements were made (this will be done in the future) the Titanium tube "appeared" rougher than the Aluminum tubes when received from the supplier.

Another interesting effect may be observed by comparing Fig. 8 (data taken with the units above surface) with Figs. 9 and 10 (data taken with the units submerged). The fouling rates are consistently lower in the latter case. This difference is possibly due to one or both of the following causes. There may be a larger-than-expected seasonal variation (July vs. February) in the general level of biological activity of those organisms responsible for microbiofouling. (Seasonal variations are expected to be much less in these waters than, for example, in the temperate zones.) Another possibility is that there is a significant vertical gradient in the density of microbiofouling organisms (for example, bacterial densities are expected to be greater at the surface than at greater depths in the mixed layer). Since the data of Fig. 8 correspond to water taken from 20 ft. depth, and the data of Figs. 9 and 10 correspond to water at about 50 ft. depth, this could explain the differences.

We do not have measurements of the level of biological activity in the waters corresponding to these data. Although such measurements were in the general plan, the press of time deadline militated against implementation in these experiments. (Of course, biological, chemical and physical measurements of water conditions are planned for future work, as soon as these plans can be realized.)

In summary, the data indicate the possible existence of certain phenomena which could be important to OTEC design and should be investigated further. Among these are:

a) Biofouling rates are very slow at early times, but accelerate rapidly after several weeks.
b) Biofouling rates probably increase with pumping velocity.
c) The surface roughness of a tube may significantly affect the biofouling rate. If so, the use of schemes such as Amertap or M.A.N. brushes, which would be expected to polish the surfaces, might be beneficial not only in removing existing fouling, but also in slowing further growth.
d) There may be a strong depth dependence of the biofouling rates.
e) There may be a significant seasonal variation in biofouling rates even in the relatively constant-condition waters of the tropical Pacific.

We re-emphasize that these conclusions are very tentative and will be so until considerably more data are available.

There are many other factors which could affect fouling rates. Some of those which are likely to be important, and which we therefore hope to study soon are the following.

We need to extend the velocity range studied. It may be that at higher velocities, the stresses experiences by the organisms make it difficult to attach and the fouling rate may level off or decrease. The range of materials and surfaces tested should be expanded. The effect of a change in temperature of the water passing through the system should be studied. Other tube geometries should be looked at (i.e., does the fouling rate go with diameter as expected; what will be the effects of attempts at enhancement, such as fluting, etc.). The effect of placing the pumps upstream of the test section should be looked at (the pumps so far have been downstream in all cases). If the added stresses experienced by the organisms significantly reduce the fouling rates this could be an important design factor in OTEC plants. There is obvious need to look at other kinds of water in other ocean locations.

We hope to study these and other important parameters as soon as conditions allow.

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