DATA ANALYSIS FOR OCEAN THERMAL ENERGY CONVERSION (OTEC)

SUSAN M. TUOVILA
ADMINISTRATIVE INFORMATION

The Heat Exchanger Heating task was sponsored by the Department of Energy under Interagency Agreement ET-78-I-01-3218, Task Number 13218, Work Unit Number 01.

The author wishes to thank Mr. David Boswell of DTNSRDC, Annapolis, Maryland for his work on OTEC software development. The assistance of Mr. Glenn Grannemann of Carnegie-Mellon University, Pittsburgh, Pennsylvania, in reviewing Panama City OTEC data analysis techniques is acknowledged.

Released by
W. H. Tolbert, Head
Environmental Sciences Division
November 1979

Under Authority of
M. J. Wynn, Head
Coastal Technology Department
This report describes computer control and analysis techniques for the Ocean Thermal Energy Conversion (OTEC) system at the Naval Coastal Systems Center (NCSC) in Panama City, Florida.

Test site characterization, cleaning systems, and the physical structure of the OTEC system are discussed briefly. Data sampling and analysis techniques are then explained in detail. A discussion of heat transfer theory and copies of software analysis routines are also included.
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INTRODUCTION

Ocean Thermal Energy Conversion (OTEC) is the concept for a system which will extract energy from the ocean by taking advantage of the sizable temperature difference between surface and bottom water in a tropical ocean. A fundamental part of an OTEC system is a large section of heat exchangers through which the energy transfer is made. It is crucial to keep the surface of these heat exchangers clean because fouling by organisms in sea water can cause deterioration of the heat transfer effectiveness. The Naval Coastal Systems Center (NCSC) investigated cleaning techniques that would effectively prevent fouling in metal tubes over a long period of time.

The physical structure and cleaning systems of the OTEC assembly at Panama City, Florida have been described in several papers and will be dealt with only briefly here. This report will describe the computer driven control and data analysis system used in conjunction with the mechanical system. This will include explanations of the physical computer setup and its interaction with hardware components of the system, the software methods of sampling and data management, and data analysis techniques. A brief discussion of the underlying theory of heat transfer is also included.


TEST SITE CONFIGURATION

The test site at NCSC is located on the shores of St. Andrew Bay, an estuary of the Gulf of Mexico, at Panama City, Florida. The OTEC piping assembly and computer system was located on a pier, with the seawater being pumped to test sections from a depth of approximately 7 feet\(^{(3)}\). Three self-priming centrifugal pumps were available with one or two being used to pump seawater from the bay into a header. Twelve tubes were fed from the header; six were of titanium and six of 5052 aluminum so that the cleaning systems could be tested on two different metals. Water flowed from each tube back into the bay, with the flowrate manually adjusted with a valve at the outlet.

CLEANING SYSTEMS

The tubing system contained four control tubes, two tubes in a flow-driven brush cleaning system, two tubes in a reciprocating sponge ball cleaning system, and four tubes in a chlorination system. All cleaning systems worked automatically and were controlled by timers.

One pair of control tubes (one aluminum and one titanium) were allowed to foul freely to provide data on the amount and kind of fouling present. The other pair of control tubes were cleaned daily and served as an internal check of the data gathering system.

The flow-driven brush cleaning system consisted of one aluminum and one titanium tube through which a nylon brush was passed. At each end of the tube was a nylon basket in which the brush was trapped. Periodically, water flow in the tube was reversed to force the brush to the other end of the tube. The brush diameter was slightly larger than the tube's inner diameter and would shear the fouling material off the tube walls.

The recirculating sponge ball cleaning system consisted of one aluminum and one titanium tube in which a sponge ball of a slightly larger diameter than the tube was circulated. The ball was held in a valve and released periodically when the valve was turned. When the ball had gone past an optical sensor, the valve was turned back to its original position and the ball was diverted into a catcher which placed it back into the circulating system.

\(^{(3)}\) ibid.
The control, brush, and sponge ball systems have been described by Lott and Tuovila\(^4\). Tests with the chlorination system have not yet begun. This system consists of two aluminum tubes and two titanium tubes. A chlorine generator releases a known concentration of chlorine into the system; chlorine release may be pulsed at regular intervals or may be continuous so that the concentration of chlorine within the tubes remains constant.

**COMPUTER CONTROL SYSTEM**

A DEC PDP-11/34 computer was used to provide system control and data analysis. Ideally, this system should run continuously without much operator assistance. The main areas of computer control are pump selection, tube selection, and heater control; if necessary, the entire test could be halted by the computer.

Pump performance was monitored throughout a test. If a pump failed to provide uniform flow, an error message was printed to alert the operator to a problem. If the bad pump performance continued, the computer was programmed to automatically shut down the malfunctioning pump and simultaneously activate another pump through a relay panel.

Heaters in the OTEC system consisted of copper heater cylinders which were press fitted to the outside of the heat exchanger tubes. Voltage to the heaters was controlled by a Variac panel, which must be set manually and read into the computer via a DEC AD11-K analog to digital converter. The computer was programmed to be responsible for turning individual heaters on and off, monitoring rates of heat up and cool down of sea water in the tubes, and setting heater voltage limits. The timing schedule for heat up and cool down, and the allowable voltage limits were pre-set by the computer but these default conditions could be altered by the operator at the beginning of a test. Once a test had begun, the computer would continuously turn the heaters on and off according to the prescribed cycle, monitor heater performance, and periodically sample and print voltages. If a heater built up more voltage than a prescribed upper limit, that heater was turned off by the computer and the corresponding tube was "dropped" from the test. This was to prevent damage to heat transfer units.

\(^4\)ibid.
Sonic flow meters were used to measure flow velocity and read into the computer via the A to D converter. Flow had to be set manually via a PVC valve at the output of each tube, but the computer monitors flow rate throughout a test. Maintaining a constant water flow was crucial to correctly determining the heat transfer characteristics of a tube, so any sudden change in flow would trigger an error message to alert the operator. Intermittent or sluggish water flow would cause the heaters to heat the tube excessively or erratically, and that tube would be dropped from the test.

DATA SAMPLING

Software sampling programs, in FORTRAN IV and MACRO assembly language, were initially planned and written by personnel at the David W. Taylor Naval Ship Research and Development Center (DTNSRDC) at Annapolis, Maryland. These routines allowed the computer to read signal output by hardware components of the OTEC systems. An analysis cycle consisted of two parts: (1) heat up, when the heaters are on, and (2) cool down after the heaters have been shut off. Samples were taken during the cool down cycle to determine the exponential heat decay curve for each tube.

The general data analysis scheme is outlined in Figure 1. Four quantities were sampled for each tube: (1) time, (2) heater voltage, (3) water temperature in degrees Celsius, and (4) flow rate in feet per second. Aluminum tubes were sampled successively with heater voltage and water temperature sampled every 3 seconds, and flow rate measured every 9 seconds. For titanium tubes, the sampling rates were twice those for aluminum tubes because the cooling curve for a titanium tube has a longer time constant than that of an aluminum tube. For clean tubes, a time constant of 50-55 seconds is typical of the cooling curve for a titanium tube and 30-35 seconds for aluminum. Sampled values were displayed on a CRT, which was updated every 3 seconds, and printed on a teletype every 10 minutes. Time was provided continuously by a battery driven quartz clock inside the computer and provided for automatic restarting of an OTEC test following any interruption of power to the computer. Sampled values were stored in an array for the duration of sampling cool down time and were printed on a teletype during the next heat up cycle; and were used to provide an analysis of that tube. Heat up time was set at 18 minutes with a cool down time of 12 minutes yielding 48 analyses per tube each day.

(Text Continued on Page 6)
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FIGURE 1. OTEC DATA SAMPLING AND ANALYSIS
DATA ANALYSIS

Data analysis techniques were based on those developed at Carnegie-Mellon University\(^{(n)}\) and were intended to determine changes in the fouling resistance based on the transfer of heat from the tube walls to the sea water flowing inside.

In determining the heat transfer coefficient in a tube, it was assumed that all resistance in the system was due to buildup of a fouling layer at the interface of the pipe interior and the flowing sea water. The resistance at other sites within the unit, such as that present in the copper block and at the interface between pipe and copper block, were assumed to contribute only negligibly to the total resistance in the system.

As a test progressed, the amount of fouling present was estimated from the changes in resistance from a baseline value determined from a Wilson Plot\(^{(6)}\) done on data taken from each tube when it was clean. This plot is essentially a linear regression relating the inverse of flow velocity \((1/\nu^{0.8})\) with fouling resistance \((1/h)\), where \(h\) is a measure of heat transfer. A sample Wilson Plot is shown in Figure 2. Slope was determined experimentally to be approximately \(3.4 \times 10^{-3}\) and the intercept at \(1/\nu^{0.8} = 0\) should ideally be zero. The intercept normally takes a small positive value (approximately \(1.0 \times 10^{-4}\)) which represents the total amount of resistance in the system which is not due to biological fouling (assuming the tube has been properly cleaned). As fouling increases, the Wilson line slope should remain unchanged while the intercept increases, providing an estimate of how much the fouling resistance has increased over the baseline value.

During a test, sea water flowing through tubes in the heat transfer units was heated until the temperature of the tube walls stabilized at a temperature slightly above that of the water flowing inside. Then the heaters were turned off and the tubes cooled by the colder sea water flowing through them. Assuming a constant flow velocity, the voltage decay of the cooling curve can be defined by the relation:

\[
V(t) = V_0 e^{-t/\tau}
\]


where \( t \) is time; \( V \) is the steady state voltage achieved after a tube has been heated; \( T \) is the time constant of the cooling curve; and \( V(t) \) is the voltage at time \( t \). A plot of an exponential decay curve is shown in Figure 3. As fouling increases in a tube, the above relation will continue to hold, with increasingly larger values of \( T \).

In actual practice, the raw cooling curve data are modified before a time constant is determined. The first few seconds of the curve are discarded to ensure that the heater was turned off before data were taken. The actual time was deduced from experience with the physical system and set at 15 seconds for aluminum tubes and 30 seconds for titanium tubes for our system. Secondly, the cooling curve was normalized to zero by subtracting the minimum voltage achieved by the heater; this minimum was estimated by averaging the values of the last several voltages at the end of the cooling curve where the voltage had stabilized to a constant value. Finally, the curve was weighted to minimize bias caused by equipment noise, flow irregularities, and other random system perturbations.

The value of this background noise bias was assumed to be constant and was estimated by the standard deviation in the points used to determine the minimum heater voltage. Since low voltage values in this cooling curve will be affected by the bias more than greater voltage values, the weighting function, based on the determined system bias, weights higher voltages more than lower ones, using the relation:

\[
\text{w}(t) = \frac{(V_n(t))^2}{s}
\]

(2)

where \( t \) is the time, \( V_n(t) \) is the normalized voltage at time \( t \), \( s \) is the standard deviation of the "zero" voltage, and \( w(t) \) is the weight applied to the voltage at time \( t \).

Rather than performing an exponential regression on the cooling curve data, the logarithm, base \( e \), of each data point was taken and a linear equation fit to the resulting line. Weighting of the curve was done in the linear regression routine LINFIT\(^{17}\). Taking the logarithm of both sides of Equation (1) yielded the relation:

\[
\ln V(t) = \ln V_0 - \frac{t}{T}.
\]

\(^{17}\) Bevington, P. R., \textit{Data Reduction and Error Analysis for the Physical Sciences}, pp. 104-105, 1969.
FIGURE 3. COOLING CURVE PLOT
Linear regression then determined the values of the unknowns \( V \) (starting or maximum voltage) and \( \tau \) (time constant of the cooling curve). A correlation coefficient, \( R \), and root mean square error, RMS, were also calculated for the linear fit.

Linear regression was performed twice for each cooling curve. The fit was done on the entire cooling curve (except for the points at the beginning which were previously deleted) and a preliminary estimate of the time constant (\( \tau \)) determined. Then one time constant's worth of data from the beginning of the curve was fit and a final value of \( \tau \) was determined. A more accurate fit was gained by not including the "tail" of the cooling curve where the voltage was approaching its constant minimum value.

Once the value of \( \tau \) has been determined, the heat transfer coefficient can be calculated with the equation:

\[
\ln h = A + B(\ln \tau) + C(\ln \tau)^2 + D(\ln \tau)^3
\]

(4)

where \( A, B, C, \) and \( D \) are constants based on physical characteristics of the tube (dimension, heat capacity, thermal conductivity, etc.). Table 1 gives a description of tube parameters with actual values for each tube being listed in Table 2.

This value of \( h \) had to be corrected because its calculation was based on the assumption that all the heat lost from the tube walls during cool down cycles was transferred to the water flowing through the tube. Two other sources of heat loss were considered: (1) into the air and (2) axial loss along the tube wall. Heat loss into the air was allowed for with the equation:

\( (8) \quad (9) \quad (10) \)


(Text Continued on Page 13)
## TABLE 1

### DESCRIPTION OF TUBE PARAMETERS

<table>
<thead>
<tr>
<th>Parameter No.</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>A: First constant for calculation of h</td>
</tr>
<tr>
<td>2</td>
<td>B: Second constant for calculation of h</td>
</tr>
<tr>
<td>3</td>
<td>C: Third constant for calculation of h</td>
</tr>
<tr>
<td>4</td>
<td>D: Fourth constant for calculation of h</td>
</tr>
<tr>
<td>5</td>
<td>RAD1: Inside radius of tube (in)</td>
</tr>
<tr>
<td>6</td>
<td>RAD2: 1/2 Machined O.D. of tube or copper heater I.D. (in)</td>
</tr>
<tr>
<td>7</td>
<td>RAD3: 1/2 O.D. of copper heater section (in)</td>
</tr>
<tr>
<td>8</td>
<td>AKCYL: Thermal conductivity of copper heater (B/hr ft°F)</td>
</tr>
<tr>
<td>9</td>
<td>AKTUB: Thermal conductivity of tube (B/hr ft°F)</td>
</tr>
<tr>
<td>10</td>
<td>HAIR: Air heat transfer coefficient for heat loss to air</td>
</tr>
<tr>
<td>11</td>
<td>HINTR: 1/h intercept on Wilson Plot (different for each tube)</td>
</tr>
<tr>
<td>12</td>
<td>ALENGTH: Length of heater section on tube (in)</td>
</tr>
<tr>
<td>13</td>
<td>TTHWLL: Wall thickness of thin tube section near heater (in)</td>
</tr>
<tr>
<td>14</td>
<td>VNOM: Nominal water velocity to which results are corrected (fps)</td>
</tr>
<tr>
<td>15</td>
<td>HRSLPE: Slope from Wilson Plot (different for each tube)</td>
</tr>
<tr>
<td>16</td>
<td>THINT: Thermistor calibration curve intercept (°C)</td>
</tr>
<tr>
<td>17</td>
<td>THSLP: Thermistor calibration curve slope</td>
</tr>
<tr>
<td>18</td>
<td>FMINT: Flow meter calibration curve intercept (gpm)</td>
</tr>
<tr>
<td>19</td>
<td>FMSLP: Flow meter calibration curve slope</td>
</tr>
<tr>
<td>20</td>
<td>IWNST: Points after cooling curve starts for data collection to start</td>
</tr>
<tr>
<td>21</td>
<td>IWN: Number of τ's for second data fit</td>
</tr>
</tbody>
</table>

1-19 are real numbers

20-21 are integers
## Table 2
VALUES OF THE PARAMETERS

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<td>1 1 1 1 1 1</td>
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<td></td>
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</tr>
</tbody>
</table>

*Wilson Plot values not entered
An adjustment for axial heat loss yields:

\[ h'' = \frac{h'}{1 + \frac{2}{L\sqrt{\frac{C \times T}{h'}}}} \]  

(6)

where \(L\) is the length of the copper block in inches, \(C\) is thermal conductivity of the tube, and \(T\) is the wall thickness of the tube.

To allow for comparison between values of \(h\) calculated at different times, \(h\) was referenced to a nominal water temperature and flow velocity. The nominal water temperature and flow velocity were chosen to be 70°F and 6 feet per second. The heat transfer coefficient was adjusted with the equations:

\[ h'' = h'' \times \frac{1 + 0.0105 \times 70}{1 + 0.0105 \times T} \]  

(7)

where \(T\) was average water temperature in degrees Fahrenheit measured during the current test, and

\[ \frac{1}{h} = \frac{1}{h''} - \text{SLOPE} \times (F^{-0.8} - 0.8) \]  

(8)

where SLOPE was the slope of the Wilson Plot line and \(F\) was the average water flow velocity measured during the test.

The fouling resistance was calculated by observing the difference in the rate of heat transfer from that of a clean tube

\[ R_f = \frac{1}{h} - \frac{1}{h_{initial}} \]  

where \(h_{initial}\) was the initial heat transfer coefficient as determined from the Wilson Plot.

Tube data analyses were performed by the software subroutines HTCOEF, CCN, and LINFIT; listings of these programs are in Appendix A. Figure 4 shows a typical analysis printout; Table 3 contains an explanation of the analysis parameters. These parameters are also stored on a DEC RK01 floppy disk for future retrieval. Software was developed to print out tube data in a more easily read format, and to compute and plot the daily average and standard deviation of each parameter. An example printout is shown in Table 4; a plot of mean daily fouling resistance values is shown in Figure 5.

(Text Continued on Page 18)
### TABLE 3
ANALYSIS PARAMETERS  
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<table>
<thead>
<tr>
<th>Parameter Number</th>
<th>Parameter Name</th>
<th>Explanation</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>ITUBE</td>
<td>tube number</td>
</tr>
<tr>
<td>2</td>
<td>IDATE</td>
<td>date</td>
</tr>
<tr>
<td>3</td>
<td>ITIME</td>
<td>time</td>
</tr>
<tr>
<td>4</td>
<td>VZERO*</td>
<td>minimum voltage to which thermopile dropped at the end of the cooling curve</td>
</tr>
<tr>
<td>5</td>
<td>DEV</td>
<td>standard deviation of VZERO</td>
</tr>
<tr>
<td>6</td>
<td>IFIT,II,12</td>
<td>fit number, beginning and end point number in cooling curve used for regression</td>
</tr>
<tr>
<td>7</td>
<td>VSTART*</td>
<td>maximum thermopile voltage at beginning of cooling curve</td>
</tr>
<tr>
<td>8</td>
<td>DEV</td>
<td>standard deviation of VSTART</td>
</tr>
<tr>
<td>9</td>
<td>TAU</td>
<td>time constant (seconds) of cooling curve</td>
</tr>
<tr>
<td>10</td>
<td>DEV</td>
<td>standard deviation of TAU</td>
</tr>
<tr>
<td>11</td>
<td>A</td>
<td>intercept of line in logarithmic cooling curve plot</td>
</tr>
<tr>
<td>12</td>
<td>DEV</td>
<td>standard deviation of A</td>
</tr>
<tr>
<td>13</td>
<td>B</td>
<td>slope of line in logarithmic cooling curve plot</td>
</tr>
<tr>
<td>14</td>
<td>DEV</td>
<td>standard deviation of B</td>
</tr>
<tr>
<td>15</td>
<td>R</td>
<td>correlation coefficient of logarithmic cooling curve plot</td>
</tr>
<tr>
<td>16</td>
<td>RMS</td>
<td>root mean square error of cooling curve plot</td>
</tr>
<tr>
<td>17-27</td>
<td></td>
<td>same as 6-16 except for second fit to cooling curve data</td>
</tr>
<tr>
<td>28</td>
<td>T</td>
<td>mean water temperature (degrees Celsius) during cooling cycle</td>
</tr>
</tbody>
</table>

*Values listed in A to D converter units can be converted to voltages by the relation:

\[
\text{volts} = \frac{10 \times \text{AD}}{4096}
\]
### TABLE 3
(Sheet 2 of 2)

<table>
<thead>
<tr>
<th>Parameter Number</th>
<th>Parameter Name</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>29</td>
<td>DEV</td>
<td>standard deviation of T</td>
</tr>
<tr>
<td>30</td>
<td>F</td>
<td>mean flow velocity in feet per second during cooling cycle</td>
</tr>
<tr>
<td>31</td>
<td>DEV</td>
<td>standard deviation of F</td>
</tr>
<tr>
<td>32</td>
<td>HUNCOR</td>
<td>uncorrected heat transfer coefficient (h)</td>
</tr>
<tr>
<td>33</td>
<td>HCOREW</td>
<td>h corrected for air and axial heat losses</td>
</tr>
<tr>
<td>34</td>
<td>TCOR</td>
<td>temperature correction to apply to h</td>
</tr>
<tr>
<td>35</td>
<td>HCREWT</td>
<td>temperature corrected 1/h</td>
</tr>
<tr>
<td>36</td>
<td>VCOR</td>
<td>velocity correction to apply to 1/h</td>
</tr>
<tr>
<td>37</td>
<td>HNOM</td>
<td>corrected, final h</td>
</tr>
<tr>
<td>38</td>
<td>FR</td>
<td>fouling resistance (ft^2-hr-°F BTU⁻¹)</td>
</tr>
<tr>
<td>39</td>
<td>IREC</td>
<td>record number for data storage</td>
</tr>
</tbody>
</table>

**FIGURE 4. TYPICAL ANALYSIS PARAMETERS PRINTOUT**
<table>
<thead>
<tr>
<th>RECI</th>
<th>DATE</th>
<th>TMC</th>
<th>VZER</th>
<th>TMP</th>
<th>FLOU</th>
<th>FLOWR</th>
<th>TAF</th>
<th>HNNM</th>
<th>R</th>
<th>SNS</th>
<th>FEOUL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>May 22</td>
<td>2:00</td>
<td>110</td>
<td>26.91</td>
<td>5.627</td>
<td>0.031</td>
<td>25.42</td>
<td>0.87</td>
<td>0.99994</td>
<td>4.26</td>
<td>0.60</td>
</tr>
<tr>
<td>2</td>
<td>May 22</td>
<td>0:30</td>
<td>207</td>
<td>27.13</td>
<td>5.615</td>
<td>0.025</td>
<td>25.76</td>
<td>0.94</td>
<td>0.99994</td>
<td>4.63</td>
<td>0.68</td>
</tr>
<tr>
<td>3</td>
<td>May 22</td>
<td>1:00</td>
<td>203</td>
<td>24.98</td>
<td>5.607</td>
<td>0.003</td>
<td>25.82</td>
<td>0.94</td>
<td>0.99994</td>
<td>4.91</td>
<td>0.69</td>
</tr>
<tr>
<td>4</td>
<td>May 22</td>
<td>1:30</td>
<td>206</td>
<td>27.21</td>
<td>5.576</td>
<td>0.023</td>
<td>25.65</td>
<td>0.91</td>
<td>0.99994</td>
<td>4.59</td>
<td>0.60</td>
</tr>
<tr>
<td>5</td>
<td>May 22</td>
<td>2:00</td>
<td>211</td>
<td>27.12</td>
<td>5.792</td>
<td>0.003</td>
<td>25.76</td>
<td>0.94</td>
<td>0.99994</td>
<td>4.23</td>
<td>0.68</td>
</tr>
<tr>
<td>6</td>
<td>May 22</td>
<td>2:30</td>
<td>218</td>
<td>27.22</td>
<td>5.678</td>
<td>0.030</td>
<td>25.46</td>
<td>0.87</td>
<td>0.99994</td>
<td>4.26</td>
<td>0.60</td>
</tr>
<tr>
<td>7</td>
<td>May 22</td>
<td>3:00</td>
<td>226</td>
<td>27.22</td>
<td>5.661</td>
<td>0.000</td>
<td>25.36</td>
<td>0.90</td>
<td>0.99994</td>
<td>3.61</td>
<td>0.01</td>
</tr>
<tr>
<td>8</td>
<td>May 22</td>
<td>3:30</td>
<td>224</td>
<td>27.06</td>
<td>5.764</td>
<td>0.004</td>
<td>25.30</td>
<td>0.97</td>
<td>0.99994</td>
<td>3.18</td>
<td>0.72</td>
</tr>
<tr>
<td>9</td>
<td>May 22</td>
<td>4:00</td>
<td>207</td>
<td>27.08</td>
<td>5.603</td>
<td>0.023</td>
<td>25.46</td>
<td>0.96</td>
<td>0.99994</td>
<td>3.61</td>
<td>0.34</td>
</tr>
<tr>
<td>10</td>
<td>May 22</td>
<td>4:30</td>
<td>201</td>
<td>27.02</td>
<td>5.603</td>
<td>0.012</td>
<td>25.92</td>
<td>0.91</td>
<td>0.99994</td>
<td>4.06</td>
<td>0.67</td>
</tr>
<tr>
<td>11</td>
<td>May 22</td>
<td>5:00</td>
<td>207</td>
<td>27.03</td>
<td>5.588</td>
<td>0.008</td>
<td>25.17</td>
<td>0.91</td>
<td>0.99994</td>
<td>3.62</td>
<td>0.68</td>
</tr>
</tbody>
</table>

**TABLE 4**

**TUBE DATA LISTOUT**

**NCSC TM-271-79**

16
FIGURE 5. MEAN DAILY FOULING RESISTANCE VALUES
SYSTEM RELIABILITY

The OTEC computer system at Pinaama City demonstrated good reliability throughout testing, with brief and infrequent computer "down" times. Computer hardware performed well despite round-the-clock operation and an operating environment (a trailer on the pier) with poor temperature and humidity control. Only one major breakdown was experienced last year due to a lightning strike blowing out one of the computer power supplies.

Computer software was continuously modified to allow for system expansion and enhancement of control techniques, and allowing for more accurate analysis of data. Additional software routines, written in BASIC language for use on a Hewlett-Packard 9830A programmable calculator, have provided for cross-checking of results as well as allowing for graphical representation of data.

Fouling resistance was determined for each tube at the end of the cool down cycle; a maximum of 48 analyses were done for each tube in a 24 hour period. The main loss of data was due to a tube being dropped from a test because of flow or heater problems; in such a case, no analyses were done for that tube. All analysis data were rechecked and not used if other problems, such as high flow deviation or high RMS errors, were detected. Errors on the analysis parameters from one run are listed in Table 5. These errors varied between tubes but were consistent for each tube. They appeared to be small enough to allow for adequate day-to-day comparison of RFOUL values.
### Table 5
**Parameter Errors**

<table>
<thead>
<tr>
<th></th>
<th>Tube 1</th>
<th>Tube 2</th>
<th>Tube 3</th>
<th>Tube 4</th>
<th>Tube 5</th>
<th>Tube 6</th>
<th>Tube 7</th>
<th>Tube 8</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Date</strong></td>
<td>0625</td>
<td>0625</td>
<td>0625</td>
<td>0625</td>
<td>0625</td>
<td>0625</td>
<td>0625</td>
<td>0625</td>
</tr>
<tr>
<td><strong>VZERO</strong></td>
<td>333.50</td>
<td>196.55</td>
<td>367.15</td>
<td>202.20</td>
<td>132.90</td>
<td>229.60</td>
<td>235.80</td>
<td>135.30</td>
</tr>
<tr>
<td><strong>σ</strong></td>
<td>2.33</td>
<td>3.58</td>
<td>2.28</td>
<td>2.55</td>
<td>1.33</td>
<td>6.06</td>
<td>3.69</td>
<td>5.24</td>
</tr>
<tr>
<td><strong>VSTART</strong></td>
<td>2425</td>
<td>2183</td>
<td>3018</td>
<td>2666</td>
<td>2771</td>
<td>2483</td>
<td>2694</td>
<td>2194</td>
</tr>
<tr>
<td><strong>σ</strong></td>
<td>2.9</td>
<td>6.5</td>
<td>3.1</td>
<td>4.2</td>
<td>1.7</td>
<td>9.9</td>
<td>4.6</td>
<td>9.4</td>
</tr>
<tr>
<td><strong>τ</strong></td>
<td>46.565</td>
<td>54.122</td>
<td>42.906</td>
<td>69.382</td>
<td>49.661</td>
<td>63.819</td>
<td>43.046</td>
<td>52.424</td>
</tr>
<tr>
<td><strong>σ</strong></td>
<td>0.103</td>
<td>0.301</td>
<td>0.080</td>
<td>0.228</td>
<td>0.065</td>
<td>0.482</td>
<td>0.122</td>
<td>0.391</td>
</tr>
<tr>
<td><strong>A</strong></td>
<td>7.7937</td>
<td>7.6884</td>
<td>8.0124</td>
<td>7.8884</td>
<td>7.9268</td>
<td>7.9172</td>
<td>7.8989</td>
<td>7.6935</td>
</tr>
<tr>
<td><strong>σ</strong></td>
<td>0.0006</td>
<td>0.0015</td>
<td>0.0005</td>
<td>0.0008</td>
<td>0.0003</td>
<td>0.0020</td>
<td>0.0009</td>
<td>0.0021</td>
</tr>
<tr>
<td><strong>B</strong></td>
<td>-0.02148</td>
<td>-0.01848</td>
<td>-0.02331</td>
<td>-0.01441</td>
<td>-0.02014</td>
<td>-0.01567</td>
<td>-0.02323</td>
<td>-0.1908</td>
</tr>
<tr>
<td><strong>σ</strong></td>
<td>0.00002</td>
<td>0.00005</td>
<td>0.00002</td>
<td>0.0002</td>
<td>0.0001</td>
<td>0.0006</td>
<td>0.0003</td>
<td>0.0007</td>
</tr>
<tr>
<td><strong>R</strong></td>
<td>-0.99978</td>
<td>-0.99991</td>
<td>-0.99991</td>
<td>-1.0000</td>
<td>-1.0000</td>
<td>-9.9996</td>
<td>-0.99979</td>
<td>-0.99967</td>
</tr>
<tr>
<td><strong>σ</strong></td>
<td>0.007</td>
<td>0.007</td>
<td>0.006</td>
<td>0.004</td>
<td>0.003</td>
<td>0.003</td>
<td>0.005</td>
<td>0.007</td>
</tr>
<tr>
<td><strong>F</strong></td>
<td>5.501</td>
<td>5.976</td>
<td>5.989</td>
<td>5.430</td>
<td>5.653</td>
<td>4.830</td>
<td>5.714</td>
<td>6.322</td>
</tr>
<tr>
<td><strong>σ</strong></td>
<td>0.001</td>
<td>0.027</td>
<td>0.006</td>
<td>0.006</td>
<td>0.028</td>
<td>0.006</td>
<td>0.019</td>
<td>0.086</td>
</tr>
<tr>
<td><strong>FR</strong></td>
<td>0.99e-4</td>
<td>0.72e-4</td>
<td>4.73e-4</td>
<td>6.90e-4</td>
<td>4.29e-4</td>
<td>2.39e-4</td>
<td>2.84e-4</td>
<td>1.90e-4</td>
</tr>
</tbody>
</table>
APPENDIX A

ANALYSIS PROGRAM LISTOUT

```
TT:DX:HHTCOEF.FOR
C FILE HHTCOEF.FOR 3/22/79-2
C ASF FOR OTEC
C
SUBROUTINE HHTCOEF(ITUBE)
BYTE ITUBE
COMMON /DATA/IVTC(300),IVTH(300),IVFM(300)
COMMON /FLOPPY/INTS(4),REALS(24)
DIMENSION Y(300),WT(300)

ITUBE=THE TUBE NUMBER

COMMON /PRE.IDTEST,IHR,IIMIN,NPREL,MEND,NZERO
COMMON /HISC/ISAMP
COMMON /DATE/IDAY

IDAY,IHR,IIMIN=DAY, HOUR, MINUTE OF START OF DATA
NPREL=#POINTS BEFORE HEATER OFF
MEND=TOTAL # DATA POINTS
ISAMP=SAMPLING INTERVAL IN SECONDS

COMMON /HPARAM/ACCN,BCCN,CCHC,BCCN+RAD1,RAD2,RAD3,
1 AKCV,AKTUBE,TMC,HINT,ALNTH,TWALL,VMOM,HRSLPE,
2 THINT,THSLP,FMINT,FMSLF,IWNST-IWN

ACCN,BCCN,CCHC+BCCN CURVE FIT FOR H=F(TAU)
RAD1=1/2 ID OF TUBE (IN)
RAD2=1/2 OD OF TUBE (IN)
RAD3=1/2 OD OF TUBE (IN)
AKCV= THERMAL COND. OF HEATER CYLINDERS (BTU/HR FT F).
AKTUBE= THERMAL COND. OF TUBE (BTU/HR FT F).
HINT= CONVECTIVE COEFFICIENT FOR HEAT LOSS TO AIR
MOM= MOMENT ON ORIGINATE AXIS IN 'H VRS. 1/V**.8 FLOT
ALNTH= LENGTH OF HEATER CYLINDER SET (IN)
TWALL=WALL THICKNESS OF THIN-WALLED SECTION OF TUBE (IN)
VMOM=MINIMUM FLOW VELOCITY IN TUBE IN FT/SEC
HRSLPE=SLOPE OF 1/H TO 1/(V**.8) CURVE (WILSON FLOT)
IWNST=INTERCEPT IN CENT. DEG. OF THE THERMISTER CURVE
(TWATER=THINT+THSLP*IVTH)
IWNST=INTERCEPT IN GAL/MIN OF THE THERMISTER CURVE
(FLOW=FMINT+FMSLF*IVFM)
FMSLF=SLOPE OF FLOW METER CURVE
IWNST=SAMPLE AT WHICH WINDOW TO START AFTER NPREL
IWN=NUMBER OF TIME CONSTS. FOR FINAL WINDOW
IWNST FUDGE FACTOR TO ALLOW FOR AIR HEAT LOSS

TUBEID-ID OF HEAT EXCHANGER TUBE (IN)

COMMON /ICOLL/IPRTC
ISAMP=ISAMP/50

IF TUBE IS TITANIUM - LOOK AT EVERY OTHER SAMPLE
SO ISAMP SHOULD BE DOUBLED

IF(AKTUBE.LT.50.)ISAMP=ISAMP*2
IHR=IOD(IHR,24)
INTS(1)=ITUBE
INTS(2)=IDAY
INTS(3)=IHR
INTS(4)=IIMIN

WRITE(7,1300)ITUBE,IDAY,IHR,IIMIN
1300 FORMAT(///' TUBE 'I2/' DATE 'I4/' TIME 'I12:'I12

A-1
Best Available Copy
```
GET PARAMETERS FOR THE TUBE
TUBEID=RAD1*2.

GET THERMOCOUPLE ZERO POINT AND STD.DEV.
VTCZRO=0.

DO 100 I=I1,IEND
VTCZRO=VTCZRO+IVTC(I)

100 VTCZRO=VTCZRO/NZERO
STDZRO=0.

DO 110 I=I1,IEND
STDZRO=STDZRO+(IVTC(I)-VTCZRO)**2

110 STDZRO=SQRT(STDZRO/NZERO)
REALS(1)=VTCZRO
REALS(2)=STDZRO
WRITE(7,1000)VTCZRO,STDZRO

IF(STDZRO.NE.0.)GO TO 606

WRITE(7,6077)

6077 FORMAT(//' ANALYSIS ERROR''//)
RETURN

CONTINUE

DO 200 I=I1,IEND
Y(I)=IVTC(I)-VTCZRO

200 WRITE(7,979)IVTC(I),IVTH(I),IVFM(I)

979 FORMAT(4X,12I2)
978 CONTINUE

SHIFT THERMOCOUPLE DATA TO THE ZERO POINT
NP1=NPRELM+1

DO 201 I=I1,IEND
Y(I)=IVTC(I)-VTCZRO

201 WRITE(7,979)IVTC(I),IVTH(I),IVFM(I)

979 FORMAT(4X,12I2)
978 CONTINUE

SET UP DATA ARRAY FOR FIT

DO 300 I=NP1,IEND
ARG1=Y(I)

300 WT(I)=(ARG1/STDZRO)**2

DO FITS OF DATA
DO 999 IFIT=1,2
IF (IFIT.EQ.2)GOTO 350

FIRST FIT FROM NPRELM TO IEND

11=NP1
12=IEND
GOTO 400

SECOND FIT FROM IWST TO IWN TIME CONSTANT

350 I1=IWST+NP1
WRITE(7,1100)VO,DU,TAU,DTHU
1100 FORMAT('VSTART ',F5.0,' TAU ',F5.1,' DTHU ',F5.1)
WRITE(7,1150)A,RA
1150 FORMAT('A ',F7.4,' RA ',F6.4)
GET WATER TEMP AND FLOW VEL. OVER ANALYSIS
AVETH=0.
AVEFU=0.
ALINFN=4085/10001**2
DO 425 1=11+12
AVETH=AVETH+THSLF*AVTH(1)
AVEFU=AVEFU+ALINFN*(FINH*FSLF*TUFN(1))
425 CONTINUE
AVETH=AVETH/NPTS
AVEFU=AVEFU/NPTS
STNFU=0.
DO 450 1=11+12
STNT=STNT+(THSLF*TUFN(1)-AVETH)**2
450 STNFU=STNFU-(STNFU/STNT)**2
STN=STNT-(STNFU/STNT)**2
1200 FORMAT('T ',F7.3,' DEG ',F5.3)
      "F" ('F姊.3* REV. 'F姊.3")

C

C   NOW DET H

CALL CON(TAN,ARCTAN,AVETN,AVETN,IFIT,RHS)
IF (IFIT.EQ.0) WRITE(7,1500)
1500 FORMAT(/)
C
999 CONTINUE
C
IF (.NOT. IDK) RETURN
C
WRITE OUTPUT TO FLOPPY DRIVE IF POSSIBLE
C
CALL ASSIGN(A,'DX1:OUTPUT.MAT','14*','OLB:)
DEFINE FILE 6(2300,52,14,V)
READ(8)IRECNO
IF (IRECNO.GT.2300)
   1.5X,IRECNO,LT,0)
2   50 TO 9999
WRITE(7,3077)IRECNO
WRITE(7,3077)IRECNO
3077 FORMAT(' ARCHIVED ON DATA DISK AS RECORD NUMBER ',GR,1X)
IRECNO=IRECNO+1
WRITE(0,1)IRECNO
CALL CLOSE(8)
RETURN
9999 WRITE(7,3499)IRECNO
2349 FORMAT(' ILLEGAL RECORD NUMBER FOR FLOPPY OUTPUT ',1X)
   1 1X,30(1X,1H*))/
   2 1' PREVIOUS RECORD NOT ARCHIVED',1X,30(1H*))/
   3 ' PLEASE ARRANGE FOR NEW DATA DISK ',1X,30(1H*))/
   4 CALL CLOSE(8)
RETURN
RETURN
END
END
SUBROUTINE CON(TAU, WATER, FLOWEL, HNM, THL, THP)

COMMON (THPAR, P, B, BAN, BAN2, BAN3, ANG, RMTURC,
1 HAT, HINT, ALNGTH, THWLL, VHG, HRSLPE, THINT, THLHP,
2 FINT, FMSL, INWS1, INW)

COMMON (FLOFF, INT54: REALS(24))

RAIR=0 DUE TO PREVIOUS CORRECTION IN HTAIR

IF (TAU.LT.0.001) RETURN

FPNTAU=ALOG(TAU)

THM=2*FPNTAU*(P*FPNTAU*(C1*FPNTAU))

HUNCOR=EXP(THM)

RETURN

HUTC=HUNCOR/ATHCN

WLLCN=(2./ALNGTH+12.)*SORT((AKT*THWLL)/12.)

RALLS=WLLCN/SORT(HUTC)

HDCREW=HUTC/11.0*WALLS

ANORM=(1.4*Q105#70.;/1.4*Q105*(1.8*WATER#32.))

HCREW=ANORM*HDCREW

HCREW 1.0/HCREW

REALS(16)=HUNCOR

REALS(17)=HDCREW

REALS(18)=ANORM

REALS(19)=HCREWT

IF (F1.EQ.2) WRITE(7,100) HUNCOR, HDCREW

100 FORMAT(8, HUNCOR, HCREW)

IF (F1.EQ.2) WRITE(7,200) ANORM, HCREWT

200 FORMAT(10, ANORM, HCREWT)

VBR=FLOWEL**(-.8)

UNNNBM=VNNNBM**(-.8)

VELCOR=HRSLPE*(VBR-UNNNBM)

HRNOM=HENTX-VELCOR

HNOM=1./HRNOM

RFOUL=HRNOM-(-HINT+HRSLPE*VNNBM)

REALS(20)=VELCOR

REALS(21)=HNOM

REALS(22)=RFOUL

REALS(23)=RMS

REALS(24)=0.0

RFOULP=RFOUL*1.E4

IF (F1.EQ.2) WRITE(7,300) VELCOR, HNOM, RFOULP

300 FORMAT(8, VELCOR, HNOM, RFOULP)

RETURN

END
SUBROUTINE LINVIT(Y,WT,NPTS,A,SIGMA,B,SIGMA,B,R,
                    RMS,CHITOT,STD,D1,ISAMP,NPRELH,IDK)

DIMENSION Y(I),WT(I)

IDK=.TRUE.
SUM=0.
SUMX=0.
SUMY=0.
SUMX2=0.
SUMY2=0.
ITIME=(II-2-NPRELH)*ISAMP

DO 10 I=1,NPTS
  XI=I*ISAMP+TTIME
  YI=Y(I)
  WEIGHT=WT(I)
  SUM=SUM+WEIGHT
  SUMX=SUMX+WEIGHT*XI
  SUMY=SUMY+WEIGHT*YI
  SUMX2=SUMX2+WEIGHT*XI*XI
  SUMY2=SUMY2+WEIGHT*YI*YI
  SUMXY=SUMXY+WEIGHT*XI*YI

C CONTINUE

DELTA=SUMP*SUMX2-SUMX*SUMX
A=(SUMX2*SUMY-SUMX*SUMXY)/DELTA
B=(SUMXY*SUM-SUMX*SUMY)/DELTA

C COMPUTE RMS ERROR ON COOLING CURVE FIT

CHITOT=0.
DO 947 I=1,NPTS
  XXX=A+B*(I*ISAMP+TTIME)
  CHITOT=CHITOT+WT(I)*((XXX-Y(I))**2)
RMS=SQRT(CHITOT/FLOAT(NPTS))

947 CONTINUE

VAL1=SUM/DELTA
VAL2=SUM/DELTA
999 IF(VAL1.GE.0.AND.VAL2.GE.0)GO TO 606
WRITE(*,6077) IDK,.FALSE.
RETURN
6077 FORMAT('///ANALYSIS ERROR///')
606 CONTINUE

SIGMA=SORT(VAL1)
SIGMAB=SORT(VAL2)
VAL1=DELTA*(SUM+SUMY2-SUMY*SUMY)
IF(VAL1.GT.0.)GO TO 6061
WRITE(7,6077) ,
IOK=.FALSE.
RETURN

6061 CONTINUE
R=(SUM*SUMXY-SUMX*SUMY)/SORT(VAL1)
IF(SUM.EQ.0.)GO TO 999
IF(NPTS-2.EQ.0.)GO TO 999
IF(CHITOT.LT.0.,OR.SUM.LT.0.,
1 .OR.FLOAT(NPTS)/(FLOAT(NPTS)-2.),LT.0)GO TO 9995
STD=SQRT((FLOAT(NPTS)/(FLOAT(NPTS)-2.)))*(CHITOT/SUM))
RETURN

9995 WRITE(7,9996)CHITOT,SUM,NPTS
9996 FORMAT(' CHITOT ','E14.6',' SUM ','E14.6',' NPTS ','I5')
IOK=.FALSE.
RETURN
END
VARIABLES - HTCOEF, LINFIT, CCN Analysis Programs (others defined at beginning of HTCOEF routine)

1) VTCZRO average minimum value of voltage at tail of cooling curve (VZERO on analysis print out)
2) STDZRO standard deviation of VTCZRO, should be small
3) NZEKO # points used for VTCZRO calculation
4) NPRELIM # points at beginning of cooling curve to ignore
5) NP1 first good cooling curve point (NPRELIM +1)
6) IEND last cooling curve point
7) I1, I2 first, last point of cooling curve to put through linear fit
8) NPTS # points put into linear fit
9) VØ beginning voltage (A/D units) for linear fit (VSTART on analysis printout)
10) DV standard deviation of VØ
11) TAU time constant of cooling curve
12) DTAU standard deviation of TAU
13) A intercept of logarithmic cooling curve fit
14) SIGMAA standard deviation of A
15) B slope of logarithmic cooling curve fit
16) SIGMAB standard deviation of B
17) R correlation coefficient of linear fit
18) RMS RMS error of linear fit
19) AVETW, TWATER average water temperature (T on analysis printout)
20) AVEFV, FLOVEL average flow velocity (F on analysis printout)
21) IFIT # of linear fit to cooling curve (is done twice)
22) **ALINFM**  gal/min to ft/sec conversion
23) **STDWT**  standard deviation of water temperature
24) **STDFV**  standard deviation of flow velocity
25) **OUTPUT.DAT**  disk storage file for analysis parameters
26) **IRECNO**  record # for storage on disk
27) **SUM, SUMX, SUMY, SUMX2, SUMXY, SUMY2**  summation indices
28) **ITIME**  beginning sampling time minus one point
29) **XI**  time for sample I
30) **YI**  point #I for linear fit (normalized logarithm of sample)
31) **WEIGHT**  weight to apply to YI
32) **FNTAU**  log of TAU (base e)
33) **FNH**  log of heat transfer coefficient, L (base e)
34) **HUNCOR**  uncorrected L
35) **RTHENT**  correction to L for air heat loss inside PVC housing (horizontal tubes)
36) **WLLCON, RWALLS**  correction to L for axial heat loss along tube wall
37) **HVDTE**  h, corrected for heat loss to air
38) **HCOREW**  h, corrected for axial heat loss
39) **ANORM**  temperature correction for h (TCOR on analysis printout)
40) **HCREWT**  h, normalized to 70% temperature
41) **HCEWTR**  1 / HCREWT
42) **V8R**  average flow velocity to -.8 power
43) **VNOM**  nominal flow velocity (6 fps)
44) **VNOM8R**  VNOM to -.8 power
45) VELCOR  velocity correction for 1/h (VCOR on analysis printout)
46) HRNOM  1/h (corrected)
47) HNOM  corrected h
48) RFOUL  fouling coefficient (FR on analysis printout)
49) RFOULP  RFOUL * 1.0E4
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