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A STUDY OF FOULING AND CORROSION PROBLEMS RELATED TO A SOLAR SEA POWER PLANT

Progress Report, April 1—June 30, 1977

By
John G. Fetkovich
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September 1, 1977

Work Performed Under Contract No. EY-76-S-02-4041

Carnegie-Mellon University
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MASTER

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RELATED TO A SOLAR SEA POWER PLANT**

PROGRESS REPORT

**Covering the period
April 1, 1977 to June 30, 1977**

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ABSTRACT

The OTEC heat transfer simulation device, which was developed at CMU in order to investigate heat exchanger biofouling by monitoring heat transfer coefficients, has now been used in several experiments at Kea-hole Point, Hawaii. The field results have confirmed that the equipment works as expected with a precision in measuring heat transfer coefficients of about 1%. The results show that the biofouling growth is very slow during an initial transient period of about six weeks at which time the fouling resistance is $R_f = 20 \times 10^{-5} \text{ hr ft}^2 \text{ }^\circ\text{F/BTU}$. After this transient, the growth is essentially linear, rising at the rate of about $7 \times 10^{-5} \text{ hr ft}^2 \text{ }^\circ\text{F/BTU-week}$. These results are independent of material (titanium or aluminum) and flow velocity (6 or 3 feet per second). During the course of these same experiments a preliminary cleaning test was done with a M.A.N. brush. It was found that six passes of the brush reduced the fouling resistance from about $32 \text{ hr ft}^2 \text{ }^\circ\text{F/BTU}$ to zero.

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I. INTRODUCTION

During the three month period from April 1, 1977 to June 30, 1977, the CMU Biofouling and Corrosion Group was engaged in three major areas of effort. A large fraction of our resources was devoted to the first effort, Keahole Point, Hawaii. There, measurements of thermal resistance (due to biofouling and corrosion) as a function of time were in progress for a titanium pipe with a nominal seawater velocity of 6 ft/sec and two aluminum (6061-T6 alloy) pipes with nominal seawater velocities of 3 ft/sec and 6 ft/sec. These pipes were instrumented and encased in a protective housing and attached to a buoy which was submerged at a depth of approximately 50 feet.

Prior to June 6, no attempt was made to inhibit the fouling. Data taken during this time can be examined for possible velocity dependence or material dependence in the rate of fouling buildup. On June 6, the two aluminum pipes were cleaned in a mechanical fashion. In so doing, the first (crude) measure of the difficulty of removing extensive biological growth was made. Following June 6 until the end of the report period, thermal resistance was again measured as a function of time for the two aluminum pipes. This was done to determine whether, for the given cleaning technique, the fouling rate would follow along as if from the initial clean pipe state or if the fouling rate would be significantly altered from that initially observed.

The second effort was involved with preparations for a warm water biofouling experiment at another potential OTEC site, the U.S. Virgin Islands. This experiment is to differ somewhat from that in Hawaii in that the experimental units (two heat exchanger pipes, their

instrumentation and housings) will be mounted above the ocean surface, on the deck of a barge moored seven miles from the island of St. Croix. This difference, with the accompanying accessibility to the units, allows for generally simpler operation. At least one aspect of the St. Croix set-up, the incorporation of "pipe electronics," is regarded as a significant improvement in experimental design and could be carried over to the Hawaii installation or to other biofouling installations.

In order to assist in expanding the biofouling program, the third effort was aimed at transferring information from the CMU group to other involved groups. Included in the transfer are principles of operation of the instrument for measuring thermal resistance of the biofouling and corrosion layer, and fabrication and assembly techniques for the device. In addition, the newly involved groups were made aware of the requirements of a field installation, of procedures for proper acquisition of data and of methods for data analysis.

II. RESEARCH AT KEAHOLE POINT, HAWAII

A. Biofouling Data

The results of the analysis of the Keahole Point data are presented in considerable detail in Appendix I. This is a copy of a paper to be presented at the OTEC Biofouling and Corrosion Symposium in Seattle, Washington, October 10-12, 1977.

B. Condition of Buoy, Cable and Biofouling Units

Periodic examinations of the buoy and cable were made by divers, particularly Hank White of the University of Hawaii. His observations included the following:

1. Minor corrosion of the metal frame of the buoy and some local penetration of the paint layer was seen;
2. The flotation module was found to be slightly separated from the buoy proper and action was taken to keep the separation from increasing;
3. Down to maximum diving depths of -200 ft, the electromechanical cable shows no deterioration either from the buoy end or from the beach end;
4. The lead wrapping of the cable which serves as protection in the surf zone shows no signs of significant wear;
5. A one-foot long extension was installed on the electromechanical cable so that the terminals in the main cable need never be exposed to seawater;
6. The filters at the intake of the heat exchanger pipes under test were found to accumulate significant biological growth including barnacles and algae and were cleaned at regular intervals;
7. As detailed in a Letter Report from E. C. Haderlie to R. H. Gray dated August 2, 1977, the buoy was relatively lightly fouled after being in the water for approximately six months. The dominant fouling growth consisted of algae and encrusting bryozoans, fuzzy hydroids and simple and complex sponges.

C. Improved Data Handling and Analysis Capabilities

A more in-depth probe of the physical reasons underlying the dispersion of the heat transfer coefficient measurements on a given day was made. Evidence points to a strong correlation between the goodness

of fit of the raw thermopile decay data to an exponential function and the magnitude of water temperature variations during the decay. In addition to providing a sound physical criterion for acceptance of a particular thermopile decay curve as representative, this knowledge of the source of the dispersion permits a reliable estimate of the precision of the measurement techniques. For a typical set of 16 thermopile decay curves taken on one day, the heat transfer coefficient is measured with a precision of 0.5%. This is the standard deviation of the mean of the accepted decay curves. From this it follows that the thermal resistance due to fouling is determined with a standard deviation of $0.00001 \text{ (hr ft}^2 \text{ }^\circ\text{F/BTU)}$ or better for flow velocities ranging from 3 ft/sec upward. This resolution is entirely adequate for present studies.

In order to lighten the burden of data analysis for our research staff, a more nearly automated procedure was developed. This consists of using a PDP-15 computer from the Physics Department to transfer the raw data from the paper tapes generated at the ocean site to magnetic tape. This magnetic tape then serves to input the data to a refined analysis program. After an appropriate conversion from ASCII code (in which the paper tapes are written) to alphanumeric code (which the Fortran analysis program can interpret) the analysis program is able to determine which experimental unit is reporting data and therefore determine which set of thermistor, flowmeter, etc. calibration constants is appropriate. By the presence of certain codes it is able to recognize and treat various types of peripheral data such as temperature inside the submerged buoy electronics box and excitation voltage applied

to the flowmeter strain gauge bridges. Having its own characteristic code, the data associated with the thermopile decay is analyzed and the results are stored. After all decay curves are analyzed, those which fail to meet certain preset criteria are rejected, and the results from the remaining curves are compiled in a summary table along with appropriate errors. Sufficient logic can be built into the program to be able to treat data taken at sites other than Keahole Point. In particular, the necessary modifications are to be made to accept data taken aboard the moored barge at St. Croix.

The Intel 8080 microprocessor system*, which is meant to interface with the Beach and Buoy Electronics at Keahole Point is in the final stages of testing. The microprocessor software is designed to control the experiment and to acquire and partially analyze biofouling data. Control consists essentially of turning the heater of a particular unit on and off at appropriate times and cycling over other biofouling devices in order to repeat the measurement of heat transfer coefficient a prescribed number of times. Raw data are acquired by the action of pulse counters and interval timers and are stored in buffer memory locations. The analysis software essentially provides as output a critical subset of the thermopile decay data along with the average and rms deviation of flow velocity and water temperature during selected time intervals of the thermopile decay period. This output is stored on paper tape whose contents must be passed to a larger computer for final analysis and compilation. The bulk of data that must be handled is reduced manyfold by the presence of the microprocessor system. The microprocessor

*A design report on this system will be prepared after thorough testing.

has been programmed with the option of dumping all raw data onto paper tape for more detailed scrutiny or for checking or troubleshooting purposes. The output from the microprocessor of course will be thoroughly checked against the output from the standard analysis of the raw data. It is expected that the microprocessor will be a fully-functioning addition to the present data acquisition system when the second series of biofouling experiments begins in early September. In addition to alleviating the burden of data analysis, the microprocessor will then also free the operator at Keahole Point from a very large part of the tedium of data acquisition and allow him to perform other necessary tasks.

III. RESEARCH AT ST. CROIX, U.S. VIRGIN ISLANDS

A. Hardware, Changes and Improvements

As mentioned in the INTRODUCTION, the biofouling experiment at St. Croix will be conducted with the biofouling monitoring devices mounted on the deck of a moored barge. This change from the conditions of submerged operation at Keahole Point is reflected in the relaxation of certain requirements that existed at Keahole Point, particularly those pertaining to the electronics of remote control and data transmission.

Material was ordered and two complete biofouling monitoring devices were fabricated by the Physics Department Machine Shop. A complete monitoring device includes a properly machined heat exchanger pipe, heater cylinder set with a potted thermopile, flow meter, thermistor, appropriate adapters and PVC housing. A mechanical change that was deemed prudent was to move the copper cylinder containing the reference junctions of the thermopile down the heat exchanger pipe so that the

cylinder would not be in thermal contact with the top PVC plate of the housing. Unlike at Keahole Point where the submerged housing would be at the ambient temperature of the ocean water, in the St. Croix installation the housing would be in the open air and would therefore be at a temperature different from that of the seawater flowing through the pipe. Since the reference temperature for the thermopile is meant to be that of the flowing seawater, the reference cylinder was moved and replaced with a "dummy" cylinder which served solely to anchor the heat exchanger pipe to the PVC housing.

Considered to be a mechanical improvement were heater cylinder support disks with which the St. Croix biofouling devices were equipped. These support disks serve to keep the heat exchanger pipe centered in the housing and prevent the pipe from bending if the relatively heavy cylinders are rapidly accelerated as, for example, by the rolling motion of the barge.

The DC signal strength from the three transducers (thermopile, thermistor bridge, flow meter strain gauge bridge), which serve to instrument the heat exchanger pipe, ranges from the submicrovolt level to the millivolt level. In order to transmit these signals from the biofouling device to the data acquisition and control electronics with only an insignificant contamination by noise it was decided to boost the signal level to the 0 to 10 volt range at the point of origin of the signals. This was accomplished by incorporating "pipe electronics" into the instrumentation. The pipe electronics consists of three chopper-stabilized DC amplifiers for the three transducers, along with a power supply for the flowmeter bridge and a power supply for the DC

amplifiers. These components are mounted on two parallel boards which are clamped to the heat exchanger pipe. In addition to providing robust signals, the pipe electronics also makes the entire data acquisition system more modular.

In the Keahole Point system the low level thermopile signal from each of the six biofouling devices is multiplexed to a single amplifier which is contained in the electronics box attached to the submerged buoy. If this amplifier fails, no biofouling data can be taken on any of the six devices until the electronics box is brought to the surface and the amplifier is repaired. Where pipe electronics is included as part of the instrumentation package, a failure of a particular thermopile amplifier causes a shutdown only of that single unit and not of the entire system. Since disassembly of the faulty device is required for repairs, however, the biofouling experiment on that device could most likely not continue beyond the time when the fault appears.

Since the data signals are in the 0 to 10 volt range they can be transmitted along a cable of reasonable length without serious noise problems. For the St. Croix installation two 93 foot cables are required for each biofouling device. One cable is used to carry power from the main control box to the heater and pipe electronics in the device. The second cable serves to carry the three data signals from the device to the main control box. The cables, plugs and bulkhead connectors were obtained from Enviro Con in Houston, Texas and are suitable for use underwater to depths of 20,000 feet. They are not, however, underwater-pluggable as are the Electro connectors at Keahole

Point. The use of individual cables for each device rather than a single cable for all devices (as required at Keahole Point) greatly simplifies the problem of transmitting the data from the device to the control box.

The control box receives and scans the analog data from a selected unit, displays the data, converts it to digital form and passes it to a teletype where it is punched on paper tape. In its present form the data acquisition system is operated manually. However, rather than going to a teletype, the data could equally well go to a serial input port of a microprocessor along with an appropriate data transfer pulse while an output bit of the microprocessor could be used to turn the heater on and off. By means of programmed logic, data could be acquired and partially processed largely without aid from an operator. This means that data could be taken around the clock in order to examine the biofouling state of more devices more frequently with the burden of data analysis being simultaneously reduced.

The data acquisition system including pipe electronics, cables and control box as described above has been designed and built by personnel of the Physics Department Electronics Shop and has been tested by members of the CMU Biofouling and Corrosion Group. A comprehensive design report on the data acquisition system has been prepared and is to be submitted to ERDA about September 1, 1977.*

B. Lab Tests, Calibrations and Refinements

Extensive calibration and testing of the components making up the two biofouling devices was carried out. The gain of each of the three

*Design Report for PS-105 Data Acquisition System for Biofouling Studies of Heat Exchangers in Seawater, COO-4041-6.

DC amplifiers on both sets of pipe electronics was measured. The thermistors and flow meters to be used were calibrated and the operation of the thermopiles in the copper cylinder sets was checked, all using the electronics of the data acquisition system.

One refinement of the original design was made for the thermopile amplifier (Datel AM-490-2C) on the pipe electronics. The gain of this amplifier was 10,000 and the time constant of the RC feedback network was 0.1 second. This yielded a noise voltage of $1.8 \mu V_{\text{rms}}$ referred to the input of the amplifier. In a fit of the thermopile decay curve to extract a time constant for the decay, $1.8 \mu V_{\text{rms}}$ equivalent input noise was calculated to give rise to an uncertainty in the fitted time constant of 0.99%, an uncomfortably high value. In order to reduce this expected uncertainty, the time constant of the RC feedback network was increased from 0.1 second to 1.0 second. With this 1 second time constant, the output of the amplifier is still linearly related to the decaying exponential input to within 0.01% provided one waits at least 7 seconds after the heater is turned off to accept thermopile data for analysis. These statements apply to our worst conceivable case where the time constant of the thermopile decay is as small as 15 seconds. The 7 second waiting period presents no problem since in the data analysis procedure the first 10 seconds of the thermopile decay curve are ignored as a matter of course. This increase in feedback time constant to 1 second served to reduce the equivalent input noise level to $0.8 \mu V_{\text{rms}}$ which in turn is associated with an uncertainty in the fitted value of the thermopile time constant of 0.39% or less. This was considered to be satisfactory.

Following these tests the system of two biofouling monitoring devices and associated electronics was declared fit for field service. Shipment to St. Croix was effected during the third week of June.

IV. INFORMATION TRANSFER

Responses to requests for information related to general system operations, device fabrication, data analysis and a miscellany of other aspects of the biofouling measurement were made to the following:

1. V. Castelli, W. Adamson and A. Fritsch of the David W. Taylor Naval Ship Research and Development Center; Bethesda, Maryland.
2. W. Sheppard, F. Spieler, F. Remond and C. Hill related directly or indirectly to the NOAA Data Buoy Office, Bay St. Louis, Mississippi.
3. J. Hirschmann of Tracor Marine, Port Everglades, Florida.
4. A. Walker of Applied Equipment Company, Van Nuys, California.
5. R. Moles, G. Jensen and W. Laity of Battelle Pacific Northwest Labs, Richland, Washington.

DEGRADATION OF HEAT TRANSFER RATES DUE TO
BIOFOULING AND CORROSION AT KEAHOE POINT, HAWAII

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ABSTRACT

By using a method developed at CMU, the biofouling buildup associated with seawater flowing through a simulated OTEC heat exchanger tube was measured by monitoring heat transfer rates with a precision of 1% or better. Two series of experiments were carried out. In the first series seawater was pumped up to two simulated tubes (aluminum 6061-T6) which were mounted in protective housings on board a research vessel moored off Keahole Point. In the second series three simulated tubes (aluminum 6061-T6 and titanium) in their housings were attached to a buoy which was submerged at a depth of 50 feet. Flow velocities of 3 ft/sec and 6 ft/sec were used. In addition, preliminary data on cleaning fouled tubes using M.A.N. brushes were obtained.

INTRODUCTION

In late 1973, the biofouling group at Carnegie-Mellon University, based on discussions with the Zener OTEC group, recognized the critical importance of understanding and solving the problem of biofouling in OTEC heat exchangers. This group at that time started a program of instrumentation and research into the problem. By early 1974, a group at the University of Hawaii, under F. C. Munchmeyer, had agreed to join this effort, providing essential marine engineering knowledge. In July 1975, when the initial funding of this program started (by NSF-RANN at that time), the effort at last began to acquire some momentum.

By July 1976, the instrumentation had been developed and laboratory-tested, and the analysis procedures designed. We were ready to begin acquiring the first field data. This was done with two simulated heat transfer tubes mounted aboard the UH Research Vessel NOII off the coast of Hawaii at Keahole Point. These accumulated data through the period July-September 1976.

It was shortly before this that the Battelle Pacific Northwest Laboratories entered the biofouling effort as program manager.

In February 1977 a new series of experiments was started, in which three simulated heat exchanger tubes were mounted on a submerged (about 50 feet deep) buoy near the location of the NOII experiments. With this apparatus, in the period from February to July 1977, a series of biofouling experiments was done, including the first results on cleaning fouled tubes.

In this paper we summarize the data available to date, discuss some conclusions suggested by the data, and indicate some important

future research directions.

APPARATUS

We will not give a detailed description of the apparatus and methods used, since these have been extensively covered elsewhere (Fetkovich et al., 1976; Fetkovich et al., 1977). Here, we limit ourselves to the following brief comments on the apparatus. Each experimental unit is comprised of a simulated heat exchanger tube (1" nominal ID, 8-1/2 ft. long) followed, in the direction of flow of the seawater, by a flow-meter and a pump. The system is run continuously over the several weeks or months of an experiment. It is instrumented to allow measurement at will (usually done approximately weekly) of flow velocity, seawater temperature and heat transfer coefficient (h) to the flowing water. These measurements are taken without interrupting flow conditions.

Laboratory studies on the repeatability of measurements taken with this apparatus show that a measurement of h has a random error of about 1/2%. In the field, this is found to rise to about 2% due mainly to rapid seawater temperature fluctuations. (It is not unusual to see a change of $.05^{\circ}\text{C}$ within a minute.) In practice, the error is reduced to less than 1% by making repeated measurements of h (usually 16) and eliminating those which were affected by large water temperature changes.

As has been previously discussed (Fetkovich et al., 1976) it is possible to "tune" the system so that it will be insensitive to water temperature fluctuations. Since the procedure is somewhat awkward, it has never been used, except approximately. We are now testing an alternative, analytic, procedure for dealing with these fluctuations. If

it works as expected, we should be able to approach laboratory precision even in the field.

In the experiments to be discussed here (buoy data), three test units were mounted on a submerged buoy, 50 ft. deep, off Keahole Point, Hawaii. The units were: Aluminum 6061-T6 with nominal 6 ft/sec. flow (actually about 7 ft/sec.); Aluminum 6061-T6 with nominal 3 ft/sec. flow (actually about 3.1 ft/sec.); Titanium B337-76, with nominal 6 ft/sec. flow (actually about 6.4 ft/sec.). Before submersion, the interior (water-side) surfaces were all given the same treatment. They were scrubbed with a bristle brush and commercial cleanser (100 strokes each). The three units were positioned on the buoy and the pumps started on February 13, 1977.

In a previous report (Petkovich et al., 1977) we described the results from the "NOII" experiments. We will repeat these here for comparison purposes. In this case two test units were mounted on the deck of the NOII (Al 6061-T6 at 3 ft/sec., and Al 6061-T6 at 6 ft/sec.). The 3 ft/sec. unit was given the same surface treatment described above. The 6 ft/sec. unit was used as received from the supplier, except that the surface was gently swabbed with a solvent to remove dirt and oil. The 3 ft/sec. unit was placed in service on July 13, 1976, while the 6 ft/sec. unit was started on August 19, 1976.

DATA

The detailed data from the buoy units are tabulated in Tables I, II and III. The indicated values of heat transfer coefficient, $\langle h \rangle$, are averages of several readings (usually 10-12) taken on the same day. Two

error values are indicated with each entry. The smaller one (in parentheses) is determined from the spread of the averaged points. It is a measure of the repeatability of the data and is an indicator of the precision of relative h values. The larger one (1%) is our estimate of the absolute error in the points, limited by our knowledge of the flow-meter calibration. The errors on the other entries in the table are calculated using the larger of these two errors.

The value of h depends on the flow velocity as well as water temperature. For ease of comparison, each value of h is normalized to the same temperature (70°F) and flow velocity (the velocity corresponding to the chosen nominal value). The measured thermal resistance $\langle \frac{1}{h} \rangle$ is calculated and the difference between $\langle \frac{1}{h} \rangle$ and the initial value of $\langle \frac{1}{h} \rangle$ is shown next as $\Delta \langle \frac{1}{h} \rangle$. This corresponds to the thermal resistance of the accumulated fouling layer, R_f . Finally, we show t_f which is the average thickness of the fouling layer. It is calculated assuming that the fouling layer has the thermal conductivity of seawater.

In Tables IV and V, the NOII data are tabulated in the same way. In this case, only one error value is given with $\langle h \rangle$. This is calculated from the spread of the points. When these measurements were made, the magnitude of the seawater temperature variations was not yet appreciated. They lead to the correspondingly larger error values shown here.

These tabulations are useful in giving precise details of the data. However, it is much more helpful, in understanding what is happening, to display the data graphically. Figure 1 shows the data from the three buoy units (R_f vs. time). For the time being, we discuss only the part of the data corresponding to 0-11.4 weeks. The reasons for the structure

at $t > 11.4$ weeks are complex and will be discussed below. The line segments connecting adjacent points are merely to aid the eye, and have no significance.

Note that the data for Titanium go only to 10.6 weeks. At that point the Titanium experiment was terminated by a failure of its pump.

The seawater temperature over the same time interval is shown in Fig. 2. We see some large and rapid fluctuations on this scale as well. In one case, for example, we find a change of over 1.4°C (2.6°F) in three days. The data shown in Fig. 2 were measured with a thermistor mounted on the simulated heat exchanger tube of the Aluminum 6 ft/sec. unit. Similar data were also taken with the other two units. Since these are virtually identical, they are not shown.

The data of Fig. 1 show that the fouling rate is the same for the Aluminum unit as for the Titanium. They also show that, in the range 3 ft/sec. to 7 ft/sec., the fouling rate is not dependent on the flow velocity. We note also that the data taken at about 11.3 weeks suggests that the value for the 3 ft/sec. unit is beginning to deviate from that for the 6 ft/sec. unit.

Figure 3 shows the NOII data as well as the Aluminum 6 ft/sec. buoy data for comparison. There are several notable points. The 6 ft/sec. NOII fouling rate is significantly higher than the 3 ft/sec. rate. When these data were first obtained, this seemed to be evidence for a strong velocity dependence. The existence now of the buoy data of Fig. 1 shows this not to be so. We therefore must look for another source of this difference. Several possibilities exist. The two NOII experiments did not start simultaneously, beginning more than a month apart. A variation

in the overall biological activity during that interval could cause a corresponding variation in fouling rates. A second consideration, as mentioned before, is the difference in the surface treatment accorded the two NOII units. The NOII 6 ft/sec. unit (which had not been brushed with a cleanser) had the rougher surface. We will consider the time variation first.

Figure 4 shows the variation with time of biological activity in these waters implied by the assumption that the observed fouling rate differences are entirely due to this cause. Here, we plot the fouling resistance after 5 weeks of operation for the three cases shown. The points are plotted at times of the year corresponding to 2-1/2 weeks after the start of each run. We see that to ascribe the differences to this cause implies that the biological level in these waters had changed by roughly a factor of two in a month. We can find no evidence to support the assumption of such rapid variation. Our tentative conclusion, then, is that the major part of the difference between the two NOII results is due to differences in surface roughness (but see also below). If this is confirmed by further results, it will mean that we must attach great importance to the question of surface preparation of heat exchanger tubes.

The difference in results between corresponding BUOY and NOII data (BUOY (1977) vs. NOII 3(1976) points in Fig. 4), on the other hand, could well be due to time variation of the oceanic biological levels. However, another difference between the Buoy and NOII results could possibly have had some effect on this difference. The NOII units were mounted on deck. The seawater therefore had to be pumped through about 40 ft. of plastic pipe before getting to the test section. The (submerged) buoy units, on

the other hand, had the test section opening directly to the sea. One important result was that the organisms passing through the NOII apparatus suffered much more pressure drop before passing through the test section than those in the Buoy experiments. One might expect such a difference, however, to have the opposite of the observed effect.

The 40 feet of inlet pipe on the NOII units developed colonies of organisms inside it. Conceivably, because of this, the biological content (bacteria, etc.) of the water flowing into the test section was higher than that of the surrounding seawater. This, if true, could be the cause of the fact that the buoy fouling rates are lower than the NOII ones. It might also contribute to the difference between the two NOII results if the pipe leading to the 6 ft/sec. unit was more heavily fouled than the other. One could perhaps understand such a difference, for example, based upon the higher velocity bringing in nutrients at a higher rate.

CLEANING TESTS

Returning to Fig. 1, we note the precipitous drop in R_f in both the Aluminum 6 ft/sec. and 3 ft/sec. units at about 16 weeks. It was at this point that the tubes were cleaned. The cleaning was done in situ by divers using a M.A.N. brush which was pushed thru the test section by the flow and retrieved using an attached line. This was done to simulate the cleaning effects of one of the cleaning systems being proposed for OTEC in hopes of getting at least a rough measure of the difficulty of removing such an accumulation of fouling.

We first consider the 6 ft/sec. unit (dotted curve in Fig. 1). At week 16.3, R_f was 25.0 ± 1.4 (in units of the Figure). After one (back-and-forth) pass of the M.A.N. brush, R_f fell to -2.7 ± 1.2 . After five more passes R_f dropped to -8.2 ± 1.2 , where the heat transfer rate was back to the new tube value. (The negative value of R_f is not believed to be real. It is due to causes which are explained below.) After the cleaning, the fouling resistance increased again as shown by the curve from 16.3 to 20.6 weeks. We note that after cleaning, the fouling resistance increases from zero at a much higher rate than for a new tube. Presumably this is because the "cleaned" tube still has a microscopic layer of organic material coating the surface, which, of course, a new tube does not. It would be interesting to see how aggressively a tube must be cleaned in order not only to achieve "clean tube" conditions ($R_f=0$), but also to achieve "new tube" conditions ($dR_f/dt=0$). In any case, it is encouraging that it is so easy to clean the tube even after 16 continuous weeks of fouling growth.

The 3 ft/sec. unit (dashed curve in Fig. 1) was dealt with similarly. At 16.1 weeks we had $R_f = 84.7 \pm 2.7$. After one pass of the brush, R_f fell to 44.6 ± 6.6 , and after 11 passes, to 29.8 ± 2.7 . It was noted by the divers that there were barnacles visible inside the tube, and the cleaning was halted for fear that one might be dislodged and would damage some part of the apparatus.

Although apparently easy to clean also, the 3 ft/sec. unit was more difficult to clean than the 6 ft/sec. unit. The reason for this difference is not entirely clear. It is known, however, that different kinds of organisms can attach and grow at lower velocities (especially

zooplankton). We saw no evidence of barnacles, for example, in the 6 ft/sec. test section.

PUMP STOPPAGE

In Fig. 1, we see a significant structure in the interval from 11.4 weeks to 16 weeks. The variation of R_f in this region was due to an equipment failure which caused both pumps to stop at an unknown time between 11.4 weeks, when the pumps were known to be on, and 12.6 weeks when the pumps were seen to be shut down. When the pumps were restarted at 12.6 weeks, it was observed that R_f in both units had dropped. Apparently this was due to the demise of some of the accumulated organisms in the slime film. Either the thermal resistance of the dead organisms is lower than that of the live ones, or, more probably, some of the dead layers sloughed off when pumping was resumed.

One problem caused by the pump stoppage was a change in the flowmeter calibrations. The effect is seen in Fig. 5. Here we plot the flow velocity vs. time for each unit (the Titanium unit had stopped functioning earlier due to an unrelated problem). We see that in both units, the flow velocity remained stable until the stoppage, but both became erratic afterwards. The apparent variations afterwards are not all real. They were apparently caused by the growth of macrofouling organisms within the flowmeters. These organisms (including barnacles) were observed when the apparatus was disassembled.

The evidence indicates that these macrofoulers attached and began to grow during the pump shutdown. Two factors support this assumption. First, similar growths were not observed after the earlier NOII

experiments in which there was not a lengthy stoppage. Second, as Fig. 5 shows, both flowmeter problems began immediately after the pump stoppage.

An important question is how does the flowmeter problem affect the interpretation of the subsequent heat transfer data. To investigate this point, we use the Aluminum 6 ft/sec. data which exhibits the more serious deviations. To this end we have recalculated the velocity of flow in this unit using three different assumptions about the nature of the problem. (The justification for these assumptions involves a detailed discussion of the instrumentation which we will not go into here.) The resulting velocity curves are shown in Fig. 6. The lowest curve here is identical to that in Fig. 5. The important thing is that we are confident that the true curve lies between the two extremes shown.

To see how this uncertainty in the flow velocity affects our determination of R_f , we have recalculated R_f for each of the velocity assumptions. The three resulting R_f curves are shown in Fig. 7, where the dashed curve is identical to that shown for this unit in Fig. 1. Again, the true curve almost certainly lies between the extremes shown here. The dashed curve in Fig. 7 is not likely to be right, since it leads to negative values of R_f . This in turn means that the true velocity curve lies higher than the lowest one shown in Fig. 6. It is clear that even the highest curve of Fig. 6, yielding the solid curve of Fig. 7, gives a value of R_f consistent with zero at 16.3 weeks (after cleaning), which gives us confidence that "clean tube" conditions were achieved after cleaning.

Finally, we ask whether we can understand the unusual structure exhibited in the two curves of Fig. 1 in the interval from 11.4 weeks to

16.1 weeks. The 3 ft/sec. case is the more straightforward. As mentioned earlier, the drop from 11.3 to 12.6 weeks is presumed due to the death of accumulated organisms. After the pump was restarted, the biofouling growth resumed and continued until the tube was cleaned.

The 6 ft/sec. case is more complicated. Again, after the drop due to pump stoppage, growth resumed. But at 13.7 weeks, it began again to drop. This is difficult to explain. A possible clue to the cause is the fact that in the interval from 11.4 to 16.3 weeks, the structure of the R_f curve (Fig. 1) is strikingly similar to that of the velocity curve (Fig. 5). This suggests the possibility that although the lowest curve of Fig. 6 is not the true one, the velocity after 13.7 weeks is dropping. This could conceivably lead to the death of previously attached organisms due to reduced food supply^a. This "conclusion" is of course highly conjectural. It is offered mainly to suggest possible future studies of this point.

DISCUSSION

Several interesting conclusions are suggested by these data. The biofouling builds slowly, but at an increasing rate. It is apparently very easy to clean the tubes, but the fouling grows back faster afterwards. Fouling rates apparently either increase when long inlet pipes are part of the apparatus or they are rather sensitive to surface condition (roughness). Finally, the accumulated fouling appears to be sensitive to flow variations.

This last point may be a significant one. If merely a brief interlude

^a There are also other relevant factors related to the velocity, such as rate of removal of metabolic products.

in stagnant seawater does as much damage to the microfouling organisms as is suggested by these data, then it is possible that chemical means much less aggressive than those being considered (such as continuous chlorination) could serve as biofouling controls. For example, perhaps if the heat exchangers are bathed briefly in stagnant fresh water, or a mixture of equally benign and inexpensive chemicals, the microfouling film will be sloughed off merely by reenergizing the pumps (perhaps briefly at a higher flow velocity). One doesn't know whether any such schemes will work, but they are so simple to try that they should be investigated.

There are many experiments which need to be done with this kind of apparatus in the future. Some of those which we have proposed and discussed at length are, for example: time and position dependence of biofouling rates; study of tube material and surface structure effects; studies over an increased velocity range; effects of pump location (up- or down-stream of the test unit); effects of ΔT (tube-water temperature difference); fouling of enhanced surfaces; and, of course, tests of various cleaning methods.

Most of these studies are either in progress or will soon be. In addition, however, there are several projects which we feel are of critical importance and should be pursued with greater urgency. One of these was touched on in this paper. We refer to what we will call the intake hose enhancement effect. The interior walls of the intake hose (when there is one) develop colonies of organisms on them. The data may indicate that (as discussed above) the heat exchanger fouling rate is then higher than when there is no intake hose. Whether this

effect is ultimately confirmed or not, a related phenomenon is well known. That is that a structure, such as an OTEC plant, in the open ocean will cause a burgeoning of sea life in its neighborhood. Because of this the fouling rates which are now being measured could be much lower than would be representative of OTEC heat exchangers.

One way of quickly getting information on this point would be to mount several test units on an existing oil production rig in the Gulf of Mexico. Our group began investigating this possibility almost two years ago with very positive results. A major oil company has agreed to give us access to almost any of their rigs for this purpose at no cost. It appears to us to be by far the cheapest and quickest way to get useful biofouling data of many sorts, even if we ignore the possible importance of the enhancement effect.

In addition, some of the oil rigs are in sufficiently deep water so that useful data could be obtained on the potentially critical problem of cold water (condenser) fouling. The cold water data could be obtained in this way at 1/3 to 1/10 the cost of alternative methods, and in a much shorter time.

Several times in the past year we have proposed that these efforts be started as soon as possible. We again urge ERDA and the Biofouling Project Office to give them serious consideration.

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TABLE I

SUMMARY OF DATA FROM SUBMERGED BUOY AT KEAHOLE POINT, HAWAII

Nominal Flow Velocity: 3.0 ft/sec

Material: Aluminum (6061-T6)

Time (Weeks)	$\langle h \rangle$ $\left(\frac{\text{BTU}}{\text{hr ft}^2 \text{ } ^\circ\text{F}} \right)$	$\Delta \langle 1/h \rangle \equiv R_f$ $\left(\frac{\text{hr ft}^2 \text{ } ^\circ\text{F}}{\text{BTU}} \right) \times 10^5$	τ_f (mils)
0.3	680 $\pm$ 7 (5)	0.0 $\pm$ 2.1	0.0 $\pm$ 0.09
1.3	671 $\pm$ 7 (1)	2.0 $\pm$ 2.1	0.08 $\pm$ 0.09
1.9	673 $\pm$ 7 (4)	1.6 $\pm$ 2.1	0.07 $\pm$ 0.09
3.3	661 $\pm$ 7 (1)	4.1 $\pm$ 2.1	0.17 $\pm$ 0.09
4.3	670 $\pm$ 7 (3)	2.3 $\pm$ 2.1	0.10 $\pm$ 0.09
5.3	662 $\pm$ 7 (1)	3.9 $\pm$ 2.1	0.16 $\pm$ 0.09
6.3	654 $\pm$ 7 (2)	5.8 $\pm$ 2.1	0.24 $\pm$ 0.09
7.3	629 $\pm$ 6 (3)	12.0 $\pm$ 2.2	0.50 $\pm$ 0.09
8.3	584 $\pm$ 6 (2)	24.2 $\pm$ 2.3	1.02 $\pm$ 0.10
9.3	559 $\pm$ 6 (1)	31.9 $\pm$ 2.3	1.34 $\pm$ 0.10
10.3	548 $\pm$ 5 (4)	35.6 $\pm$ 2.3	1.50 $\pm$ 0.10
11.3	538 $\pm$ 5 (2)	39.0 $\pm$ 2.4	1.64 $\pm$ 0.10
12.6	578 $\pm$ 6 (2)	25.9 $\pm$ 2.3	1.09 $\pm$ 0.10
13.6	523 $\pm$ 5 (4)	45.0 $\pm$ 2.4	1.89 $\pm$ 0.10
14.3	478 $\pm$ 5 (4)	63.0 $\pm$ 2.6	2.65 $\pm$ 0.11
16.1 (before cleaning)	432 $\pm$ 4 (2)	84.7 $\pm$ 2.7	3.56 $\pm$ 0.11
16.3 (after 1 pass)	522 $\pm$ 18	44.6 $\pm$ 6.6	1.87 $\pm$ 0.28
16.3 (after 11 passes)	566 $\pm$ 8	29.8 $\pm$ 2.7	1.25 $\pm$ 0.11
16.7	553 $\pm$ 6 (2)	34.0 $\pm$ 2.3	1.43 $\pm$ 0.10
18.3	427 $\pm$ 4 (1)	87.0 $\pm$ 2.7	3.65 $\pm$ 0.11
19.3	406 $\pm$ 4 (2)	99.0 $\pm$ 2.9	4.16 $\pm$ 0.12
20.3	368 $\pm$ 4 (1)	125.0 $\pm$ 3.1	5.25 $\pm$ 0.13

TABLE II

SUMMARY OF DATA FROM SUBMERGED BUOY AT KEAHOE POINT, HAWAII

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

Time (Weeks)	$\langle h \rangle$ $\left(\frac{\text{BTU}}{\text{hr ft}^2 \text{ } ^\circ\text{F}} \right)$	$\Delta \langle 1/h \rangle \pm R_f$ $\left(\frac{\text{hr ft}^2 \text{ } ^\circ\text{F}}{\text{BTU}} \right) \times 10^5$	t_f (mils)
0.4	1155 $\pm$ 12 (2)	0.0 $\pm$ 1.3	0.0 $\pm$ 0.05
1.4	1129 $\pm$ 11 (1)	2.0 $\pm$ 1.3	0.08 $\pm$ 0.05
3.1	1115 $\pm$ 11 (1)	3.1 $\pm$ 1.3	0.13 $\pm$ 0.05
3.4	1120 $\pm$ 11 (1)	2.7 $\pm$ 1.3	0.11 $\pm$ 0.05
4.6	1116 $\pm$ 11 (2)	3.0 $\pm$ 1.3	0.13 $\pm$ 0.05
5.4	1073 $\pm$ 11 (3)	6.6 $\pm$ 1.3	0.28 $\pm$ 0.05
6.4	1041 $\pm$ 10 (1)	9.5 $\pm$ 1.3	0.40 $\pm$ 0.05
7.4	975 $\pm$ 10 (1)	16.0 $\pm$ 1.3	0.67 $\pm$ 0.05
8.4	891 $\pm$ 9 (2)	25.6 $\pm$ 1.4	1.08 $\pm$ 0.06
9.4	858 $\pm$ 9 (3)	30.0 $\pm$ 1.5	1.26 $\pm$ 0.06
10.4	797 $\pm$ 8 (3)	38.9 $\pm$ 1.6	1.63 $\pm$ 0.07
11.4	726 $\pm$ 7 (4)	51.2 $\pm$ 1.7	2.15 $\pm$ 0.07
12.7	758 $\pm$ 8 (5)	45.4 $\pm$ 1.6	1.91 $\pm$ 0.07
13.7	673 $\pm$ 7 (2)	61.9 $\pm$ 1.7	2.60 $\pm$ 0.07
14.4	741 $\pm$ 7 (2)	48.4 $\pm$ 1.6	2.03 $\pm$ 0.07
16.1	858 $\pm$ 9 (2)	30.0 $\pm$ 1.4	1.26 $\pm$ 0.06
16.3 (before cleaning)	896 $\pm$ 9 (1)	25.0 $\pm$ 1.4	1.05 $\pm$ 0.06
16.3 (after one pass)	1192 $\pm$ 22	-2.7 $\pm$ 1.2	-0.11 $\pm$ 0.05
16.3 (after six passes)	1276 $\pm$ 13 (4)	-8.2 $\pm$ 1.2	-0.34 $\pm$ 0.05
16.4	1263 $\pm$ 13 (7)	-7.4 $\pm$ 1.2	-0.31 $\pm$ 0.05
18.5	1019 $\pm$ 10 (6)	11.5 $\pm$ 1.3	0.48 $\pm$ 0.05
19.4	912 $\pm$ 9 (5)	21.9 $\pm$ 1.4	0.92 $\pm$ 0.06
20.6	803 $\pm$ 8 (1)	37.9 $\pm$ 1.5	1.59 $\pm$ 0.06

TABLE III

SUMMARY OF DATA FROM SUBMERGED BUOY AT KEAHOLE POINT, HAWAII

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

Time	$\langle h \rangle$	$\Delta \langle 1/h \rangle \equiv R_f$	t_f
(Necks)	$\left(\frac{\text{BTU}}{\text{hr ft}^2 \text{ } ^\circ\text{F}} \right)$	$\left(\frac{\text{hr ft}^2 \text{ } ^\circ\text{F}}{\text{BTU}} \right) \times 10^5$	(mils)
0.6	1132 $\pm$ 11 (2)	0.0 $\pm$ 1.3	0.0 $\pm$ 0.05
1.6	1117 $\pm$ 11 (4)	1.2 $\pm$ 1.3	0.05 $\pm$ 0.05
3.3	1070 $\pm$ 11 (2)	5.2 $\pm$ 1.3	0.22 $\pm$ 0.05
3.6	1076 $\pm$ 11 (3)	4.6 $\pm$ 1.3	0.19 $\pm$ 0.05
4.7	1062 $\pm$ 11 (1)	5.9 $\pm$ 1.3	0.25 $\pm$ 0.05
5.6	1026 $\pm$ 10 (2)	9.2 $\pm$ 1.3	0.39 $\pm$ 0.05
6.6	980 $\pm$ 10 (1)	13.7 $\pm$ 1.3	0.58 $\pm$ 0.05
7.6	925 $\pm$ 9 (2)	19.8 $\pm$ 1.4	0.83 $\pm$ 0.06
8.6	859 $\pm$ 9 (1)	28.1 $\pm$ 1.5	1.18 $\pm$ 0.06
9.6	820 $\pm$ 8 (1)	33.6 $\pm$ 1.5	1.41 $\pm$ 0.06
10.6	773 $\pm$ 8 (2)	41.4 $\pm$ 1.6	1.74 $\pm$ 0.07

TABLE IV

SUMMARY OF DATA FROM NOII, KEAHOLE POINT, HAWAII

Nominal Flow Velocity: 3 ft/sec
 Material: Al 6061-T6

Time (Weeks)	$\langle h \rangle$ $\left(\frac{\text{BTU}}{\text{hr ft}^2 \text{ } ^\circ\text{F}} \right)$	$\Delta \left(\frac{1}{R} \right) = R_f$ $\left(\frac{\text{hr ft}^2 \text{ } ^\circ\text{F}}{\text{BTU}} \right) \times 10^5$	t_f (mils)
0	627.2 $\pm$ 8.0	0.0 $\pm$ 2.8	0.0 $\pm$ 0.12
4.0	608.8 $\pm$ 7.5	4.9 $\pm$ 2.8	0.21 $\pm$ 0.12
7.0	551.6 $\pm$ 4.3	21.9 $\pm$ 2.4	0.92 $\pm$ 0.10
9.1	478.8 $\pm$ 3.3	49.5 $\pm$ 2.4	2.08 $\pm$ 0.10
10.1	435.4 $\pm$ 3.7	70.2 $\pm$ 2.8	2.95 $\pm$ 0.12

TABLE V

SUMMARY OF DATA FROM NOII, KEAHOLE POINT, HAWAII

Nominal Flow Velocity: 6 ft./sec.
 Material: Al 6061-T6

Time (Weeks)	$\langle h \rangle$ $\left(\frac{\text{BTU}}{\text{hr ft}^2 \text{ } ^\circ\text{F}} \right)$	$\Delta \left(\frac{1}{R} \right) = R_f$ $\left(\frac{\text{hr ft}^2 \text{ } ^\circ\text{F}}{\text{BTU}} \right) \times 10^5$	t_f (mils)
0	1083.9 $\pm$ 30.0	0.0 $\pm$ 3.7	0.0 $\pm$ 0.16
1.6	1079.0 $\pm$ 12.9	0.4 $\pm$ 2.8	0.02 $\pm$ 0.12
3.6	963.1 $\pm$ 11.1	11.5 $\pm$ 2.9	0.48 $\pm$ 0.12
4.3	946.6 $\pm$ 24.6	13.3 $\pm$ 3.7	0.56 $\pm$ 0.16
5.4	848.0 $\pm$ 14.9	25.6 $\pm$ 3.3	1.08 $\pm$ 0.14

FIGURE CAPTIONS

1. Thermal resistance (R_f) vs. time for the three buoy units.
2. Seawater temperature vs. time for the Aluminum 6 ft/sec. buoy unit.
3. Comparison of R_f vs. time for the two NOAA units and the Aluminum 6 ft/sec. buoy unit.
4. This graph shows the relative values of biological activity off Keahole Point, Hawaii as a function of time of year implied by the (probably incorrect) assumption that the observed differences in fouling rates are due to seasonal variations.
5. Flow velocity vs. time for the three buoy units.
6. Flow velocity vs. time for the Aluminum 6 ft/sec. buoy unit calculated using three different assumptions about the meaning of the erratic flow-meter readings after 11.4 weeks. The true curve is most likely between the extremes shown here.
7. Thermal resistance vs. time of the Aluminum 6 ft/sec. buoy unit as determined using the three velocity curves of Fig. 6. The true curve most likely lies between the extremes shown here.