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# A SYSTEM FOR MEASURING THE EFFECT OF FOULING AND CORROSION ON HEAT TRANSFER UNDER SIMULATED OTEC CONDITIONS

By
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December 1976

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# A SYSTEM FOR MEASURING THE EFFECT OF FOULING AND CORROSION ON HEAT TRANSFER UNDER SIMULATED OTEC CONDITIONS

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## ABSTRACT

In this report is described a complete system designed to measure, with high precision, changes in heat transfer rates due to fouling and corrosion of simulated heat exchanger tubes, at sea and under OTEC conditions. All aspects of the system are described in detail, including theory, mechanical design, electronics design, assembly procedures, test and calibration, operating procedures, laboratory results, field results and data analysis programs.

## ACKNOWLEDGMENTS

Many people in addition to the authors of this report contributed to the development of the system. Professor F. C. Munchmeyer and his group at the University of Hawaii provided the boat (research vessel NOI'I) on which two test units were mounted in taking field data at sea, and generally supported the operation during the field tests. Important contributions were also made by Frank Sharkey and Lee Sisselsky. We are greateful to Betsy Schweppe and Ana Morales for untiring effort in typing the manuscript. We thank Paul Kuharic and the machine shop crew, and the electronics shop crew for their efforts.

# 1. INTRODUCTION

1.1. General. In this report, we describe a system which was designed to measure changes in heat transfer rates, due to fouling, in carefully simulated OTEC heat exchanger tubes. The conditions under which these measurements were to be made in some ways impose very stringent constraints. This necessitated the design of an unusual method for measuring heat transfer rates.

The principal constraints which determined the design of the method are these.

a) The test units are, at times, expected to be operated at remote locations. This imposed two requirements on the method. First, power input should not be excessively large. Second, since the apparatus might be inaccessible for long periods of time, it is necessary that the method not be sensitive to absolute calibrations of, e.g., power or temperature sensors.

b) In some circumstances these test units will be used for basic biofouling studies. In order to allow for the study of biofouling without affecting the viability of the responsible organisms the method should allow precise heat transfer rate measurements with minimal temperature rise of the inside tube surface. This also implies the need for small power inputs.

c) The method should be as flexible as possible in its application. This requirement led to the design of a basic experimental unit which is nearly self-contained. This means that a battery of any number of such units may be assembled to permit a variety of experiments to be performed in parallel. Also, the design allows operation with horizontal or vertical tubes (or any other orientation), with the units submerged or mounted on a pier or floating platform, with the pump(s) upstream or downstream of the test section, and with a wide range of flow velocities. The system is adaptable for use in conjunction with fouling cleaning systems for tests.

1.2. The Basic Method. We have developed a simple system for monitoring fouling by monitoring the rate of heat transfer from a tube wall to the seawater flowing inside. We find that the system satisfies all the above constraints.

The method used is to heat a segment of tube wall slightly above the water temperature and then to observe its cooling rate after the heat input is removed. The cooling curve (vs. time) is exponential, according to Newton's law of cooling, with a time constant which is shown to be (apart from small, calculable corrections) inversely proportional to the heat transfer coefficient, h.

The data analysis consists of two main parts. First, given measurements of wall temperature vs. time, an exponential is least-squares fitted to determine the time constant. Second, the time constant and the physical parameters of the system (dimensions, thermal conductivities, etc.) are used to calculate h.

The system which has been devised to perform these functions is described in detail in this report. It has been tested both in the laboratory and in the field. As mentioned above, the system was designed so that it could be used either submerged (down to at least 100 ft.), or mounted on a surface platform. At present it has been used only in the latter mode.

The field experience which proved the design occurred between July 13 and September 30, 1976. During this period two units (as described in this report) were mounted on the deck of the University of Hawaii research vessel NOI'I. Seawater from a depth of 20 feet was pumped up to the units through 2 inch reinforced flexible plastic tubing. The pumps used were downstream of the test units. The pump exhausts were ducted back to the sea through 1 inch flexible plastic tubing.

The electronics used in these runs was designed for an operation in which 6 units are mounted on a submarine buoy, and signals and power are transmitted between the buoy and a shore station through submarine cable. For such operation complex multiplexing circuitry was provided. For applications in which the apparatus is directly accessible (as aboard a boat or other floating platform or on a dock), much simpler electronics may be used. Also, if the units are not to be submerged, the mechanical design may be simplified in construction and use. Suggestions for these and other modifications are discussed later in this report.

1.3. Conclusions. We have developed a system designed to measure the thermal resistance of the fouling layer on the inside of OTEC heat exchanger tubes. This requires only that we be able to measure changes in the heat transfer coefficient. Laboratory results show that we can do this very precisely (<1% error, see Sec. 3). The ultimate potential of the system is discussed in more detail elsewhere (Sec. 3).

The laboratory results also indicate that, although it was not specifically designed to do so, the system can be used to determine absolute values of heat transfer coefficients to high precision (1-2%).

1.4. Plan of Report. The organization of this report is as follows.

Section 1. Introduction.

Section 2. Theory and Data Reduction. This section discusses in detail the equations for finding the time constant, $\tau$, from the cooling data and the equations for determining h from $\tau$, including all necessary corrections. The computer programs for implementing these calculations, and their use, are described.

Section 3. Laboratory and Field Results. In this section laboratory tests of the system are discussed in detail. Typical data are analysed and compared with theoretical expectations. The potential of the system (for example, expected precision corresponding to a given power input) is discussed. Typical field results are exhibited.

Section 4. Mechanical Design. Here we provide a description of the design and construction of a complete test unit including shop drawings, specifications and tolerances, construction and assembly notes, vacuum and pressure tests.

Section 5. Electronics. The electronics design is discussed here including complete circuit diagrams and descriptions of the logic.

Section 6. Operating Procedure. In this section we discuss the general plan for data taking including calibration and check procedures. We include the detailed instructions used by the operator during the NOI'I operation in Appendix E.

Section 7. Modifications and Improvements. The specific system described in this report was designed for remote operation in a submerged location. This same system can also be used in other circumstances. However, when used in conditions of easy access, the equipment, and its use, may be considerably simplified. We provide suggestions for such simplifications. Further, laboratory and field experience with this system have suggested to us improvements of the design. We discuss these also.

# 2. HEAT TRANSFER MEASUREMENTS - THEORY

## 2.1 Basic Considerations: Idealized Theory.

The heat transfer coefficient, h, between the metal tube and the seawater inside it is measured using a method which, to our knowledge, has not been used before. The basic theory of this method is easily elucidated by reference to Fig. 2-1.

Assume the thick-walled section of the tube is of inner diameter D, length L, and has total heat capacity C. Let the heat transfer coefficient from the inner surface of the tube to the flowing water be h (including effects of fouling). If T is the temperature difference between the wall and the flowing water, then the rate of heat loss from the wall (block) is determined by the rate of heat transfer to the water (assuming no other mechanism for heat transfer). If, for the moment, we further assume the thermal resistivity of the block may be neglected, then

$$\frac{dQ(t)}{dt} = C\,\frac{dT(t)}{dt} = \pi DLh\; T(t) \;.$$

The solution to this equation for temperature T vs. time is

$$T(t) = T_o e^{-t/\tau_{ideal}} \tag{2-1}$$

where $T_o$ is the steady state temperature at t=0 and $\tau_{ideal}$, time constant for temperature decay in this idealized case, is given by

$$\tau_{ideal} = C/\pi DLh \tag{2-2}$$

According to this result, then, we may determine the heat transfer coefficient, h, by raising the temperature of the block to $T_o$ (using any convenient means of heat input) and then observing the time constant $\tau_{ideal}$ as the temperature exponentially decays.

We re-emphasize that these are idealized relations presented to clarify the basic ideas. The detailed calculations, including corrections, are presented below.

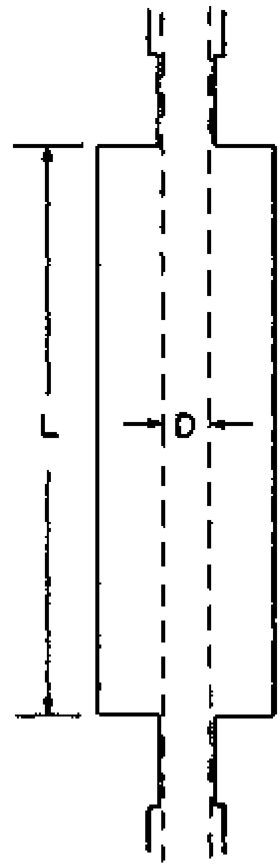



Figure 2-1. Thick-walled section of the tube.

<u>2.2. Detailed Calculations.</u> In order to treat a real system we must eliminate the idealizations imposed in the above calculation. The system being treated is shown in more detail in Fig. 2-2. As shown, a cylindrical copper block (OR=$r_3$) is clamped onto a pipe (OR=$r_2$, IR=$r_1$) of a different material. The pipe wall is thinned down, above and below the block, to a wall thickness $t'$ in order to reduce the axial heat flow out of the block along the walls.

It would be exceedingly difficult to calculate the spatial and temporal temperature distribution exactly in this system. The calculation becomes tractable however if we assume cylindrical symmetry, ignore heat transfer to the air from the top and bottom surfaces of the block, and ignore axial heat flow along the walls. The first two of these approximations are negligibly small. The third is easily corrected for (see Sec. 2.2.2.).

<u>2.2.1. First Approximation.</u> With the assumptions given above, the heat flow equation for the system of Fig. 2-2 may be solved exactly. The calculation is tedious, and we here give only the essential results. The details are given in App. A.

It is shown in App. A that the equation giving temperature (measured by the thermocouples) vs. time is not a simple exponential in this system. Rather it is an infinite series of the form:

$$T = \sum_{n=1}^{\infty} R_n e^{-t/\tau_n} \qquad (2\text{-}3)$$

However, we find that the successive $\tau_n$ decrease rapidly as n increases, if the conductivity is reasonably high. This means that after a short time, Eq. (2-3) reduces to the form

$$T = R_1 e^{-t/\tau_1}$$

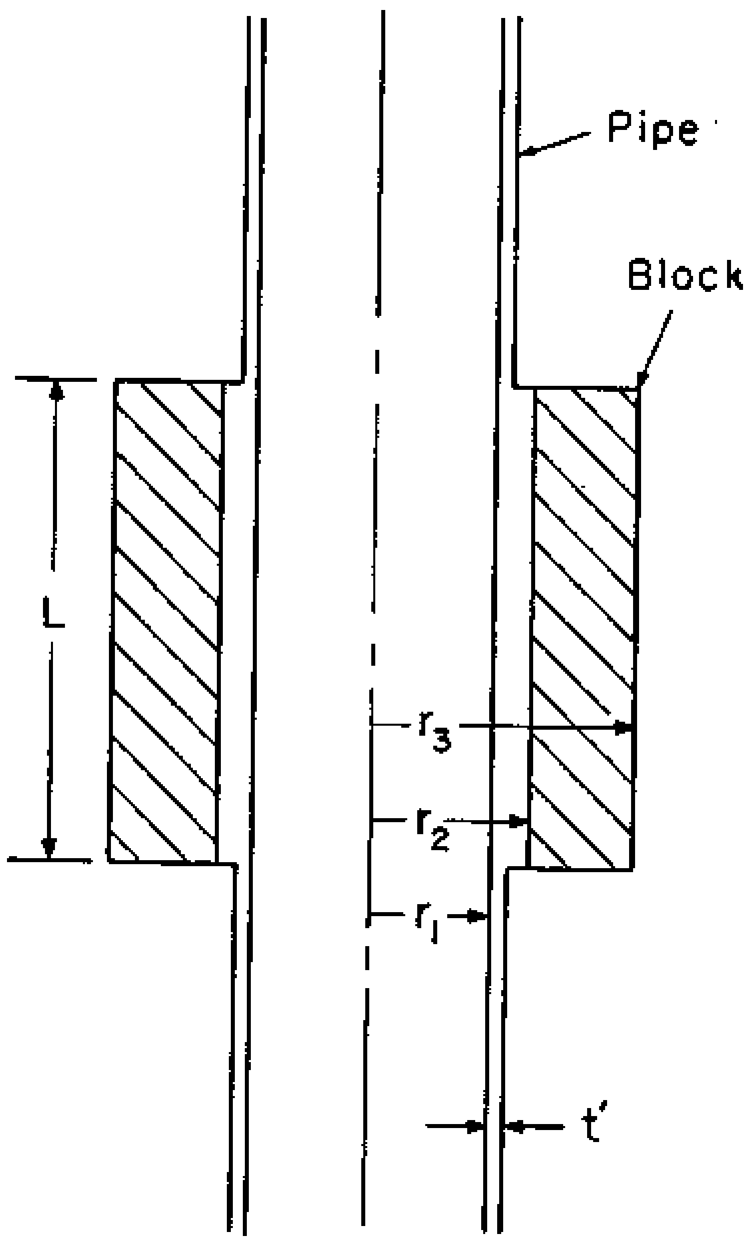



Figure 2-2 Copper Block Geometry

To illustrate the magnitudes involved we have calculated the first few time constants, for several values of h, corresponding to the geometry of our first experimental unit. These are shown in Table 2-1. We see that it only takes a few seconds until the second term in Eq. 2-3 ($e^{-t/\tau_2}$) is less than 1% of the first ($e^{-t/\tau_1}$).

TABLE 2-1. First Three Time Constants for Various Values of h

| $h(BTU/hrft^2 {}^\circ F)$ | $\tau_1$ (sec) | $\tau_2$ (sec) | $\tau_3$ (sec) |
|---|---|---|---|
| 200 | 202.87 | 0.747 | 0.201 |
| 400 | 103.92 | 0.737 | 0.200 |
| 600 | 70.92 | 0.727 | 0.199 |
| 800 | 54.44 | 0.719 | 0.199 |
| 1000 | 44.57 | 0.710 | 0.198 |
| 1200 | 37.97 | 0.702 | 0.197 |
| 1400 | 33.27 | 0.694 | 0.196 |
| 1600 | 29.74 | 0.687 | 0.196 |
| 1800 | 27.00 | 0.679 | 0.195 |
| 2000 | 24.80 | 0.673 | 0.194 |

Thus we arrive at the important result that T(r,t) quickly approaches a pure exponential (and the same exponential) independently of the location of the thermometer (r), and of the form of the initial temperature distribution.

All that remains in order to analyze the data from one of our units is to provide the relation determining $\tau_1$ for a given system, in particular how it depends on the system parameters, especially h which is to be experimentally determined.

As shown in App. A, we can determine $\tau_1$ in terms of h and the other parameters of the system by solving for the first root, $X_1$, (of an infinite number of roots) of the equation:

$$F(x) = 0 \qquad (2\text{-}4)$$

Here,

$$F(x) = \Lambda x \{ Z_1^t [x, (\gamma_2 x, \gamma_3 x)] +$$

$$(h/h_i)\beta_2 \Lambda x \cdot Z_1^t [\gamma_2 x, \gamma_3 x] \cdot Z_1 [x, \omega_2 x] \} +$$

$$\{ Z_0^t [x, (\gamma_2 x, \gamma_3 x)] +$$

$$(h/h_i)\beta_2 \Lambda x \cdot Z_1^t [\gamma_2 x, \gamma_3 x] \cdot Z_0 [x, \omega_2 x]$$

where:

$$Z^1_{\{0 \atop 1\}} [x, (\gamma_2 x, \gamma_3 x)] = j_{\{0 \atop 1\}}(x) Y_1^t [\omega_2 x, (\gamma_2 x, \gamma_3 x)] - y_{\{0 \atop 1\}}(x) \; J_1^t [\omega_2 x, (\gamma_2 x, \gamma_3 x)]$$

$$J_1^t [\omega_2 x, (\gamma_2 x, \gamma_3 x)] = j_1(\omega_2 x) Z_0^t [\gamma_2 x, \gamma_3 x] - \beta_2 j_0(\omega_2 x) Z_1^t [\gamma_2 x, \gamma_3 x]$$

$$Y_1^t [\omega_2 x, (\gamma_2 x, \gamma_3 x)] = y_1(\omega_2 x) Z_0^t [\gamma_2 x, \gamma_3 x] - \beta_2 y_0(\omega_2 x) Z_1^t [\gamma_2 x, \gamma_3 x]$$

$$Z^t_{\{0 \atop 1\}} [\gamma_2 x, \gamma_3 x] = Z_{\{0 \atop 1\}} [\gamma_2 x, \gamma_3 x] - (h_a/b)(1/\beta_2 \Lambda x) \; \tilde{Z}_{\{0 \atop 1\}} [\gamma_2 x, \gamma_3 x]$$

$$Z_{\{0 \atop 1\}} [\gamma_2 x, \gamma_3 x] = j_{\{0 \atop 1\}}(\gamma_2 x) y_1(\gamma_3 x) - y_{\{0 \atop 1\}}(\gamma_2 x) \; j_1(\gamma_3 x)$$

$$\tilde{Z}_{\{0 \atop 1\}} [\gamma_2 x, \gamma_3 x] = j_{\{0 \atop 1\}}(\gamma_2 x) y_0(\gamma_3 x) - y_{\{0 \atop 1\}}(\gamma_2 x) \; j_0(\gamma_3 x)$$

$$\Lambda = k_a/hr_1$$

$$x = \lambda_a r_1$$

$$\gamma_2 = \sqrt{\alpha_a/\alpha_b}\,(r_2/r_1) \quad , \quad \gamma_3 = \sqrt{\alpha_a/\alpha_b}\,(r_3/r_1)$$

$$\omega_2 = r_2/r_1$$

$$\beta_2 = \sqrt{k_b c_b \rho_b / k_a c_a \rho_a}$$

$$\alpha_a = k_a/\rho_a C_a \quad , \quad \alpha_b = k_b/\rho_b C_b$$

In these equations, k, C and $\rho$ are the thermal conductivity, specific heat and density. Subscripts a and b refer to heat exchanger pipe and copper block. The functions J and Y are Bessel functions of the first and second kinds respectively. Further $h_a$, $h_i$ and h are the heat transfer coefficients between the copper block and air, of the interface between the two media (copper block and pipe), and between the pipe and the flowing water, respectively. $\lambda_a$ represents one of the infinite number of separation constants in the solution of the time dependent heat conduction equation by the method of separation of variables. In particular $\lambda_{a_1}$ is related to $\tau_1$ by the equation

$$\tau_1 = \frac{\rho_a C_a}{k_a \lambda_{a_1}^2}$$

2.2.2. Corrections

The theory as outlined above and as described more fully in Appendix A properly takes into account severalfactors which are important, but which are secondary to the main phenomenon of heat transfer from the inside wall of the pipe to the flowing water. Included among these seconday factors are the effect of heat loss from the curved surface of the block to the air, the effect of a thermal resistance at the pipe-block interface, and the effect of different physical properties (specific heat, thermal conductivity, density) for the pipe and the block. There are several other factors which are not taken into account in the above development but which might affect the determination of the heat transfer coefficient from the measured time constant. Calculations have been done to show that some of these factors such as the heat flow to the air from the top and bottom (flat) surfaces of the block as well as heat leaks along the heater leads (see Drawing C-306) are negligibly small.

The theory assumes cylindrical symmetry of the pipe-block system. In practice, the blocks are designed so that they can be demounted from the pipe. An examination of Drawings B-217 and B-218 shows that incorporating this feature involves making a saw cut and drilling holes in the block and using bolts and nuts for clamping. With these modifications the system, although still highly symmetric, does not retain perfect cylindrical symmetry. The effect of this loss of symmetry is difficult to estimate. It is believed that the saw cut in the block has almost no effect. Indeed, if the cut were wedge-shaped instead of slit-shaped, the equations, boundary conditions and solutions would be entirely unaffected. The consequences of drilled holes for clamp bolts and the clamp bolts themselves are not clear. Ultimately we rely on experiment to show that their effects are negligible. To test this point,we made one unit with complete cylindrical symmetry (i.e., no saw cuts and no clamp bolts). This was done using a shrink fit between the block and the pipe. Comparison between this unit and a standard demountable unit showed that both behave according to expectations for the symmetric case (within experimental errors). The experimental data to support this conclusion are given in Section 3.1.4.

There is yet one factor which has not been incorporated into the theory and for which a correction needs to be made. This is the effect of axial heat conduction along the pipe walls, for the theory assumes only radial heat flow. The correction for this effect is calculated in Section A.3 of Appendix A. The result is:

$$h = \frac{1}{1 + (2/L)\sqrt{k_a t'/h}}\, h_{unc,wall} \tag{2-5}$$

Here $h_{unc,wall}$ is the heat transfer coefficient which is uncorrected for axial heat flow along the walls, h is the corrected heat transfer coefficient, and $k_a$ is the thermal conductivity of the pipe. As shown in Fig. 2-2, L is the length of the heater blocks and t' is the thickness of the pipe wall immediately above and below the block. We define the correction factor, $R_{wall}$, as:

$$R_{wall} = (2/L)\sqrt{k_a t'/h}$$

For the purpose of evaluating $R_{wall}$, h is approximated by $h_{unc,wall}$. This is valid because $R_{wall}$ turns out to be ~6% for an aluminium pipe, and less for most other materials. Because $R_{wall}$ <<1 Eq. 2-5 can be rewritten as:

$$h \approx (1-R_{wall})\, h_{unc,wall} \tag{2-6}$$

As described above, the theory has been developed to a point where all important effects are included except the axial heat flow along the pipe walls. It is only this effect for which a correction is required when the full theory of Appendix A is used to extract a heat transfer coefficient from a measured time constant.

However, all analyses of experimental data that have been done to date at CMU have used computer programs that are based on an earlier and less general version of the theory. Specifically, the program HTAU (see Appendix B), which establishes the relationship between heat transfer coefficient and time constant, is based on an earlier version which did not consider heat loss to the air or the effect of thermal contact resistance at the block-pipe interface. Because of this, corrections are made for these two effects as well as for the effect of heat loss along the pipe walls in the subroutine CON of the analysis program LABTTF -(see Appendix C). The manner in which these corrections are made in the analysis program is given below.

From the measured time constant $\tau_1$ we determine an approximate value of the heat transfer coefficient by using the results of program HTAU. This approximate value is not corrected for heat loss to the air or for thermal contact resistance or for heat loss along the pipe walls. It is therefore designated as $h_{unc}$.

The first correction is for heat loss to the air. As described in Section A.4 of Appendix A, if the heat flux to the air ($\dot{Q}_a$) is much less than the heat flux to the water ($\dot{Q}$), then the value for the heat transfer coefficient which is corrected for heat loss to the air (but not for heat loss along the pipe walls) is given by:

$$h'_{unc} = (1-R_{air})\, h_{unc},$$

where

$$R_{air} = (h_a\, r_3/r_1)\,(1/h_{block} + 1/h_{pipe} + (r_1/r_2)\,(1/h_i) + 1/h)$$

and:

$h_a$ is the coefficient appropriate for heat transfer from a vertical surface to the air by natural convection; ($h_a$ ~1.57 BTU/hr ft$^2$ °F for temperatures in the neighborhood of 75°F);

$r_1$, $r_2$, $r_3$ are as defined in Fig. 2-2,

$h_{block} \equiv k_b/(r_1 \ln(r_3/r_1))$ and $k_b$ is the thermal conductivity of the block;

$h_{pipe} \equiv k_a/(r_1 \ln (r_2/r_1))$ and $k_a$ is the thermal conductivity of the pipe;

$h_i$ is the coefficient for heat transfer across the block-pipe interface;

h is the coefficient appropriate for heat transfer from the inside wall of the pipe to the flowing water.

The heat transfer coefficient $h_i$ can be determined from the ordinate intercept of a Wilson plot ($1/h$ vs. $1/v^{0.8}$). Wilson plots were constructed from laboratory data taken on several experimental units and are given in Section 3.1.4. The thermal contact resistance of the block-pipe interface is given in this way as:

$$R_{contact} = (1/h_{intercept})\ (1/A_{inside}) = (1/h_{intercept})\ (1/(2\pi\ r_1 L)),$$

where $A_{inside}$ is the surface area of the interior of the pipe along the length L of the block (see Fig. 2-2). The contact resistance is physically not located at the inside wall of the pipe but rather at the outside wall of the pipe, so:

$$R_{contact} = (1/h_i)\ (1/A_{outside}) = (1/h_i)\ (1/2\pi r_2 L).$$

Thus, the heat transfer coefficient appropriate to the interface is related to the intercept of the Wilson plot by:

$$1/h_i = (r_2/r_1)\ (1/h_{intercept}).$$

From figs. 3-3 and 3-4 we see that $h_{intercept}$ ranges from ~77,000 BTU/hr ft$^2$ °F for an aluminium pipe to ~3,000 BTU/hr ft$^2$ °F for a 90-10 copper-nickel pipe. These values are for direct metal-to-metal contact between pipe and block. In practice, a thermal grease is used at the interface in order to achieve a large value of $h_{intercept}$, as shown in Fig. 3-5.

In evaluating the expression for $R_{air}$, a numerical value for h is needed Since h is not yet known, it is approximated as:

$$1/h \simeq 1/h_{unc} - 1/h_{intercept}.$$

Substituting $(r_2/r_1)$ $(1/h_{intercept})$ for $1/h_i$ and $(1/h_{unc} - 1/h_{intercept})$ for $1/h$ in the expression for $R_{air}$ yields:

$$R_{air} \simeq (h_a\ r_3/r_1)\ (1/h_{block} + 1/h_{pipe} + 1/h_{unc}).$$

All parameters in this expression are now known, so the value for the heat transfer coefficient corrected for heat loss to the air is given by:

$$h'_{unc} = (1-R_{air})h_{unc}$$

The correction for heat loss along the pipe walls remains to be made. As given in Eq. 2-6,

$$h = (1-R_{wall})\ h_{unc,wall}$$

where $h_{unc,wall}$ is the heat transfer coefficient corrected for air and interface effects but not for wall loss. In our case:

$$1/h_{unc,wall} = 1/h'_{unc} - 1/h_{intercept}$$

Then:

$$R_{wall} = (2/L)\sqrt{k_a t'/h}$$
$$= (2/L)\sqrt{k_a t'(1/h'_{unc} - 1/h_{intercept})}$$

Finally, the heat transfer coefficient, h, corrected for air loss, interface effects and wall loss is given by:

$$1/h = [1/(1-R_{wall})]\ [1/h_{unc,wall}]$$
$$= [1/(1-R_{wall})]\ [1/h'_{unc} - 1/h_{intercept}]$$
$$1/h = [1/(1-R_{wall})]\ [1/(1-R_{air})\ (1/h_{unc}) - 1/h_{intercept}] \qquad (2\text{-}8)$$

At this point it may be well to examine what effect a change in $h_{intercept}$ will have on the corrected heat transfer coefficient h. For example, we may wish to determine whether it is worth the trouble to take data and construct a Wilson plot to determine $1/h_{intercept}$ rather than to simply set $1/h_{intercept}$ to zero. In this case $h_{unc}$ is constant (i.e., we are considering only a particular value of time constant $\tau_1$) and from Eq. 2-8 we find:

$$\frac{\partial\,(1/h)}{\partial\,(1/h_{intercept})}\Bigg|_{h_{unc}} = -\frac{1}{1 - R_{wall}}$$

Since $R_{wall} << 1$ for our cases, we have:

$$\Delta\,(1/h) \simeq -\,\Delta\,(1/h_{intercept})$$

In order to put this into perspective, we see from Figure 3-5 that $1/h_{intercept} = 0.023 \times 10^{-3}$ (BTU/hr ft$^2$ °F)$^{-1}$ for a titanium pipe with thermal grease at the interface. At a flow velocity of 6 ft/sec for fresh water in a one-inch schedule 40 pipe, $1/h = 0.821 \times 10^{-3}$ (BTU/hr ft$^2$ °F)$^{-1}$ (from Eq. 3-3). Thus, if $1/h_{intercept}$ is taken to be 0 instead of $0.023 \times 10^{-3}$, a relative error [$\Delta$ (1/h) / (1/h)] of 3% will be made in 1/h.

This 3% error, however, would not be present in the determination of the thermal resistance of the fouling layer at the inside walls of the pipe This follows from the fact that fouling resistance is calculated by subtracting the total thermal resistance at the time of interest from the total thermal resistance at the beginning of the experiment. If we take the thermal resistance at the pipe-block interface to be unchanging with time, then its effect is cancelled in the subtraction process.

2.3 Computer Programs. We use two computer programs to analyze experimental data. These are called HTAU and LABTTF, and are listed in App. B and C. Here we briefly describe how these programs incorporate the calculations discussed in this section to determine values of h from experimental data.

The raw data consist of signal voltages related to copper block temperatures (measured relative to the water temperature), flow velocity values, and absolute water temperatures, each taken every six seconds during the cooling of the block. The basic job of the analysis programs is to use these data to determine a value of heat transfer coefficient to the water. This is done as described below.

2.3.1. The Program HTAU. For a given test unit, this program only needs to be run once. As input, HTAU requires the thermal conductivities ($k_a$ and $k_b$), specific heats ($c_a$ and $c_b$) and densities ($\rho_a$ and $\rho_b$) of the pipe and copper block, as well as their dimensions ($r_1$, $r_2$, $r_3$, L). With this information, and any assumed value of h, the program uses Eq. 2-4 (et seq.) to determine the corresponding value of $\tau_1$. This process is repeated for a sequence of values of h ranging from 150 to 2050 BTU/hr ft$^2$°F. The resulting set of values of h and the corresponding $\tau_1$ are then fitted to the expression

$$\ln(h) = A+B(\ln\tau)+C(\ln\tau)^2+D(\ln\tau)^3 \qquad (2\text{-}9)$$

The fitted values of the constants A, B, C and D then define the relationship, for this particular unit, between a measured $\tau_1$ and the corresponding h. These values are used as input to the program LABTTF.

Because Eq. 2-9 is an ad hoc relationship linking $\tau$ to h, the value of h as calculated from the fitted constants (A,B,C,D) for a particular value of $\tau$ does differ somewhat from the value of h that would be required by the theory in order to produce that particular value of $\tau$. The standard deviation of the percent differences between h as calculated from Eq. 2-9 and the true h from theory was found to be ~0.2% for aluminium as pipe material, ~0.4% for 90 copper-10 nickel, and ~0.7% for titanium. These values apply to the full range of h (150 to 2050 BTU/hr ft$^2$°F) that is used in fitting the constants of Eq. 2-9. These differences may be reduced to any arbitrarily small value by any convenient means. One way, for example is to construct a table of h, $\tau$ (using the output of HTAU) over the range that is pertinent to a particular application. Then, for a given $\tau$, h would be determined from the table by interpolation.

Note that the value of h given by Eq. 2-9 is uncorrected. The various corrections necessary to determine the correct value of h are made in LABTTF.

2.3.2 The Program LABTTF. LABTTF determines the cooling-curve time constant ($\tau$) from the measured thermopile data. It also determines the average water temperature, and average flow velocity as well as their rms deviations. The determination of the time constant is done in two passes by the program. In the first, the cooling-curve data are used to determine an approximate value of $\tau$. This value is approximate primarily because the analysis "time window"* which is used includes the time immediately after the heat is cut, during which transients are present in the thermopile decay curve. The output of this pass includes a listing of the measured data in a more convenient form (e.g., flow velocity rather than flowmeter voltage, and water temperature rather than thermistor bridge voltage).

In the second pass, the approximate value of $\tau$ from the first is used to define the correct analysis window beginning at a safe time after the heat has been cut and extending for an appropriate interval. For lab data, the window usually starts 20 seconds after the heat has been cut and extends for ~4 time constants (the values are not critical). The water temperature and flow velocity associated with a particular decay are then calculated as the average of the values measured during the analysis window. The determination of $\tau$ is by means of a least-squares fit to the measured cooling curve points (as described in Sec. 3.3).

The fitted time constant is then converted to a heat transfer coeffi-

* The analysis time window is the period, during cooling, from which the measurements are used to find the decay time constant, $\tau$, of the cooling curve.

cient using Eq. 2-9, and the necessary corrections are made according to Eq. 2-8. Finally, for purposes of comparison, h is normalized to a value appropriate to a water temperature of 70°F, if the actual water temperature was different from this.

## 2.4. Dealing With the Effects of Water Temperature Fluctuations: "Tuning".

As might well be expected, the ocean constitutes a much more capricious environment in which to measure heat transfer coefficients than does the laboratory. This is borne out by an examination of Fig. 2-3 where an extreme case of ocean behavior is illustrated. There the temperature of the ocean water ($T_w$) passing through an aluminum tube is plotted as a function of time. During the same time interval the natural logarithm of the thermopile decay voltage is plotted. It is obvious that there is a strong correlation between the water temperature fluctuations and the deviation of the thermopile data from the fitted curve. The decay of Fig. 2-3 should be compared with that of Fig. 3-2 which was taken under laboratory conditions where the temperature of the flowing water was much more stable. It is evident that considerable uncertainty must be attached to the extraction of a heat transfer coefficient from the slope of the decay curve of Fig. 2-3. It should be pointed out that early in the decay the thermopile voltage is high and is less sensitive to water temperature fluctuations than the lower voltages later in the decay. In addition, the proper statistical weight attached to each decay point in the fit is proportional to the square of the thermopile voltage, so that earlier points are much more heavily weighted than later points. Yet this relatively close coupling between water temperature fluctuations and thermopile voltage deviations certainly decreases the precision of the measurement of h, as revealed by the data of Fig. 3-6, Section 3.

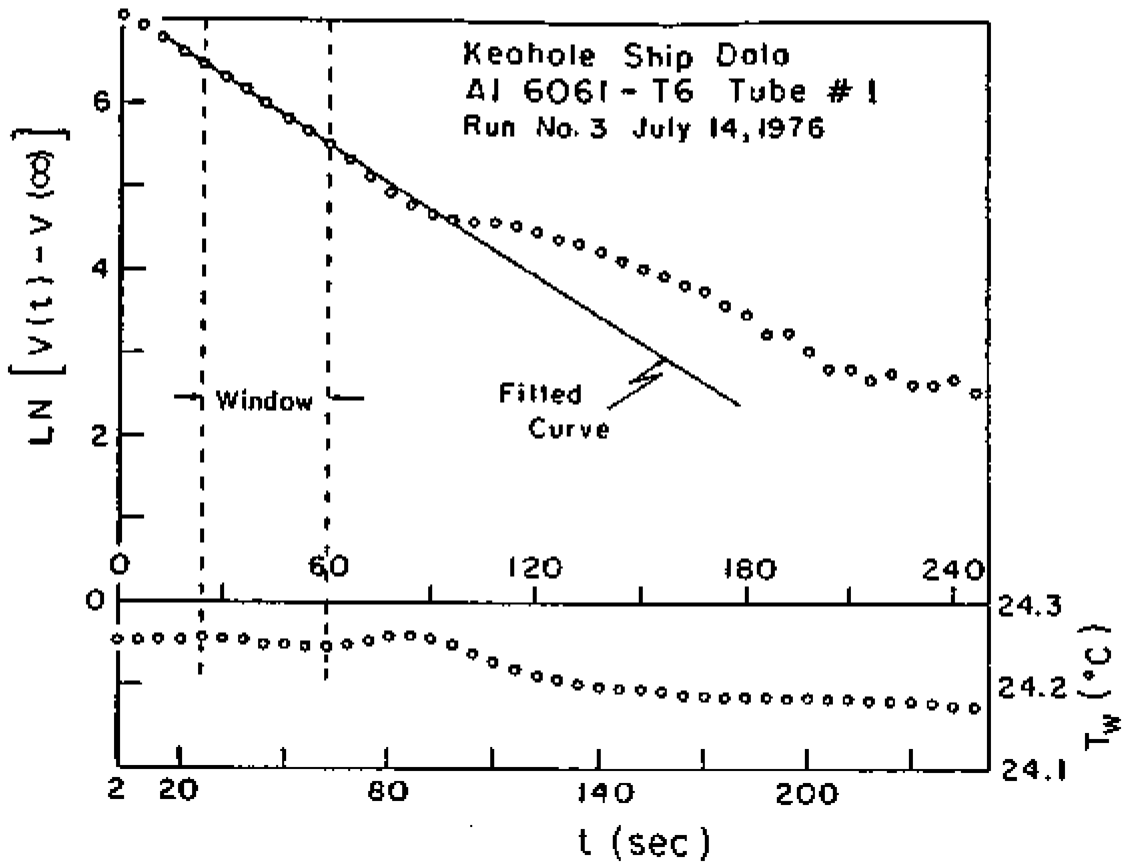



Figure 2-3. Correlation between Water Temperature Fluctuations and Deviations of the Thermopile Decay Data from the Fitted Curve.

There are two approaches in dealing with this coupling problem. The first is to incorporate the water temperature fluctuations into the data analysis. Another is to remove the source of the coupling. Here we consider the latter option.

The data of Fig. 2-3 imply that the thermal time constant of the thermopile reference cylinder is smaller than the thermal time constant of the heater cylinder. (See Sections 3 and 4 for a complete description of the reference cylinder, heater cylinder, and thermopile.) Then the reference cylinder is able to respond to the decrease in water temperature more rapidly than the heater cylinder and this relatively rapid response causes the thermopile data to pull away from the fitted curve. Nominally, the reference cylinder and the heater cylinder have the same time constant. That the time constants are not exactly the same may be due to the differences between the machined tube surface where the heater cylinder is clamped and the unmachined tube surface where the reference cylinder is clamped, to the fact that the tube wall above and below the heater cylinder is thin whereas above and below the reference cylinder it is normal thickness, to differences in potting the reference junctions and the sensing junctions of the thermopile and to other factors.

If the heater and reference cylinders had exactly the same time constant, fluctuations in water temperature would not affect the thermopile decay curve. A simple experimental technique has been developed for measuring the ratio of the time constant of the heater cylinder ($\tau_H$) to the time constant of the reference cylinder ($\tau_R$). With no heat applied to the heater cylinder, water at some temperature (arbitrarily defined as 0) is circulated around the closed loop including the heat exchanger tube, as described in Section 3. At time t=0 a quantity of water at a temperature different from that of the circulating water is quickly added to the reservoir of the circulating water system. This added quantity is chosen to be sufficient to change the temperature of the circulating water by -1°C to a value called $T_0$. The measurement then consists of recording the thermopile response to this step-function change of water temperature. The more closely the time constants of the reference and heater cylinders are matched, the more insensitive the thermopile output will be to the change in water temperature. This can be seen from the following analysis.

With the step function change in water temperature from 0 to $T_0$ being made at time t=0, the temperatures as a function of time for the reference and heater cylinders are described by:

$$\begin{aligned} T_R(t) &= T_0(1-e^{-t/\tau_R}) \\ T_H(t) &= T_0(1-e^{-t/\tau_H}) \; . \end{aligned} \tag{2-10}$$

The thermopile output voltage ($V_{TC}$) is proportional to the temperature difference $T_H(t) - T_R(t)$, so:

$$V_{TC}(t) \propto T_H(t) - T_R(t) = T_0(e^{-t/\tau_R} - e^{-t/\tau_H}) \; ,$$

or:

$$f(t) \equiv \frac{T_H(t) - T_R(t)}{T_0} = e^{-t/\tau_R} - e^{-t/\tau_H} \; . \tag{2-11}$$

A plot of the curve f(t) versus t is given in Fig. 2-4 for the hypothetical (and somewhat extreme) case of $\tau_R$ = 80 sec, and $\tau_H$ = 60 sec. The maximum of the f(t) versus t curve occurs at a time $t_{max}$, where:

$$t_{max} = \frac{\tau_H \tau_R}{\tau_H - \tau_R} \ln(\tau_H/\tau_R) \; . \tag{2-12}$$

Note that $\lim_{\tau_H \to \tau_R} t_{max} = \frac{\tau_H + \tau_R}{2}$ .

The peak height of the f(t) curve is related to appropriate temperatures by:

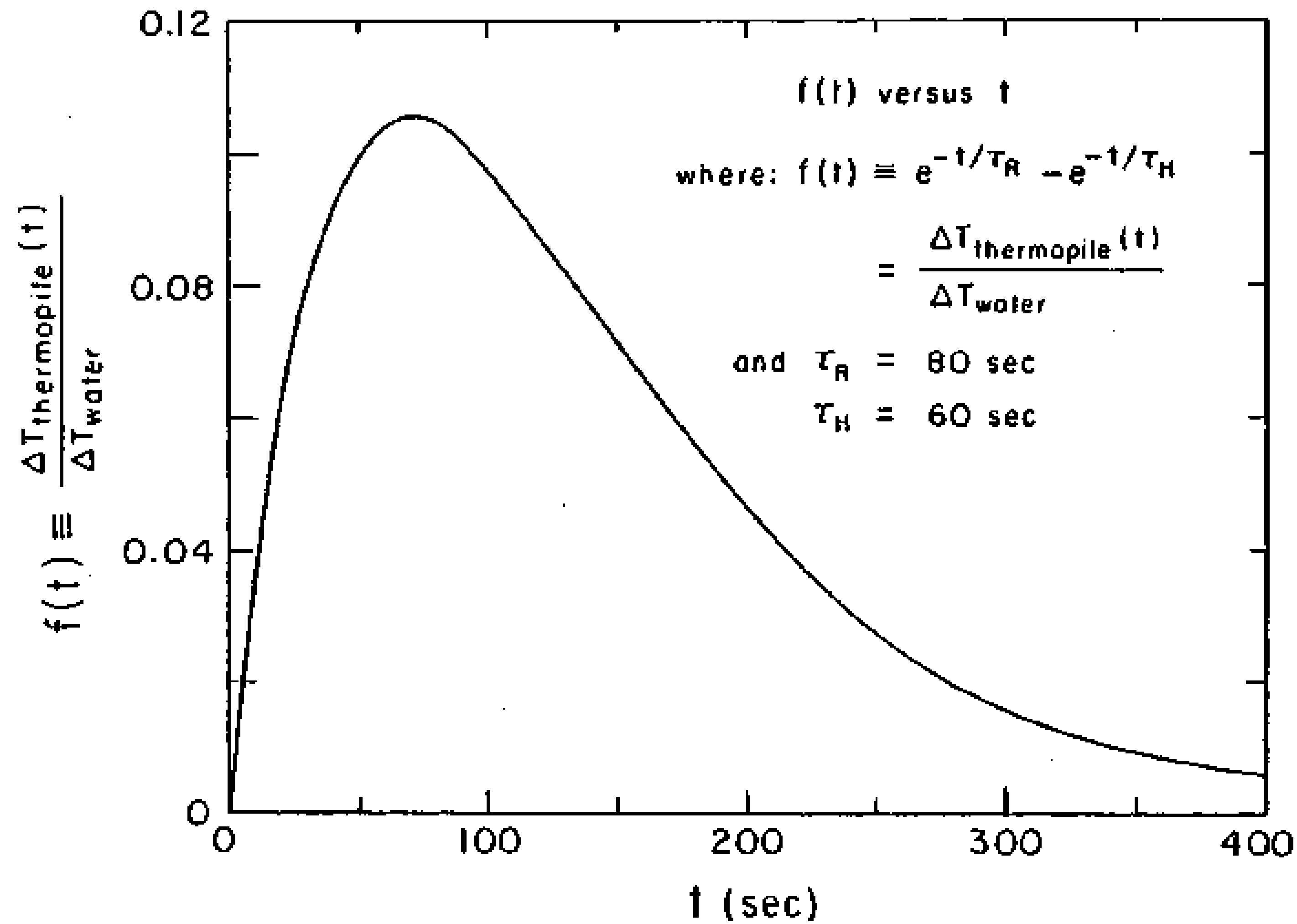



Figure 2-4. Response of the Thermopile to a Step-Function Change in Water Temperature

$$f(t_{max}) = \frac{T_H(t_{max}) - T_R(t_{max})}{T_0} = \frac{(\Delta T_{thermopile})_{max}}{\Delta T_{water}} .$$

A link between the thermopile response and the ratio of time constants ($\tau_H/\tau_R \equiv X$) is therefore given by:

$$\frac{(\Delta T_{thermopile})_{max}}{\Delta T_{water}} = X^{\left[\frac{X}{1-X}\right]} - X^{\left[\frac{1}{1-X}\right]} . \qquad (2\text{-}13)$$

A plot of Eq. 2-13 is given in Fig. 2-5, which permits a determination of the matching between $\tau_H$ and $\tau_R$ ($\tau_H/\tau_R$) required in order to achieve a given insensitivity of the thermopile to water temperature variations ($(\Delta T_{thermopile})_{max}/\Delta T_{water}$). From Eq. 2-12 and Fig. 2-4 it is evident that the impact of a rapid water temperature variation is still appreciably felt by the thermopile even three time constants after the variation has occured. For this reason it might be quite useful to "tune" the cylinders so that $\tau_H/\tau_R$ is nearly 1. Proposed methods for "tuning" include varying the pressure by which the cylinders are clamped to the tube, removing mass from the reference cylinder, and adding mass to the reference cylinder by means of rings which would clamp to the circumference of the cylinder.

If a fine tuning with $|1-\tau_H/\tau_R| \leq 0.02$ is achieved, abrupt changes in the ocean water temperature as large as 0.1°C would only show up on the thermopile as ~0.001°C peaks, as determined from Figure 2-5. This is quite satisfactory since the slight instabilities in the existing electronics limits the resolution of the thermopile circuit to 0.001°C. No problems are envisioned in achieving this degree of tuning, and consequently the thermopile output is expected to be decoupled from the variations in water temperature.

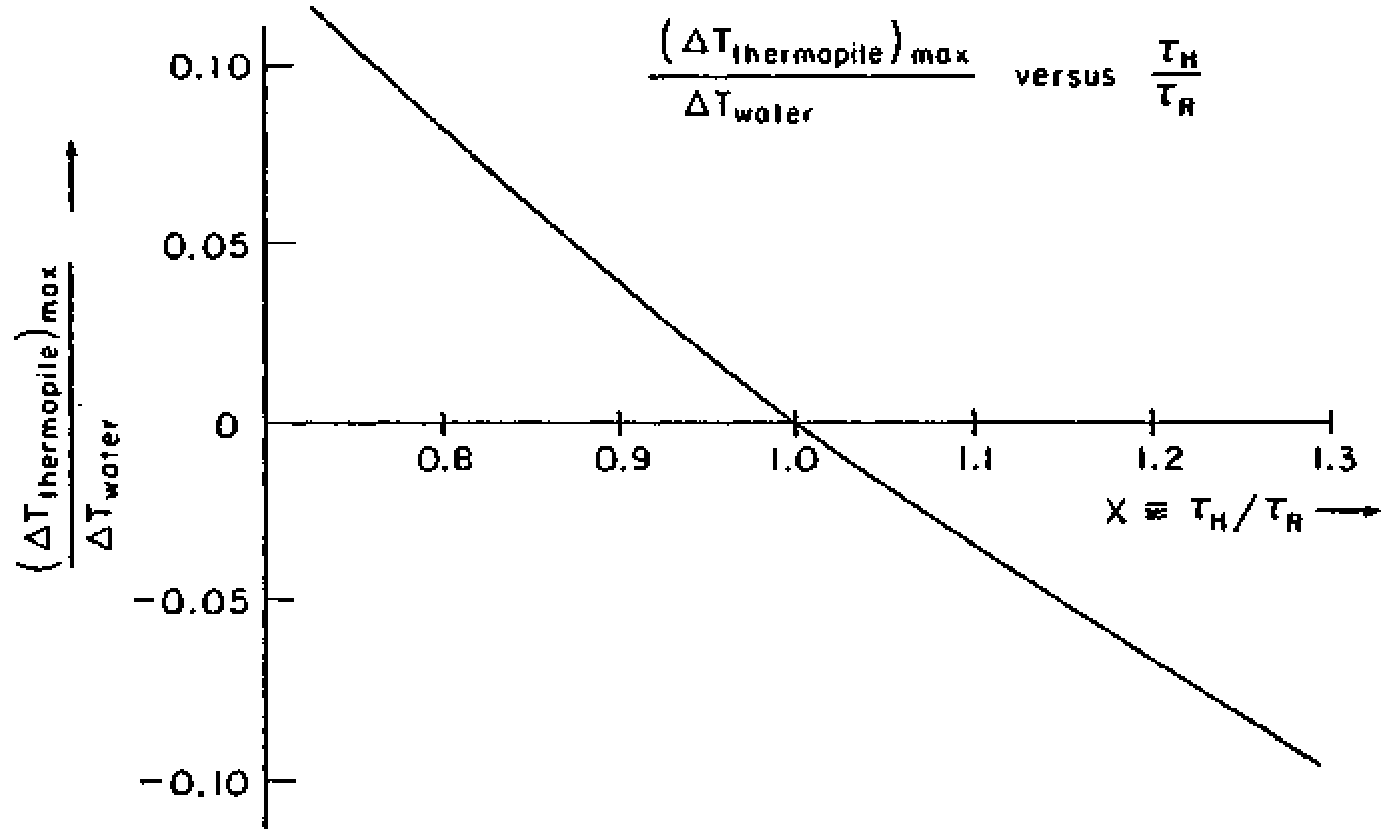



Figure 2-5. Effect of "Tuning" on the Thermopile Response to a Step-Function Change in Water Temperature.

## 3. LABORATORY AND FIELD RESULTS

Of primary importance in assessing the severity of biofouling in heat exchanger tubes is a reliable and precise method for measuring the rate at which heat is transferred from the inner wall of the heat exchanger tube to the flowing water. This rate of heat transfer is determined both by the extent to which the inner wall of the tube has been fouled and by the properties of the laminar layer of the flowing water. As detailed in Section 2, the method for measuring the heat transfer coefficient (h) essentially involves storing a quantity of heat in a thick-walled section of the tube and then observing the rate at which this quantity of heat passes into the flowing water. The apparatus required to monitor this procedure is presented below, along with some representative results and the interpretation which has been given to them.

### 3.1. Laboratory Data.

3.1.1. Apparatus. The heart of the apparatus is sketched in Fig. 3-1. The three 4 inch long sections which make up the copper heater cylinder (ID = 1.300") are clamped to a candidate heat exchanger tube (machined OD = 1.300"). The clamping for each section is done by means of two 1/4" - 20 clamp bolts with socket heads. As part of a standardized procedure, each clamp bolt is tightened with a torque wrench to 15 ft. lb. The 2 inch long copper reference cylinder is similarly mounted. Details concerning the heater and reference cylinders can be found in Drawings B-217, B-218 and B-216, respectively.

The heater cylinders are warmed by supplying an AC current to the 53 Ω nichrome heater which is wrapped around them. Typically 79 V is applied to the heater and this produces a power dissipation of 118 watts. This power dissipation results in a temperature rise at the thermocouple

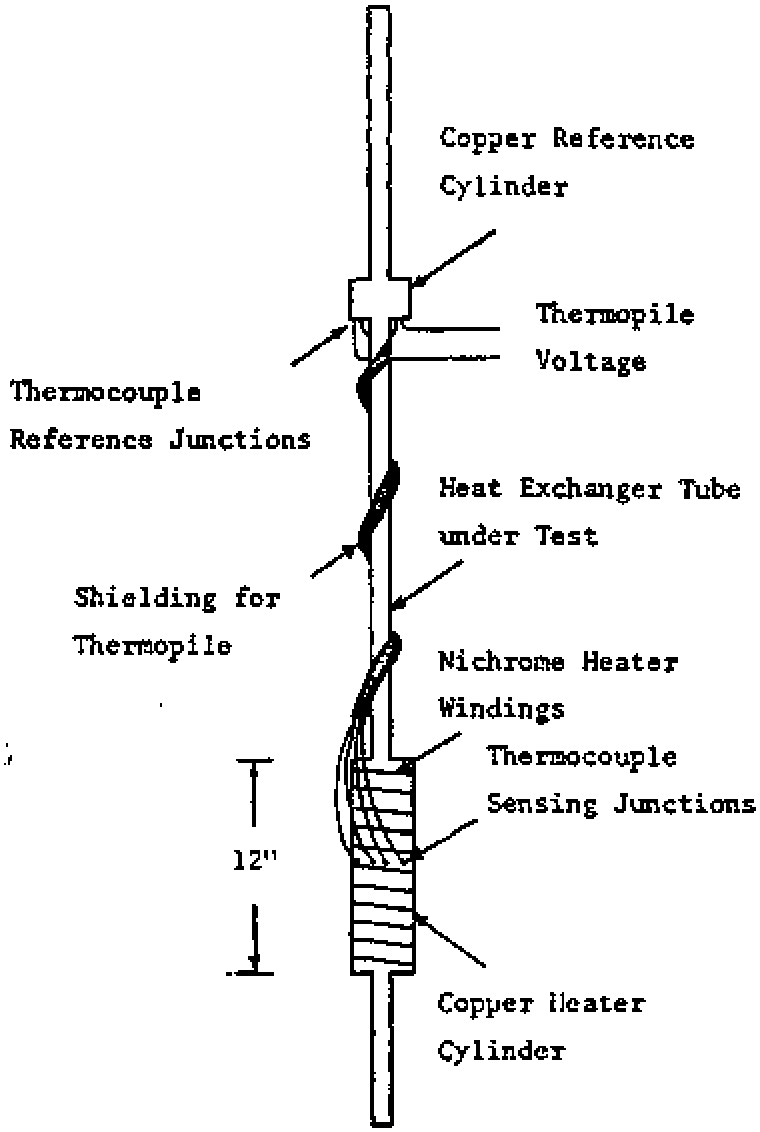



Figure 3-1 Tube with Instrumentation.

locations of ~2°F above that of the flowing water. The heater windings themselves were not found to be noticeably warm to the touch while in operation.

The temperature difference between a location in the copper heater cylinder and the flowing water is measured by means of a thermopile consisting of 11 iron-constantan thermocouples. In the range of 60°F to 80°F each thermocouple has a sensitivity of 28.6 μV/°F, thus giving a total thermopile sensitivity of 0.314 mV/°F. The reference junctions of the thermopile are epoxied into a copper cylinder which is in good thermal contact with the flowing water, while the temperature-sensing junctions are epoxied into the copper heater cylinder. The thermopile voltage was found to be sufficiently stable to allow temperature differences to be measured with a precision of 0.001°F. Details related to the construction of the nichrome heater and the thermopile are given in Section 4.

In the lab set-up, a Ramapo Mark V strain gauge flow meter is placed in series with the heat exchanger tube under test just as in the ocean set-up of Drawing D-402. Water is pumped from a 32 gallon reservoir through the tube and flow meter in a closed loop. The flow meter range is 5 to 50 gal/min (~2 to 21 ft/sec for 1" tubes) and lab tests are generally conducted over the flow range of 2 to 10 ft/sec. A Veco thermistor was potted in copper and immersed in the reservoir in order to monitor the water temperature during the lab measurements.

The thermopile, thermistor, and flow meter signals are made to fall within a common range (e.g., 0 to 10 mV DC), either by design or by proper amplification. The signals are then fed into 3 of the 10 channels of a Keithley 702/7029 Low Voltage Scanner. The three channels are then sequentially sampled by a Keithley 171 Digital Multimeter upon command from a remote clock. The timing pulses of the clock are derived from a 100 kHz crystal within the Keithley 171, so the timing intervals are accurate to within ~0.003%. A scanning rate of 1 channel every 2, 4, or 10 seconds is possible. Thermopile, thermistor, and flow meter data are transferred from the Keithley 171 to a paper tape punch on an ASR-33 teletype by means of a custom-built interface circuit. In this way a permanent and computer-compatible record of the data as a function of time is made during the course of a heat transfer coefficient measurement.

This data acquisition system is quite similar to that used to accumulate data at an ocean site, and in fact, acts as a back-up system for it. With the ocean and lab systems quite similar, it is possible to simulate effects observed in the ocean data under controlled laboratory conditions. For example, fluctuations of water temperature and their effects on a heat transfer coefficient measurement were described with regard to "tuning" in Section 2. Such fluctuations can quite readily be simulated using the lab test system. A fuller description of the lab data acquisition system is given in Appendix D.

3.1.2. Procedure. In these experiments the heat transfer coefficient was measured at several flow velocities. At a particular flow velocity the heater power is turned on and the temperature of the copper heater cylinder is seen to rise until a steady state condition is reached. At this time steady-state values of the amplified thermopile voltage as well as thermistor and flow meter data are recorded at the set intervals on paper tape. The heater power is then turned off, and the decay of the thermopile voltage and the corresponding thermistor and flow meter voltages are recorded. After a period of approximately 10 time-constants (a time-constant ranges from ~1/3 minute to ~1-1/2 minute) the thermopile voltage has decayed to its zero-point value. The final twenty thermopile points are used in the data analysis program to determine the average zero-point value and its RMS deviation. This RMS deviation is then used in estimating the error on the time constant in a least squares fitting routine. This procedure is repeated for each flow velocity.

3.1.3. Thermopile Decay Curve. A typical decay curve of amplified thermopile voltage as a function time is plotted on a semi-log scale in Fig. 3-2. After a short time (~2 sec) the decay becomes highly linear and remains so for a time in excess of four time constants. In this region the relation between thermopile voltage ($V_{TC}$) and time (t) is given by:

$$V_{TC}(t) = V_{TC}(0)e^{-t/\tau} \qquad (3\text{-}1)$$

Linearizing this relationship:

$$\ln(V_{TC}(t)) = \ln(V_{TC}(0)) - t/\tau$$

The data can now be fitted to a straight line of the form:

$$y = a + bx$$

where

$$y = \ln(V_{TC}(t))$$

$$x = t$$

$$a = \ln(V_{TC}(0))$$

$$b = -1/\tau$$

From this fit, the time constant ($\tau$) and an estimate of its error can be determined.

In order to obtain a correct fit, the data must be properly weighted. The error on $V_{TC}$ is constant for all values of $V_{TC}$, since the error arises

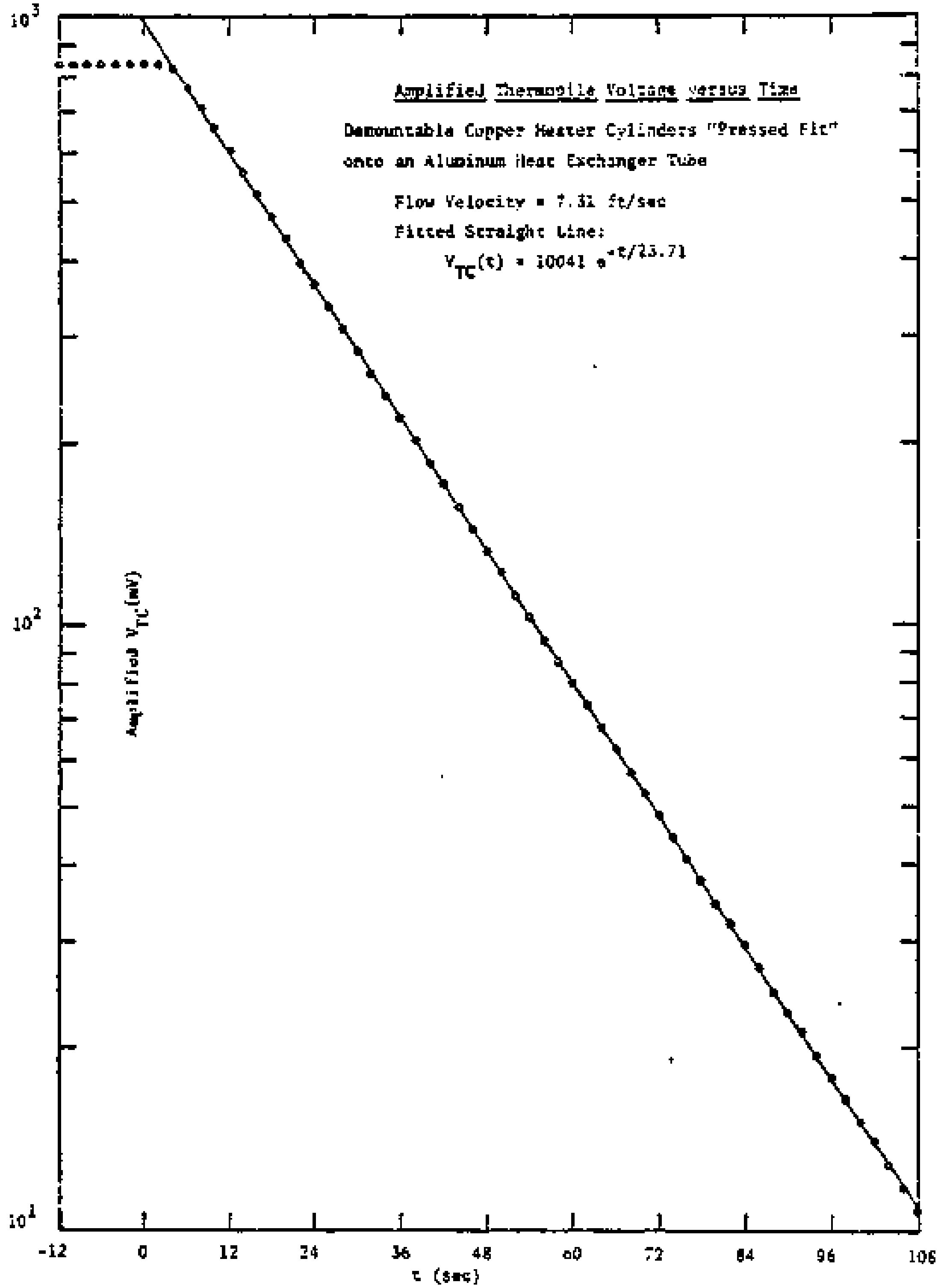



Figure 3-2. Decay of Temperature (Thermopile Voltage) with Time.

from minute changes in temperature and electronic instabilities which do not depend on the magnitude of $V_{TC}$. However it is not $V_{TC}$ that is fitted, but rather $\ln(V_{TC})$. Thus, the proper weight to be assigned to the $i^{th}$ data point is:

$$w_i = \frac{(V_{TC}^{\,i})^2}{(\delta V_{TC})^2}$$

where $\delta V_{TC}$ is the random error of the thermocouple voltage measurement. As mentioned above ($\delta V_{TC}$) is constant for all values of $V_{TC}$ and in practice is estimated from the mean square deviation of the twenty points which are used to determine the zero point.

In the fit, the data during the first 20 seconds (this could be shortened) of the decay are ignored. From the theoretical analysis of the decay it is known that for short times after the heater power is turned off the true realtionship between thermopile voltage and time is more complicated than the single exponential expression given in Eq. (3-1). Therefore the data to be fitted begin at time t=20 seconds and extend to ~4 time constants thereafter. From this fit a value of $\tau$ is obtained with an estimated uncertainty of ~0.5%.

The results of the theoretical analysis of the decay permit the conversion of the measured time constant to a heat transfer coefficient ($h_{unc}$) which is uncorrected for heat losses to the air and along the walls of the heat exchanger tube. These corrections are estimated to be accurate to within 10% and constitute a decrease in $h_{unc}$ of ~6%. Thus the overall precision to which h can be measured and corrected is estimated to be about 1/2%. The task of extracting a time constant ($\tau$) from an experimental decay curve and of converting that measured time constant to a final heat transfer coefficient which is corrected and normalized to a water temperature of 70°F is performed by the program LABTTF. A listing of LABTTF is given in Appendix C.

3.1.4. Comparison of Lab Data with Handbook Values. We expect that the heat transfer coefficient to the flowing water should vary as $v^{0.8}$, where v is the flow velocity. This result follows from a combination of dimensional analysis and correlation of existing data. In dimensional analysis, the proper groupings of the physical properties of the fluid which are pertinent to the heat transfer coefficient are determined. Thus, the ease with which heat is conducted through the laminar layer (thermal conductivity k), the amount of heat which can be stored in a given volume of the fluid (heat capacity $C_p$, density $\rho$), and the thickness of the laminar layer (dynamic viscosity $\mu$, flow velocity v) all enter a dimensional analysis which leads to:

$$\frac{h}{C_p \rho v} = \phi \left(\frac{C_p \mu}{k} , \frac{D \rho v}{\mu}\right)$$

where D is the inner diameter of the tube which carries the fluid, and $\phi$ is some undetermined function of the dimensionless variables. The functional form of $\phi$ is assumed to be:

$$\frac{h}{C_p \rho v} = \phi = \alpha \left(\frac{C_p \mu}{k}\right)^a \left(\frac{D \rho v}{\mu}\right)^b$$

where $\alpha$, a and b are constants to be determined by correlation of existing data and by analogy with theoretically tractable situations. This yields[1]:

$$\frac{h}{C_{pb} \rho v} \left(\frac{C_p \mu}{k}\right)_f^{2/3} = \frac{0.023}{(D \rho v / \mu_f)^{0.2}} \qquad (3\text{-}2)$$

where f indicates evaluation of the property at the film, or laminar layer temperature and b indicates evaluation at the bulk, or turbulent region temperature ($T_f = (T_{wall}+T_{bulk})/2$). The relation (3-2) is said to hold for Reynolds numbers ($Re = D\rho v/\mu$) between 10,000 and 120,000, for Prandtl numbers ($Pr = C_p\mu/k$) between 0.7 and 120, and for L/D>60, where L = length of heat exchanger tube. These conditions are met in the present setup with:

Re = 17,000 to 84,800 (v = 2 ft/sec to 10 ft/sec)

Pr = 6.84 (at T = 70°F)

L/D = 74

In the case where the fluid is water flowing inside clean tubes the physical properties of the fluid are lumped into a temperature dependent term and (3-2) becomes[2]:

$$h = \frac{160(1+0.012\ T_f)}{D^{0.2}}\ v^{0.8} \qquad (3\text{-}3)$$

Thus, the thermal resistance due to the laminar layer of the water (1/h) should vary as $1/v^{0.8}$.

Plots of 1/h versus $1/v^{0.8}$ for v from -2 to -10 ft/sec are shown in Figs. 3-3, 3-4, and 3-5 (data taken using three of our units). In each case a heater cylinder-reference cylinder set was clamped onto the tube as described previously. The data were taken with water temperatures near 70°F, and for purposes of comparison were normalized to 70°F by the temperature-dependent factor in Eq. 3-3.

For the aluminum pipe (alloy 6061-T6) the fitted curve is:

$$1/h = (0.013\pm0.011)\times10^{-3} + (3.442\pm0.034)\times10^{-3}/v^{0.8}$$

The results for the 90 copper 10 nickel pipe are given in Fig. 3-4. These data illustrate the reproducibility of the method, since they were taken on three separate days yet all fall essentially in the same line. The fitted line for all 90 copper 10 nickel data is:

$$1/h = (0.339\pm0.003)\times10^{-3} + (3.468\pm0.008)\times10^{-3}/v^{0.8} \quad .$$

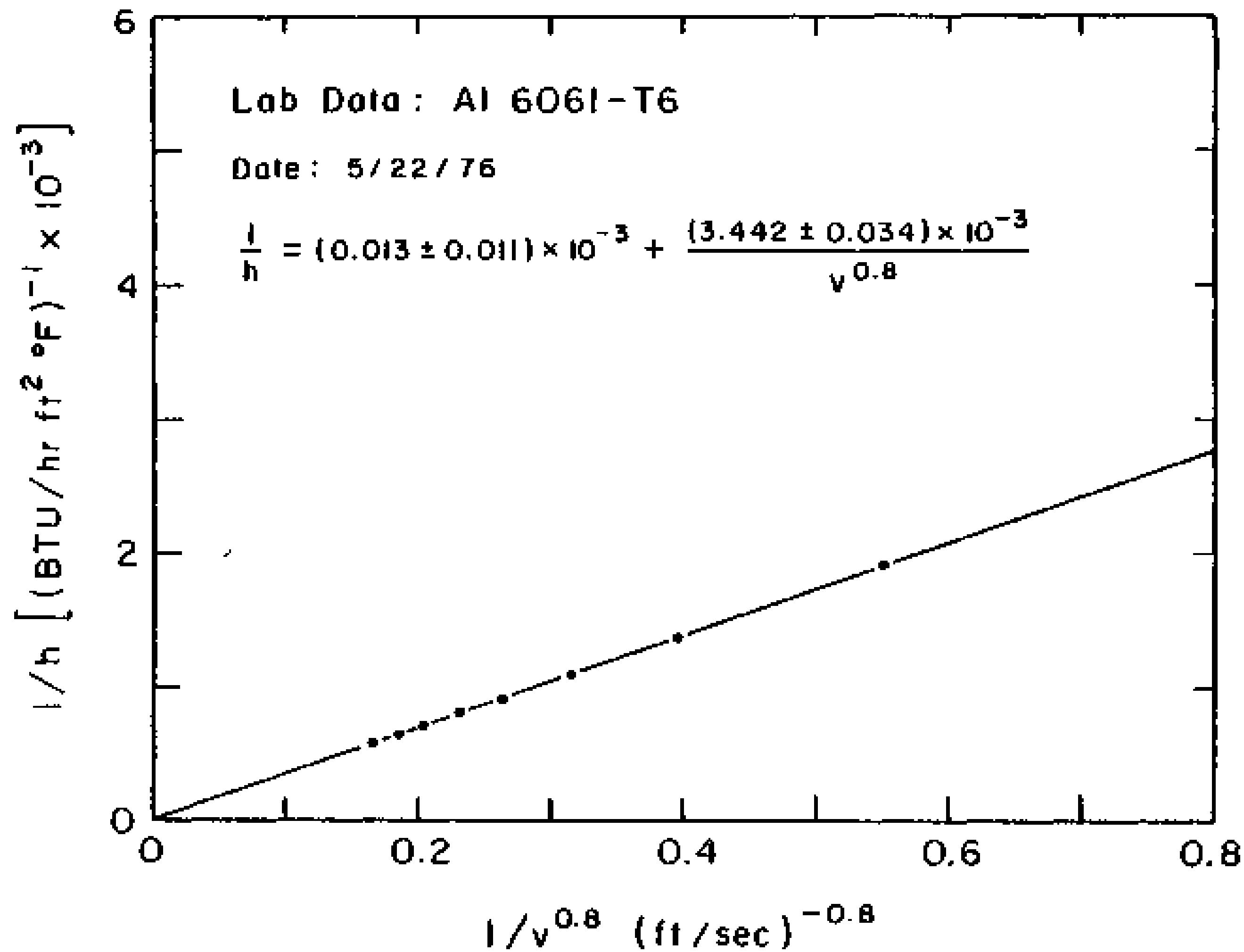



Figure 3-3. Variation of Heat Transfer Coefficient with Flow Velocity (AL 6061-T6 Pipe).

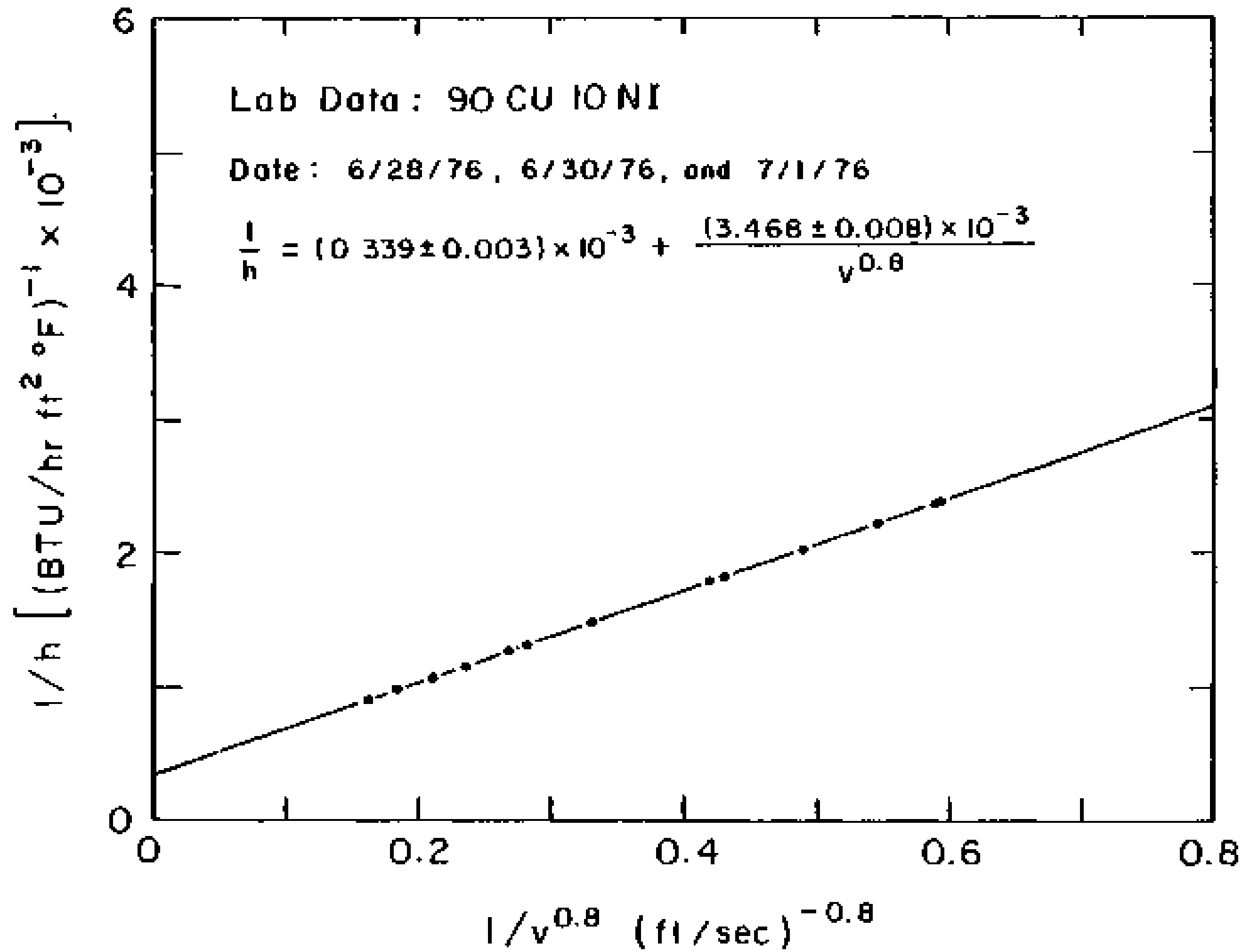



Figure 3-4. Variation of Heat Transfer Coefficient with Flow Velocity (90 CU 10 NI Pipe).

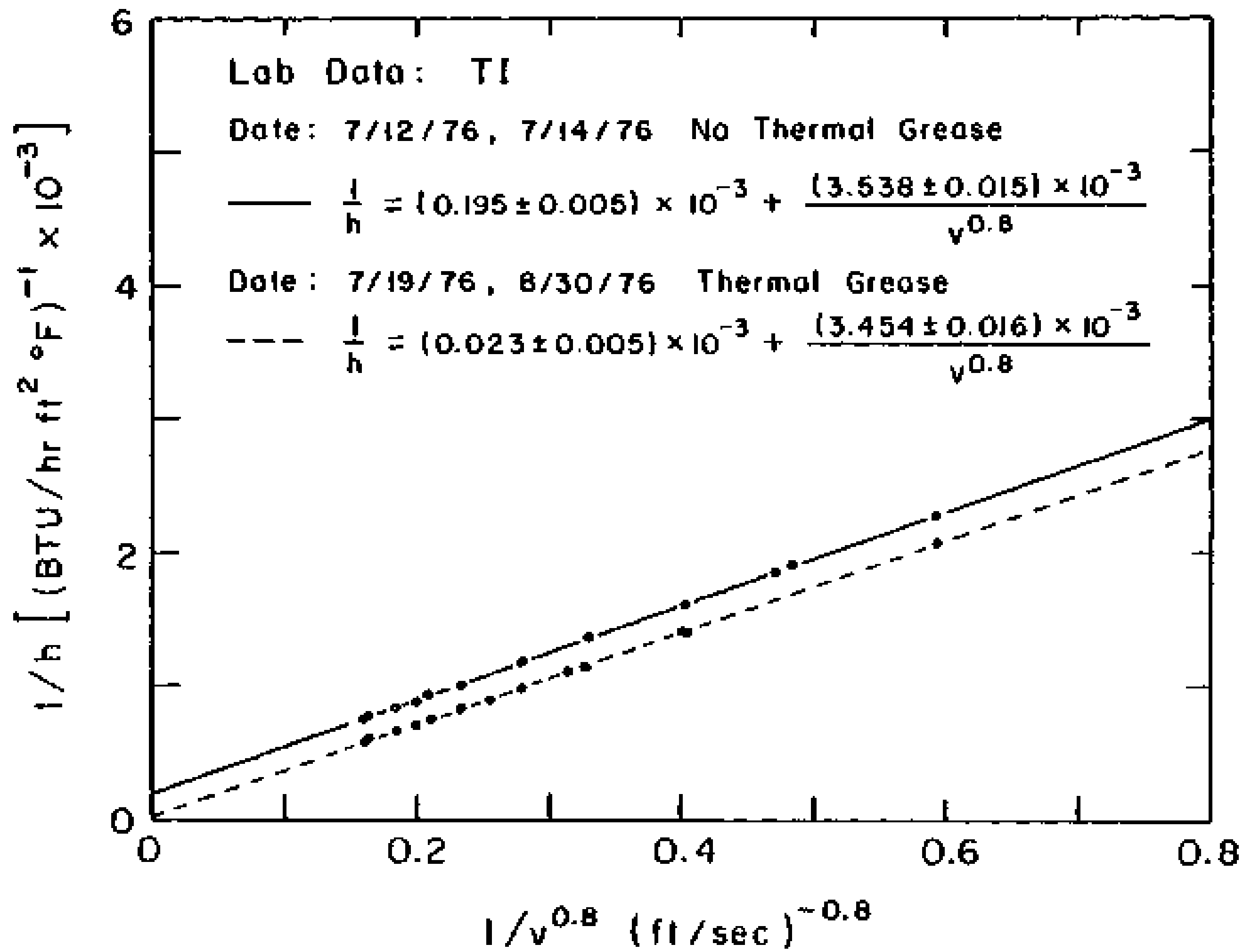



Figure 3-5. Variation of Heat Transfer Coefficient with Flow Velocity (TI Pipe).

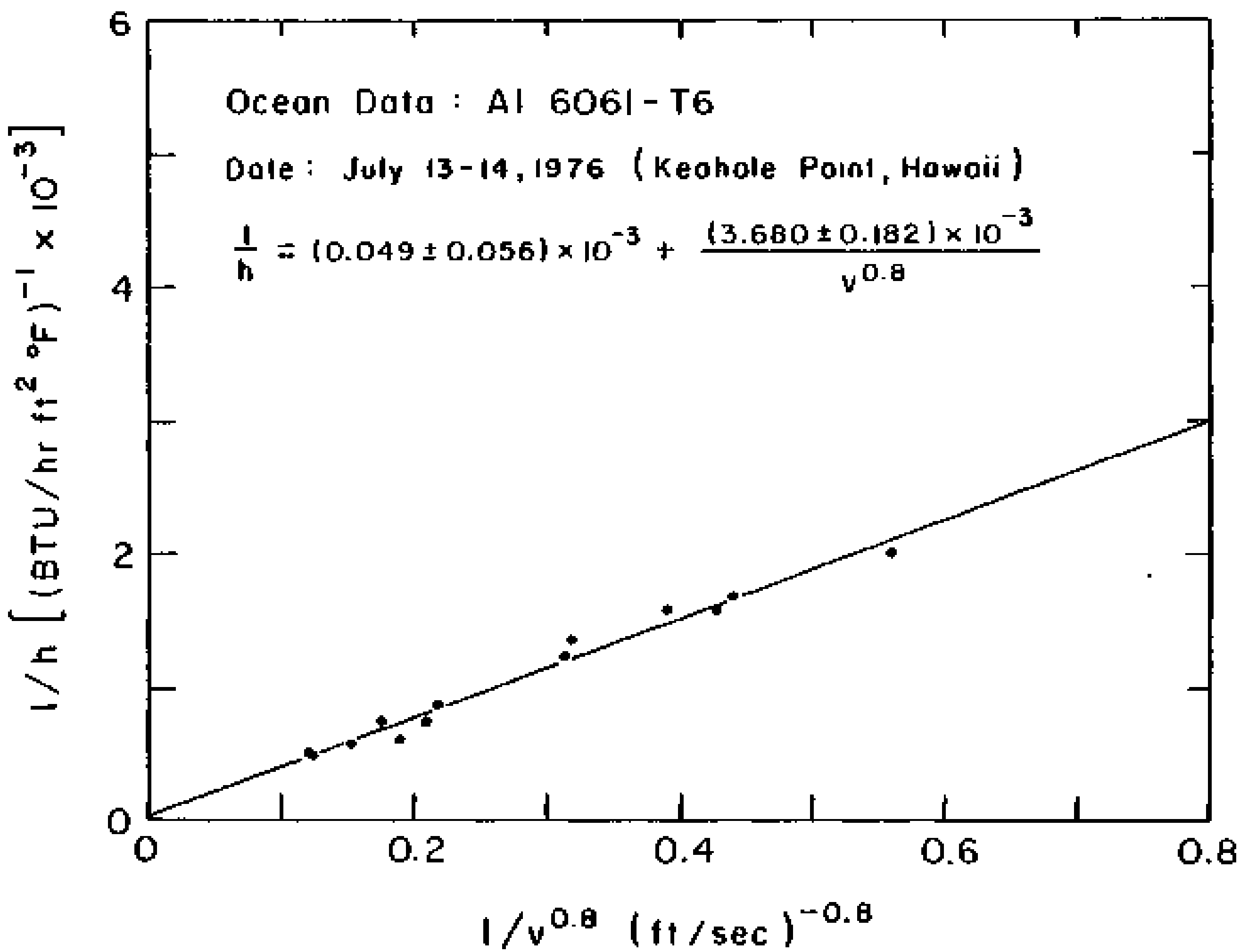



Figure 3-6. Variation of Heat Transfer Coefficient with Flow Velocity (AL 6061-T6 Pipe - Ocean Data).

Note that the 90 copper 10 nickel data, especially, give rise to a non-zero intercept on the 1/h axis. This is because the value of 1/h that is measured is that due to thermal resistances like the velocity independent contact resistance (between the heater cylinders and the tube) and the laminar layer resistance which is proportional to $1/v^{0.8}$. Thus:

$$1/h = 1/h_i + 1/h_{\text{laminar layer}}$$

$$= \text{constant} + \text{constant}'/v^{0.8} \quad .$$

The constant $1/h_i$ is small for aluminum presumably because aluminum is soft and able to deform somewhat as the heater cylinders are clamped onto it.

The data of Fig. 3-5 on a titanium tube were taken under two different conditions. First, the heater cylinders were mounted on the tube as before with a clean metallic copper-titanium interface. The results are:

$$1/h = (0.195\pm0.005)\times10^{-3} + (3.538\pm0.015)\times10^{-3}/v^{0.8} \quad .$$

Then the heater cylinders were removed and a layer of thermal grease (Wakefield Thermal Compound, Part No. 120-8 from Wakefield Engineering, Inc., Wakefield, Massachusetts 01880) was applied to the mating surfaces of the tube and the heater cylinder. The heater cylinders were clamped onto the tube as before, and the results, with the thermal grease, were found to be:

$$1/h = (0.023\pm0.005)\times10^{-3} + (3.454\pm0.016)\times10^{-3}/v^{0.8} \quad .$$

Thus, the thermal grease was quite effective in reducing the intercept to nearly zero. If some application of this method exists for which the non-zero intercept is a troublesome annoyance, it can be reduced by means of thermal grease. If one wishes to fine-tune the reference and heater cylinders to have nearly the same time constant, as discussed in Section 2, it may be desirable to use this thermal grease on the reference cylinder in order to decrease its time constant. Then small standard rings could be attached to the circumference of the reference cylinder to provide additional mass until its time constant matched that of the heater cylinders.

The exponent of v in Eq. 3-3 was also permitted to be a parameter in fitting the data of Figs. 3-3, 3-4, and 3-5. The fitted exponents were found to be 0.88±0.03 for aluminum, 0.79±0.02 for 90 copper 10 nickel, 0.80±0.04 for titanium without thermal grease, and 0.83±0.03 with thermal grease.

In the case of water at 70°F flowing through clean, smooth 1" schedule 40 pipes, the reciprocal of the coefficient of $v^{0.8}$ in Eq. 3-3 is $3.44 \times 10^{-3}$. The agreement between this Handbook value, and the slopes of the fitted curves in Figs. 3-3, 3-4, and 3-5 is quite good, which further instills confidence in the method.

It might be noted that the cylindrical symmetry assumed by the theory in Section 2 is not fully realized in practice because of the need for incorporating bolt holes and stainless steel clamp bolts, etc. in the copper cylinders (see Drawing B-216 thru B-218). These necessary departures from pure cylindrical symmetry are justified a posteriori by the data quoted above. The non-critical nature of this departure is perhaps due to two reasons. First, the amount of copper removed from a pure cylinder is relatively small. Second, the mass of copper removed is partly replaced by stainless steel (bolts and nuts) which has a higher thermal resitance than copper. The effects of decreased mass and increased thermal resistance tend to cancel each other with regard to affecting the time constant of a thermal decay (see Sec. 2.2.2.).

It is useful to point out that in the early stages of the development of this method, a copper cylinder of nearly pure symmetry was shrunk (rather than clamped) onto a 90 copper 10 nickel heat exchanger tube. The results from that set-up are:

$$1/h = (0.180 \pm 0.006) \times 10^{-3} + (3.375 \pm 0.018) \times 10^{-3}/v^{0.8} \quad .$$

3.2. Field Data. In Fig. 3-6 is given a plot of 1/h versus $1/v^{0.8}$ for an aluminum tube through which sea water was pumped. As part of a program to accumulate preliminary biofouling data, the test unit was mounted on a boat which was anchored near the test site at Keahole Point, Hawaii. Warm surface water was pumped to the unit from a depth of 20 feet. The plot of Fig. 3-6 shows considerably more scatter than its laboratory counterpart. It is, of course, highly desirable to keep the scatter of the ocean data small so that small changes in heat transfer coefficient due to biofouling can be detected.

The scatter is due primarily to two effects. The first, and dominant, effect is the temperature fluctuations of the sea water. Since the reference and heater cylinders have somewhat different thermal time constants, variations in water temperature result in variations in the thermopile output voltage, as discussed in Section 2. There are at least two experimental approaches to this problem. One is to "tune" the reference and heater cylinders to nearly the same time constant so that the thermopile output voltage is insensitive to water temperature fluctuations, as demonstrated in Section 2. The second is a "brute force" method of making many consecutive measurements of h and rejecting those which do not meet a pre-determined set of criteria on water temperature stability, etc.

The second, and less important, effect is the variation of flow velocity due to the rolling of the boat and the consequent motion of the intake hose which carries the sea water to the test unit. This effect will disappear when the test units are mounted rigidly on the subsurface buoy, in accordance with the plan to acquire long-term biofouling data.

It might be noted here that because of the difference in heat capacity, density, thermal conductivity and viscosity between fresh water and sea water, the slope of the 1/h versus $1/v^{0.8}$ line is expected to be (5.8±0.9)% higher for sea water as the fluid rather than fresh water. This result follows directly from Eq. 3-2. The observed increase in slope is (7±5)%.

<u>3.3. Limitations and Constraints.</u> It is important for any potential users of this system, or modifications of it, to appreciate what it can do, and the limitations on its performance.

First, it should be understood that the system was not designed to measure h to high accuracy. Instead, the intent was to devise a system for measuring <u>changes</u> in h (or 1/h) precisely, in order to monitor the thermal resistance of the accumulated fouling layer ($R_f = 1/h - 1/h_{initial}$).

One effect to be considered, for example, is that the wall temperature changes during the measurement of h. Because this in turn changes the relevant properties of water, h itself varies during the measurements. However, since the temperature variation is small ($\lesssim 2°F$ typically), such effects are less than one percent in magnitude. However, in determining <u>changes</u> in h (to measure $R_f$), these effects cancel, in large measure. Therefore measurements of $R_f$ are probably not affected by more than a small fraction of a percent by this effect.

Another effect not accounted for in our calculations is that, because of the short length of the heated section (1 foot), the asymptotic temperature distribution is not established in the laminar sublayer at the test section. This means that the measured value of h is slightly larger than the developed-temperature value. Again, however, in measuring differences, these effects largely cancel, and measured values of $R_f$ should be precise to a small fraction of a percent.

Even though the above effects are not corrected for in our calculations, the measured absolute values of h agree very well with theoretical expectations, as shown by the results of the laboratory measurements discussed above.

If it were desired to measure absolute heat transfer coefficients even more precisely, of course, certain obvious steps could be taken to account for the above discussed factors (e.g., calculate corrections, and/or modify the system so as to eliminate the effects). There seems no reason why, if it were desired to do so, h could not be measured with a precision nearly equal to that now achievable in the laboratory in measuring changes in h, i.e., a fraction of a percent.

As shown earlier in this section, the system is able to measure heat transfer rates with a relative precision of better than 1%. It is important to understand that this is limited by the precision of determining the flow velocity. Analysis of the cooling curve data (rms deviation of the measured points from the fitted curve) shows that the contribution to this error due to the precision of temperature measurement is less than 0.2%. This fact has two important implications. First, if a method were devised to measure (or control) flow velocity more precisely, the precision of measurement of h would be correspondingly increased. On the other hand, at least for OTEC purposes, increased precision is not needed. This means, secondly, that correspondingly less precision is acceptable in determining temperature (i.e., time constant of the cooling curve). Depending on the degree of degradation of precision which is acceptable, there are various ways in which the system could be simplified in design or operation. These are discussed in Sec. 7, and we say no more about it here.

The process of determining heat transfer rates with this apparatus depends on the measurement of four quantities: the temperature difference between the heater cylinder and the flowing water (thermopile output), the flow velocity (flow-meter output), the absolute water temperature (thermistor output), and time (during the cooling curve). As stated earlier, the flow measurement (1/2%-1%) limits the precision of the result, while the thermopile output contributes an error of about 0.1%-0.2%. Time is measured by a quartz clock, and is much more accurately determined than any other parameter. It remains to discuss the effect of errors in measuring absolute water temperature (thermistor output).

The measured water temperature is used in two ways. First, the heat transfer coefficient (h) depends upon water temperature, as shown in Eq. 3-3. Because of this, the water temperature must be known when h is measured. Reference to Eq. 3-3 shows that an error of 1°F results in an error of ~0.5% in h. The error in the thermistor output is actually about 0.1°F, corresponding to an error in h less than 0.1%. However, since we are interested in measureing changes in h, errors in thermistor calibration are less important than time variations in the calibration. The contribution to the error in changes in h is therefore even smaller, and is negligible.

The other reason for measuring water temperature is that rapid variations of water temperature introduce errors into the determination of h (see Sec. 2.4.) if the time constants of the heater cylinder and the reference cylinder are not well matched. For this purpose, the absolute calibration of the thermistor is of no importance. It is only necessary that it not vary significantly over the period of the cooling curve.

References:

1. Heat Transmission, William H. McAdams, 3rd ed., McGraw-Hill, 1954 (p. 219).
2. Standard Handbook for Mechanical Engineers, Theodore Baumeister and Lionel S. Marks, McGraw-Hill, 1966 (p. 4-100).

# 4. MECHANICAL DESIGN

The experimental unit used to monitor heat transfer rates in sea water is sketched in Fig. 4-1. The instrumented simulated heat exchanger tube and the flow meter are inside a PVC housing. The pump, also inside a PVC housing, may be connected to the tube on the downstream side as shown, or on the upstream side. Machine shop drawings D-400 thru D-404, C-300 thru C-317 and B-200 thru B-222 and the associated quality assurance section deal with the assembly and construction details of the experimental unit. Now we turn to a description of various parts of the experimental unit.

4.1. Housing. As designed, the experimental unit may be operated while submerged in the sea up to 100 feet deep as well as above the surface. It is necessary, in submerged operation, to keep the sea water from the electrical wiring and instrumentation. Therefore two separate housings are provided; one for the simulated heat exchanger tube and the other for the pump, as shown in Fig. 4-1. The pipe housing is made from three pieces of 6" schedule 80 PVC pipes (one 54" long and two 10" long), with associated flanges and a tee. The tee is needed to accommodate the flow meter. The pump housing is made from 12" schedule 80 PVC pipe with associated flanges. The PVC-pipe-to-PVC-flange joints are made with PVC cement (E-Z Weld$_{tm}$), after cleaning the mating surfaces and coating them with Primer (E-Z Weld$_{tm}$). Both these products are by PCI Industries, Inc., Riviera Beach, Florida. Alternatively, Plastic Pipe cement 925 (Fuseon$_{tm}$) and Primer 905 (Fuseon$_{tm}$) by R&G Sloane Manufacturing Co., Inc., Sun Valley, California have been used successfully. The PVC flanges are closed with end plates made from 1-1/2" PVC sheet. The end plates are bolted to the flanges with 1/16" neoprene

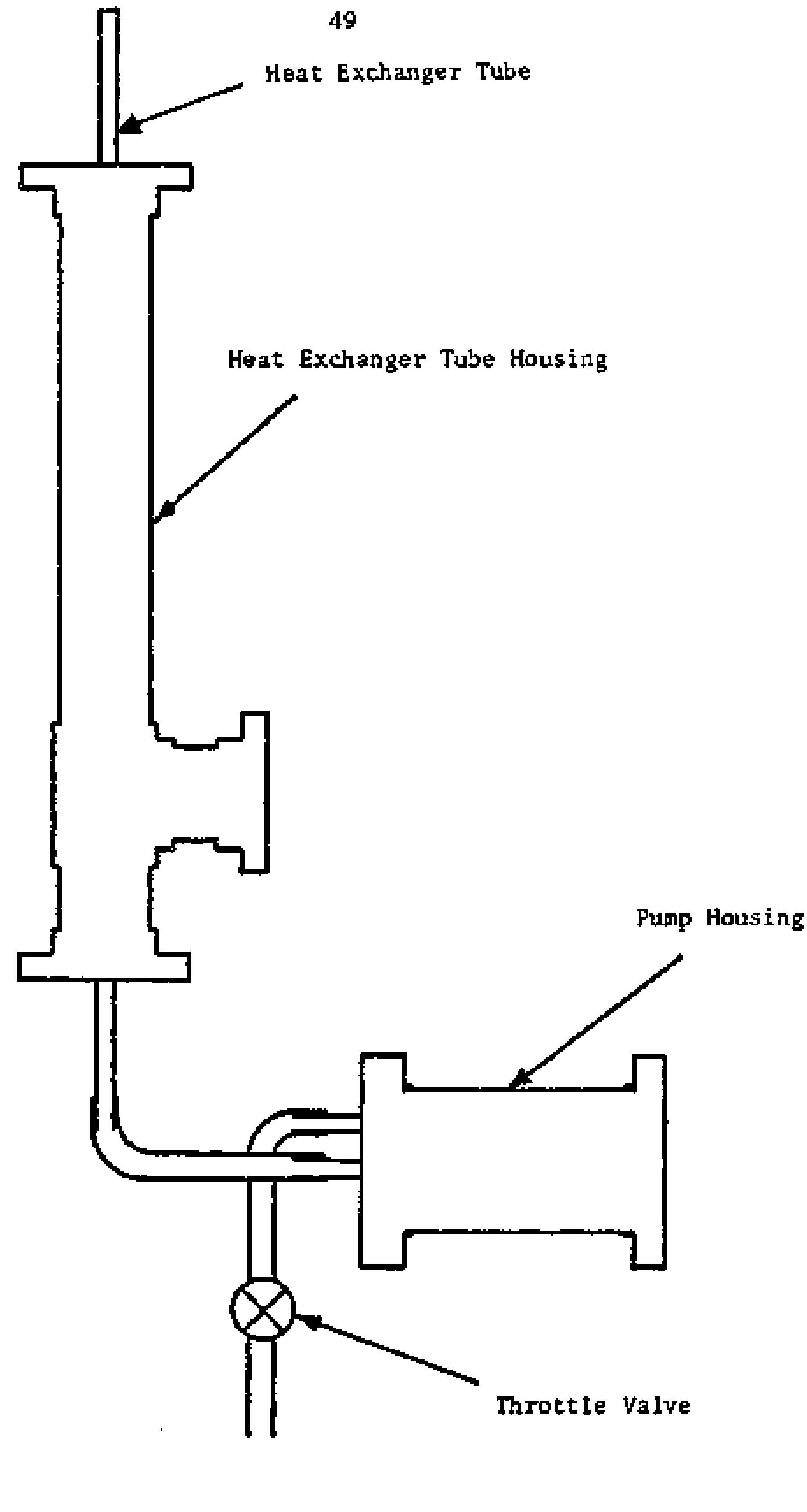



Figure 4-1. Schematic of an Experimental Unit

gaskets providing the seal. Where the simulated heat exchanger tube passes through the top and bottom end plates, rubber 'O' rings provide the necessary vacuum seal. Both the tube housing and the pump housing are vacuum tested. In addition, the pump housing is pressure tested for water pressure at ~60 psi in all water bearing parts of the pump. These procedures are further discussed in 4.9 under Vacuum and Pressure Testing.

4.2. Heat Exchanger Tube. The simulated heat exchanger tubes that are used in the unit are pipes of various alloys such as Al 6061-T6, 90-10 Cu-Ni, Ti, etc. These are standard schedule 40, 1" nominal ID and 8-1/2 feet long. They have a smooth interior surface (as produced in the manufacturing process). The outside surface of the pipe is machined to $1.300''^{+000''}_{-002''}$ for a length of 26" from the downstream end (refer Dwgs. B-205 and B-206). This part of the pipe is finished to a surface roughness of about 8 microinches in order to help reduce the thermal contact resistance between copper heater blocks and the simulated heat exchanger tube.

To reduce heat loss from the heater blocks along the walls of the pipe during a measurement, the pipe may be machined down to thinner wall sections on either side of the copper heater block assembly. This procedure has been used to limit axial heat loss along the walls to less than about 5% of the total. For a material (e.g., Ti) of low thermal conductivity (12.7 BTU/hr ft°F) such thin-walled sections are not necessary; however for Al 6061-T6 (thermal conductivity 89.5 BTU/hr ft°F), the wall is machined down to 0.056" thick.

The length of the simulated heat exchanger tube is sufficient to assure fully developed flow in the neighborhood of the copper reference block.

4.3. Reference and Heater Blocks. Both the reference and heater blocks are of copper. They are of cylindrical geometry with outer diameters of

3" and inner diameters of 1.315" for the reference cylinder and 1.300" for the heater blocks. The reference cylinder is 2" long (refer Dwg. B-216) while the heater block assembly (refer Dwgs. B-217 and B-218) is in three sections, each 4" long. Each of the blocks is partly split by a saw cut 1/32" wide. This design facilitates easy mounting and demounting of these blocks onto the tube. Hence these blocks with their thermopile mountings can be reused with different simulated heat exchanger tubes. The reference cylinder can be spread by inserting a screw driver into the slot. However the heater blocks, being more delicate, should be spread only by using the jack screws. The inner surfaces of the heater blocks are finished to a surface condition of 8 microinches to provide good thermal contact to the simulated heat exchanger tube. Each copper block is clamped onto the pipe with two bolts. The saw cut and the bolts (of SS) in each block introduce only a minor deviation from the cylindrical geometry.

4.4. Thermopile. The thermopile consists of 11 iron-constantan thermocouples, as shown in Fig. 4-2a. Each of the (B&G Gauge 30) thermocouple wires is insulated with teflon, and a teflon jacket is applied over the wires of a thermocouple pair. The thermocouple wire was purchased from Omega Engineering, Inc., Box 4047, Stamford, Connecticut 06907, Catalog number TT-J-30. The theory of this thermopile is discussed in Appendix F.

The iron and constantan wires within a (jacketed) pair are spot-welded together to form one of the sensing junctions. To form one of the reference junctions, an iron wire from one pair is spot-welded to a constantan wire

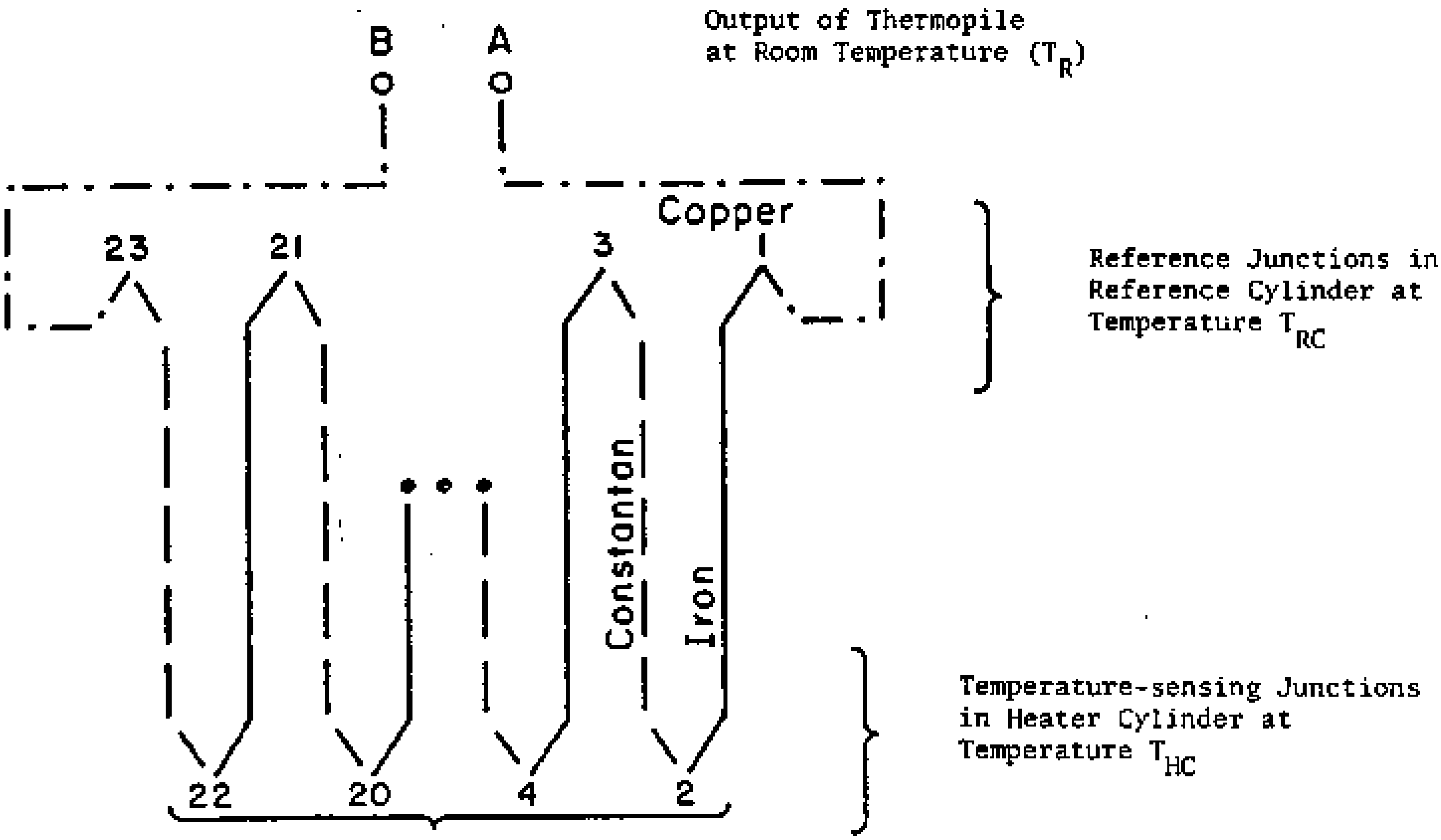



Figure 4-2a., Thermopile of 11 Thermocouples.

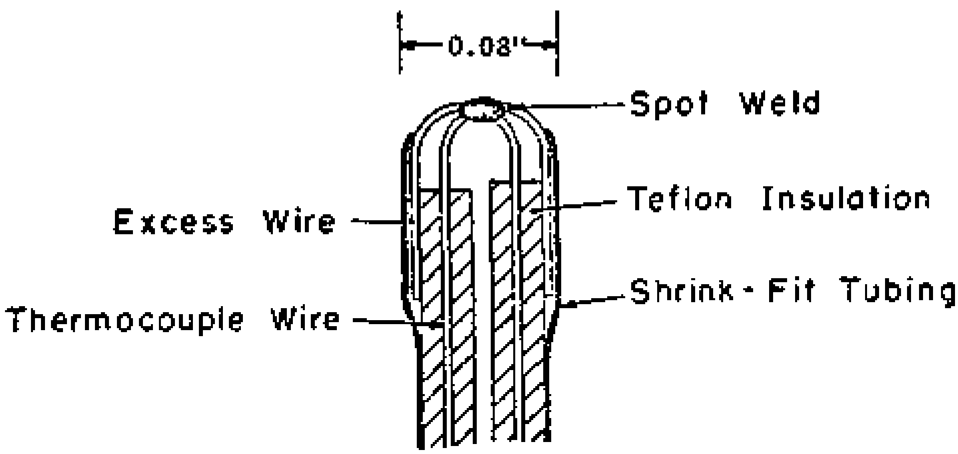



Figure 4-2b. Details of Thermocouple Junction.

from another. In this way the 11 jacketed pairs of thermocouple wires (each pair being 41" long) are coupled together to form the thermopile. Finally, a 6 foot length of #22 stranded copper wire is soldered to each end of the thermopile, as shown in Fig. 4-2a.

The technique used for insulating each junction is sketched in Fig. 4-2b. The iron and constantan wires are crossed prior to making the spot weld and the excess length of each wire is bent back parallel to the opposite wire. The result is to have a smooth, rounded tip at the junction rather than the sharp ends which would result if the excess wire were snipped off near the junction. A short section of 3/32" shrink fit tubing (Alpha Wire Corporation) is then passed along the length of the pair, just beyond the junction. By thermally shrinking the tubing around the complex, the excess wire is held securely in place and the bare wires near the junction are effectively insulated. Two coats of Glyptal (GE 1201 Red Enamel) are then applied to the junction and to the shrink-fit tubing. With this construction, the junction itself has only a thin layer of insulation and is able to respond rapidly to temperature changes.

Prior to potting the thermopile into the reference and heater cylinders, several tests are done. The thermopile is checked for electrical continuity (it should have a total resistance of approximately 135 Ω). With the reference junctions in air at 23°C, the output voltage of the thermopile is monitored while the sensing junctions are dipped in water at ~50°C. The response of the thermopile to this step-function change in temperature permits a calibration check, and an estimate of the thermal time constant. Typically, this time constant is 0.7±0.2 sec. The measured sensitivity of the thermopile is generally found to agree, to within ~3% with the handbook value of 0.319 mV/°F, which is appropriate to the 23°C to 50°C range.

The 12 reference junctions are then positioned in their holes in the reference cylinder and potted with a low viscosity epoxy. Care is taken to insure that each insulated junction is pressed against the flat bottom of its hole in the reference cylinder. Because the epoxy has low viscosity, it can be injected into the hole with a syringe and #18 needle. Its low viscosity also permits air bubbles to escape with time. The epoxy is made by mixing 2 parts (by weight) Epon 815 with 1 part Epi-Cure 855. Epon 815 is available from Miller-Stephenson Chemical Co., Inc., 7615 North Paulina Street, Chicago, Illinois 60626. Epi-Cure 855 can be obtained from Celanese Resins, 11th at Hill Street, P.O. Box 8248 Louisville, Kentucky, 40208 in large quantities, or for smaller quantities from Thermoset Plastics (phone 317-259-4161) where Epi-Cure 855 is called Thermoset Hardener #13. The setting time for this epoxy is ~24 hours. Methanol acts as a good solvent if the epoxy has not set.

After the epoxy in the reference cylinder has cured, shielding in the form of 7/32" (flat width) copper braid is put around the two #22 copper wires leading from the thermopile. Around the bundle of 11 thermocouple wire pairs coming out of the reference cylinder, 3/8" (flat width) copper braid is similarly used. The two shields are soldered together near the reference cylinder. The reference cylinder and the central heater cylinder (with heater already wound on it) are then mounted in their proper positions on a heat exchanger tube. The shield containing the 11 wire pairs is then wrapped smoothly around the tube approximately 3 times and taped in place. This is done so that the thermopile wires can adjust easily to their final position while they yet have freedom to move on the heater cylinder end.

The 11 sensing junctions are then potted in the central heater cylinder by the same technique as described above. Once again, care is taken to insure that each insulated junction is in physical contact with the flat bottom of its hole in the heater cylinder. Finally, after the epoxy has cured, a check is made for electrical isolation between the thermopile and the copper cylinders. A resistance greater than 200 MΩ is usually found.

4.5. Heater. The problem of winding a heater on the heater cylinders is complicated by the slit in the cylinders which permits them to be demountable. It would not be a good practice to wind the heater wire across the gap formed by the slit. This is because increasing and decreasing the gap width while mounting or demounting a cylinder would cause the heater wire bridging the gap to flex, and thereby be worked loose from the copper surface or possibly break. Instead, individual strips of heater wire are wrapped almost completely around each cylinder, with the strips being connected at their ends by copper jumpers, as shown in Dwg. C-306 (Heater Winding).

For purposes of electrical insulation ten 1/4" wide, 0.004" thick strips of polyester tape are placed on each 4" long heater cylinder. The spacing between adjacent strips is nominally 0.4", but the tape must be routed in such a way as to avoid the bolt holes, etc. on the heater cylinder. The tape is available from Industrial Electrical Products Division 3M Company, 3M Center, St. Paul, Minn. 55101 and is described as Scotch brand electrical tape: yellow polyester film, thermosetting, pressure sensitive adhesive.

The heater wire is nichrome (80% Ni, 20% Cu) ribbon of width 1/16" and thickness 0.004" with a resistance of 2.41 Ω/ft. The wire can be obtained under the trade name Tophet A from Wilber B. Driver Co., Newark, N.J. Strips of the wire are cut to 9-1/4" lengths and the ends are cleaned with steel wool and emery paper. The ends of each strip are tinned on one side with Eutec-Rod 157-B solder using 157 flux and heat from a large soldering iron or torch. The flux is thoroughly cleaned from the strips and 10 strips are then placed in position on the insulating tape with their tinned sides up and with one end on each side of the gap of the heater cylinder. The ends of each strip are temporarily held fixed by fastening them to the copper cylinder with masking tape. The strips, except for the ends, are then painted with Glyptal (GE 1201 Red Enamel) which serves to hold them permanently in place with an insulating coating.

Adjacent strips are connected by a #16 solid copper jumper wire which is ~0.6" in length. Connection between heater strip and jumper wire is made with 157-B solder. A piece of paper is slipped under the tinned ends of the heater strips so that the polyester tape is not damaged by excessive heat. Heat sinks in the form of alligator clips are also used to channel excess heat away from the tape. After all nine of the jumper wires have been connected, the jumpers and attached strips are held firmly against the surface of the cylinder by means of a special jig and are then coated with Glyptal for permanent anchoring.

The winding of a heater on a cylinder is now complete except for soldering a length of #16 stranded copper wire to act as a lead on either end of the heater windings. In the full set of three 4" long heater cylinders there are 4 ends of heaters which are meant to be connected to heaters on adjacent 4" cylinders. To these ends are soldered 2-1/2" lengths of #16 stranded copper wire. The free end of each 2-1/2" length had previously been soldered to a 22-18 #4 crimp-on connector which permits electrical connection between adjacent cylinders to be made with a 4-40 x 1/4" bolt and 4-40 nut. The remaining 2 ends of the heater cylinder set are the extreme ends which are not adjacent to another cylinder. To each of these ends is soldered a 25" length of the #16 copper wire. When the heater cylinder set is mounted on a simulated heat exchanger tube, the #16 wire from the long leads is wrapped several times around the tube about 8" from the cylinder, and then is taped in place. The 8" length insures that only a negligible amount of heat is drained from the heater wire and passed to the tube directly, rather than passing to the heater cylinder.

In the finished product, a layer of Glyptal covers the entire outer curved surface of the heater cylinder. The total resistance of the heater is ~53 Ω. Isolation between the heater windings and the heater cylinder is generally measured to be greater than 200 MΩ.

4.6. Flow Meter. The downstream end of the heat exchanger tube is connected to the flow meter through a PVC double flange. The flow meter is the Ramapo model Mark V - 1-1/4 - SFY (refer Dwg. B-219) by Ramapo Instrument Co., Inc., Montville, N.J. The flow meter's housing, target and sensing element all are of 316 SS. To minimize crevice corrosion in sea water, it is planned to use Hastelloy C for the construction of flow meters for future operation.

This flow meter senses the force on a 316 SS target immersed in the flowing stream. The force strains the lever rod to which the target is attached. This strain is sensed using a strain gage-bridge. A typical calibration curve is presented in Fig. 4-3.

4.7. Pump. The fouling problem is to be studied over a flow velocity range of at least 2 to 15 ft/sec. At 10 feet per second through a 1" tube, the head loss through the system is about 7', while the pump capacity required is 25 gpm.

It was felt that a very important criterion, for a pump which is to operate for long times in a situation of difficult access, is reliability. We therefore avoided pumps with metal shafts and seals which could be impaired

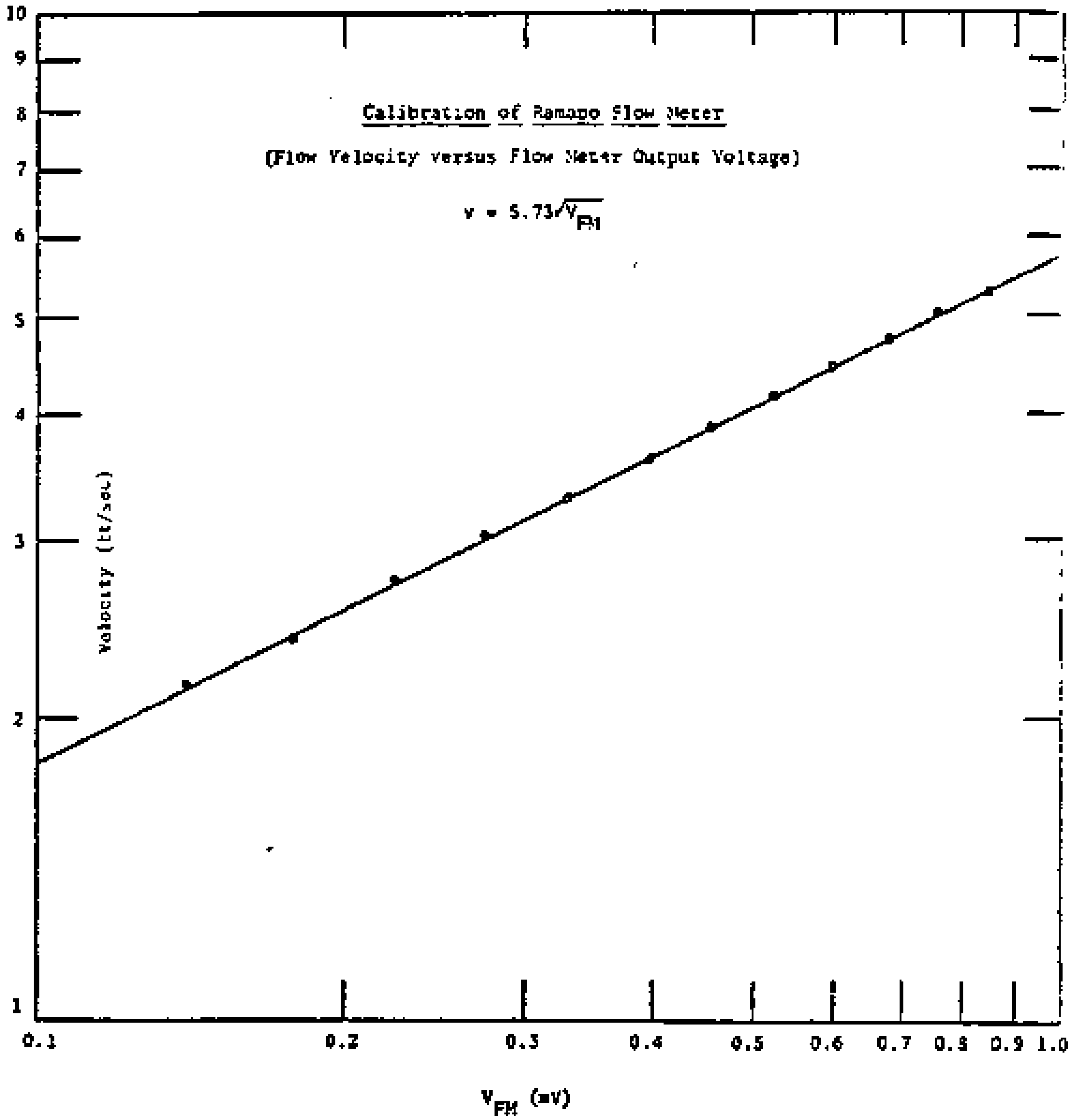



Figure 4-3. CMU Calibration of Ramapo Flow Meter.

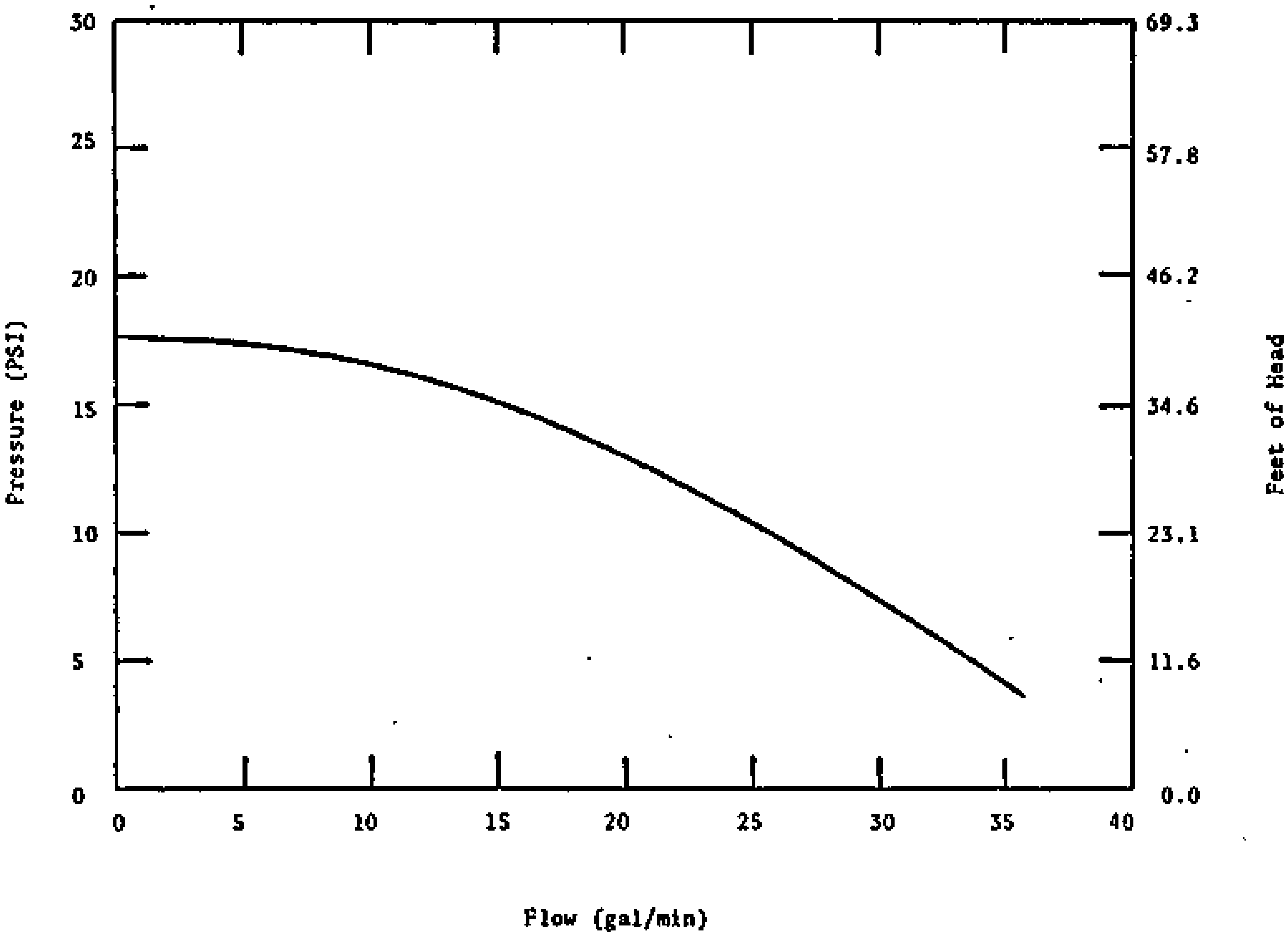



Figure 4-4. Characteristics of MDH-25 Magnetic Drive Pump.

by corrosion caused by contact with sea water.

The pump chosen is MDH-25 (supplied by Eastern Industries, P.O. 4372, Hamden, Conn., 06514). This is a magnetic drive centrifugal pump in which the sea water comes in contact only with plastic surfaces. The pump will run at 220 V, 60 Hz and 3.5 amps, or at 110 V and 7 amps. This pump (characteristics shown in Fig. 4-4) meets the above requirements.

4.7.1. Cooling Requirement for the Pump-Motor. Due to Joule heating in the motor windings heat is generated while the pump is in operation. Since the pump and motor are inside a PVC housing, if this heat is not removed the temperature of the pump motor will rise excessively. Cooling is achieved by tapping part of the water from the discharge end of the pump and circulating it through a copper cooling coil (refer to item 16 Dwg. D-403) wound around the motor housing. The paint on the outer surface of the motor is scraped off, the copper coil is tightly wound around the motor housing and soft soldered to the bare surface. The motor and copper cooling coil are repainted to guard them from corrosive sea vapor. For a flow rate of ~1.3 gal/min through the cooling coils, about 170 watts of heat are removed with 0.9°F rise in temperature between the inlet and outlet of the cooling water (at a water temperature of ~26°C).

4.8. Mechanical Assembly. In the following assembly procedure, all neoprene gasket and rubber 'O' ring seals must be made with care to yield a leak-tight seal. In making the neoprene gasket seals, first clean the mating surfaces and the two sides of the neoprene gasket with a lint free cloth or paper towel. Then apply a liberal coat of high vacuum silicone grease to the mating surfaces and the two surfaces of the gasket. Bolt down the end plates, uniformly tightening all the bolts. In the case of rubber 'O' ring seals, the 'O' ring, the groove in which it rests and the surface it seals should be relatively scratch free and clean. Apply a light coat of high vacuum silicone grease to the rubber 'O' ring. In making the seal, tighten the nuts evenly.

4.8.1. Tube Housing - Assembly Instructions. In the following description of the step-by-step procedure, reference is made to the assembly drawing D-402 and the itemized parts marked on it.

a) Mount the simulated heat exchanger tube horizontally in lab stands on a bench.

b) Clean the outside surface of the pipe with paper towels and acetone or toluene, particularly where the reference and heater blocks will be in contact with the pipe surface.

c) Spread each of the three heater blocks with jack screws. Spread the reference block with a screw driver inserted into the slot. Spread until each block moves freely onto the pipe.

d) Slide the reference block on from the downstream end until it is on the unmachined part of the simulated heat exchanger tube.

e) Slide heater block A from the downstream end. Similarly position heater blocks B and C successively. Take care not to put much load on the thin sections of the tube. Be careful to put no strain on thermocouple wires. Pay attention to the orientation of the heater leads so the solder lugs match.

f) Locate the reference block so that its upstream face is 50-1/4" from the upstream end of the pipe. Center heater blocks A, B and C between the thin sections (the downstream end of block C will be 12" from the downstream end of the pipe).

g) Rotate block B to wrap thermopile leads around the pipe between the reference and heater blocks. This should be a gentle wrap with <u>no strain</u> on the thermopile wires.

h) Torque down the blocks in place. All bolts are torqued to 15 ft-lbs., using a micrometer-type torque wrench. Apply the torque to the bolts evenly.

i) Sand the outer surface of the pipe where the 'O' ring seal at the top PVC plate is made. This is ~1.5" from the copper block. The tube must be sanded until no longitudinal ridges or scratches are present.

j) Bolt the top plate to the reference cylinder by means of the five 1/4" SS studs emerging from the bottom of this plate. Make the 'O' ring seal by bolting the lucite plate to the top plate using the four 1/4" SS studs from the top of the PVC plate.

k) Insert the electro fitting (1" - 14 threads). A special wrench or channel lock with relatively thin head will be needed.

l) Make the electrical connections between the heater blocks. Connect the heater and thermopile leads to the appropriate electro leads. Electrically insulate all connections.

m) Wrap a thin insulating foam around the reference block to thermally insulate it from the air.

n) Mount the thermistor with a hose clamp on the tube between the reference and heater blocks. Electrically connect it to the appropriate electro leads.

o) Remove the lever arm from the body of the flow meter. Assemble the PVC double flange (item 5) and the flow meter body on the pipe. Tighten the nuts on the aluminum clamp ring (item 11) to hold the flow meter to the pipe system. Make the 'O' ring seal between the pipe and the PVC flange.

p) Clean the inside of the PVC housing (item 1) with a lint-free rag. Put a 6" neoprene gasket on the top plate and slide the assembled unit into the housing. Put a temporary support under the flow meter body to insure that the pipe is approximately centered in the housing.

q) Assemble the lever arm of the flow meter to its body. Use only a new teflon "O" ring everytime this seal is made. Attach the flow-sensing target to the flow meter lever arm. Special tools (Crowfoot wrench, two-claw finger) are necessary to do this part of the assembly. Make the flow meter electrical connections to the electro leads.

r) Attach the 1-1/4" PVC pipe (item 16).

s) Bolt down the top plate (item 2), bottom plate (item 3) and side plate item 4) after putting the 6" neoprene gaskets in place.

t) Make the 'O' ring seal where the 1-1/4" PVC pipe passes through the bottom PVC plate (i.e., between items 3 and 16) by bolting the lucite plate to the bottom plate. The four 1/4" stainless steel studs emerging from the bottom of this plate are used for this.

<u>4.8.2. Pump Housing - Assembly Instructions.</u> Reference to assembly drawing D-403 is useful in the following description of step-by-step procedure. References to items are as marked on drawing D-403.

a) Make the 'O' ring seal between the PVC fitting (item 7 ) and the suction side of the pump.

b) Clean the male threads on the polypropylene pump discharge and the female threads on the PVC elbow (item 10). Use a double layer of teflon tape and screw the elbow on to produce a leak-tight seal.

c) Cut two lengths of 1-1/4" ID tygon tubing (should withstand internal pressure of ~50 psi) one of 5.8" for the discharge and the other of 5.1" for the suction side of the pump. Clean the inlet and outlet PVC stems on both the pump and front PVC cover plates. Apply a thin coat of stopcock grease. Couple the pump to the cover plate with the two pieces of tygon tubing. Keep the axis of the motor perpendicular to the PVC front cover plate (item 2). Fasten the tygon tubing with #28 hose clamps. Since they have a tendency to relax their grip on the tygon tubing, the clamps should be retightened after a couple of hours.

d) Cut two lengths of braided tygon tubing of appropriate length. With a soldering iron fuse the inner and outer layers of the tubing at both ends of both tubes. Fit these braided tygon tubings between the PVC nipple (item 7) and brass nipple (item 9) thus providing inlet and outlet paths for the cooling water. Clamp these tygon tubes with size 10 hose clamps. Be sure that the hose clamp nearest the end of each nipple is positioned over the groove in the nipple before tightening.

e) Clean the inside of the PVC housing (item 1) and insert the pump into the housing. Set it on the PVC cradle (items 4 and 5) with the PVC elbow (item 10) pointing upwards. Use a piece of (~0.65" thick) gasket on the cradle underneath the pump to cushion vibrations. Bolt down the front cover plate (torque = 110 ft-lbs.).

f) Fasten the motor to the housing using two #64 hose clamps. Slip them around the motor and around the two steel rods (items 21) as close to the PVC cradles as possible, not touching the cooling coils.

g) Connect the starting capacitor. Connect the Electro connector (1/2" 20 threads) to the front cover plate. Make electrical power connections between Electro leads and the motor.

h) Bolt down the rear cover plate (110 ft-lbs.).

4.9. Vacuum and Pressure Testing. Both the tube housing and pump housing are leak tested with a helium leak detector (Veeco, model MS9-AB) for leaks in the PVC glue joints, gasket seals and '0' ring seals. A typical tube housing pumps down to ~50 μ of Hg with a mechanical vacuum pump and to a pressure $\leq 5\times10^{-4}$ mm of Hg with a diffusion pump. Based on the sensitivity of the leak detector with a standard helium leak, the helium leak rate into the tube housing is $\leq$.0014 μcm.ft/hr (i.e., a low leak rate very easily tolerable). Similar tests with the pump housing yields no detectable leak for PVC glue joints, gasket seals. However, spraying helium on the water bearing parts of the pump does indicate a small leak. To assure ourselves that this leak rate is negligible, pressure tests have been conducted in the following way. With the pump inside the pump housing and with a water pressure of ~60 psig inside the pump, the housing is first evaluated to ~100 μ of Hg. It is then isolated and monitored for the deterioration of vacuum due to a possible water vapor leak. Such tests yield an inflation rate of $\sim 4.5\times10^{-4}$ atm/day. This implies a leak rate of $\leq$3.6 cc of water per year, a very small tolerable leak rate. Also, one instrument housing and one pump housing were pressure tested under over three atmospheres of external pressure (corresponding to a potential submergence depth of 100 feet), after which vacuum tests were again performed to confirm continued integrity against leaks.

4.10. Quality Assurance Items.

4.10.1. General. In order to assure, insofar as possible, that the OTEC Heat Transfer Monitor is constructed in a suitable manner, the following instructions shall be compiled with in accordance with their true intent.

4.10.2. Drawings and Instructions.

- Contractor shall conform to the dimensions, tolerances, machine finishes, and material specifications as shown on the detail, sub-assembly and assembly drawings. B-200 through B-222, C-300 through C-307 and D-400 through D-404.
- Assembly shall be according to the assembly instructions presented elsewhere.

4.10.3. Cementing Procedure. The heat exchanger and pump assemblies are designed to be used in sea water at 100 foot depths. To assure that the P.V.C. cement joints are watertight, the following cementing procedure shall be used.

- Clean pipe and fittings off all moisture and dirt.
- Maintain atmospheric temperature in contact with the pipe and fittings between 40°F and 90°F.
- Expose pipe and fittings to constant temperature conditions for at least one hour prior to cementing.
- Remove all burrs, chips, filing, etc. from both the pipe I.D. and O.D. before joining and installation.
- Bevel pipe ends for ease of socketing.
- Using a natural bristle brush, apply a complete coating of primer to the entire I.D. surface of the fitting and to an equivalent area on the O.D. of the pipe end. This will clean and etch the surfaces. Wipe

surfaces to remove any remaining foreign matter and apply a liberal second coat to thoroughly roughen surface.

- Using another natural bristle brush, apply solvent cement into the fittings socket and onto the O.D. of the pipe ends as follows:

    a. To the pipe:

        Flow the cement liberally once around entire surface of pipe O.D. to a width slightly more than the equivalent socket depth of the fitting.

    b. To the fitting:

        Apply cement light, but a complete coat, once around entire depth of socket surface.

    c. To the pipe:

        Apply another liberal coat onto pipe O.D.

- Immediately, upon finishing cement application, insert the pipe to the full socket depth while rotating the pipe or fitting 1/4 turn to insure complete and even distribution of the cement. A properly made joint will normally show a full bead around its entire perimeter. Any gaps at this point indicate a defective assembly.
- Hold joint together for a minimum of 10 to 15 minutes to make sure pipe does not move or back out of socket.
- Wipe off all excess cement from the entire surface of pipe and fitting.
- Allow joint to dry 24 hours before handling or testing.
- If the pipe flanges are tapered, there will be a large gap between the O.D. of the pipe and the I.D. of the flange. Fill this gap with cement as follows:

    * Prepare the surfaces as described above.
    * Apply as much cement as possible to both surfaces.

* Insert the pipe into the flange and rotate at least 1/8 turn. (This will probably require two people.)
* Pour cement into the gap until it is filled.
* Wipe off excess cement and allow joint to dry at least 24 hours.

4.10.4. Gasket "O" Ring Sealing Procedure. For the same reason as in the previous paragraph, all neoprene gasket and rubber "O" ring seal joints shall be installed according to the following procedure:

- Neoprene Gaskets
  * Clean the mating surfaces and the two sides of the neoprene gasket with a lint free cloth or paper towel.
  * Apply a liberal coat of high vacuum silicone grease to the mating surfaces and the two surfaces of the gasket.
  * Tighten all bolts uniformly.
- Rubber "O" Rings
  * Clean the "O" ring, the groove in which it rests and the surface it seals.
  * Check these surfaces for scratches that would adversely affect the proper sealing.
  * Apply a light coat of silicone vacuum grease to the rubber "O" ring.
  * Tighten all nuts evenly.

4.10.5. Water Inlet and Exhaust Seals. The sea water pumping loop - from the inlet, through the heat exchanger tube, through the pump and out the exhaust, including the pump cooling water loop must be made watertight at all joints to exclude sea water from the interior of the assemblies.

- All cement joints, gasket or "O" ring seals, pipe thread joints, hose clamp joints and solder connections shall be made according to procedures presented herein, described in the assembly instruction and according to recognized standards.

4.10.6. Fit of Heat Exchanger Tube and Copper Blocks. To provide good thermal contact between copper heater blocks and the heat exchanger pipe, the mating surfaces are finished to a surface smoothness of 8 micro inches. Similarly, the mating surfaces of the copper reference cylinder and the heat exchanger pipe are machined to a surface smoothness of 32 micro inches. Handle all these surfaces carefully and inspect them before assembly for scratches and dents. Apply thermal grease (Wakefield thermal compound part No. 120-8 from Wakefield Engineering, Inc., Wakefield, Massachusetts 01880) between the mating surfaces of the copper cylinders and the heat exchanger pipe during final assembly. Use a torque value of 15 ft. lbs. in clamping the copper cylinders to the heat exchanger pipe.

4.10.7. Electrical Continuity and Isolation. In order to determine that the thermopile heater and thermistor have been correctly assembled, the following electrical tests will be performed. These tests assume the availability of a Simpson 260 volt - ohm - milliammeter or equivalent.

- Thermopile
  * Check for continuity of thermopile after the following points of assembly. Expected value - 150 ohm.
    a) after thermopile assembly
    b) after potting in reference cylinder
    c) after potting in heater cylinder

* Check for isolation of thermopile from both the reference cylinder and the heater cylinder.

    a) as each junction is potted:
    expected value > 1 megohm

    b) after all junctions are potted every hour of working day during curing: Expected value > 1 megohm

    c) after curing is complete: Expected value > 10 megohm

* Check continuity of heater winding on each 4" cylinder:
  Expected value ~17 ohm

    a) when soldering of the jumper wire and lead is complete

    b) when final coat of insulation is dry

* Check for isolation of heater from heater block.

    a) when strips are taped down to block, check each strip
    Expected value > 10 megohm

    b) when each strip is painted into place on block
    Expected value > 1 megohm

    c) when jumpers are soldered to each strip
    Expected value > 1 megohm

    d) after final insulation coating
    Expected value > 1 megohm

    e) after final coat is dry
    Expected value > 10 megohm

- Thermistor

  * Check for continuity of thermistor. Expected value 1000 ohm at $25^\circ C$. This value should change when thermistor is brought into contact with a person's hand.

a) before potting

b) after potting material has cured.

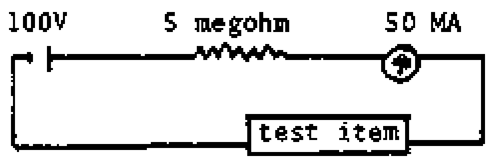
* Check for isolation of thermistor from copper tab.

a) when glued to tab

b) after final coat of epoxy has cured.

- Do Hi-Pot tests after all assembly is complete, all glues etc. have dried or cured, and all items have > 10 megohm isolation from heater block, reference block or copper tab as measured above.

* Construct Hi-Pot equipment according to following diagram:




100V can be obtained from a power supply or twelve 9 V transistor batteries in series.

The 5 megohm 50 MA combination is obtained by using the 250 VDC scale of the Simpson meter or by using individual components.

Following table gives current vs. resistance of test item:

| Current MA | Resistance megohm |
|---|---|
| 0 | $\infty$ |
| 1 | 95 |
| 2 | 45 |
| 3 | 28 |
| 5 | 15 |
| 10 | 5 |
| 20 | 0 |

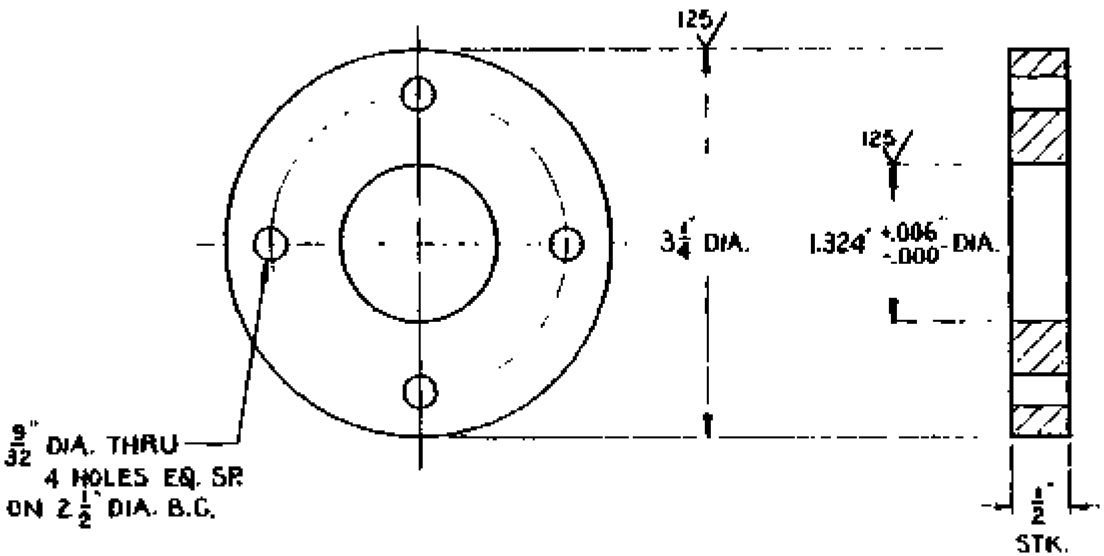
* Test isolation of Thermopile from reference block and heater block with Hi-Pot. Expected value > 10 megohm.
* Test isolation of heater from block with Hi-Pot. Expected value > 10 megohm.
* Test isolation of Thermistor from copper tab with Hi-Pot. Expected value > 10 megohm.

### 4.11. Mechanical Drawings.

The mechanical design of the heat transfer device is detailed in the following drawings (No. B-201 to B-222 incl., C-300 to C-307 incl., and D-400 to D-404 incl.). Drawings D-402 (p. 106) and D-403 (p. 107) are assembly drawings which provide references to all the necessary individual parts and materials.

LIST OF MATERIAL

| ITEM | NO. REQD. | ORDERING INFORMATION | MATERIAL | SPEC. | VENDOR - PART NO. | REMARKS | WT. |
|---|---|---|---|---|---|---|---|
| 1 | 1 | TOP SEAL PLATE | LUCITE | COM'L. | | | |

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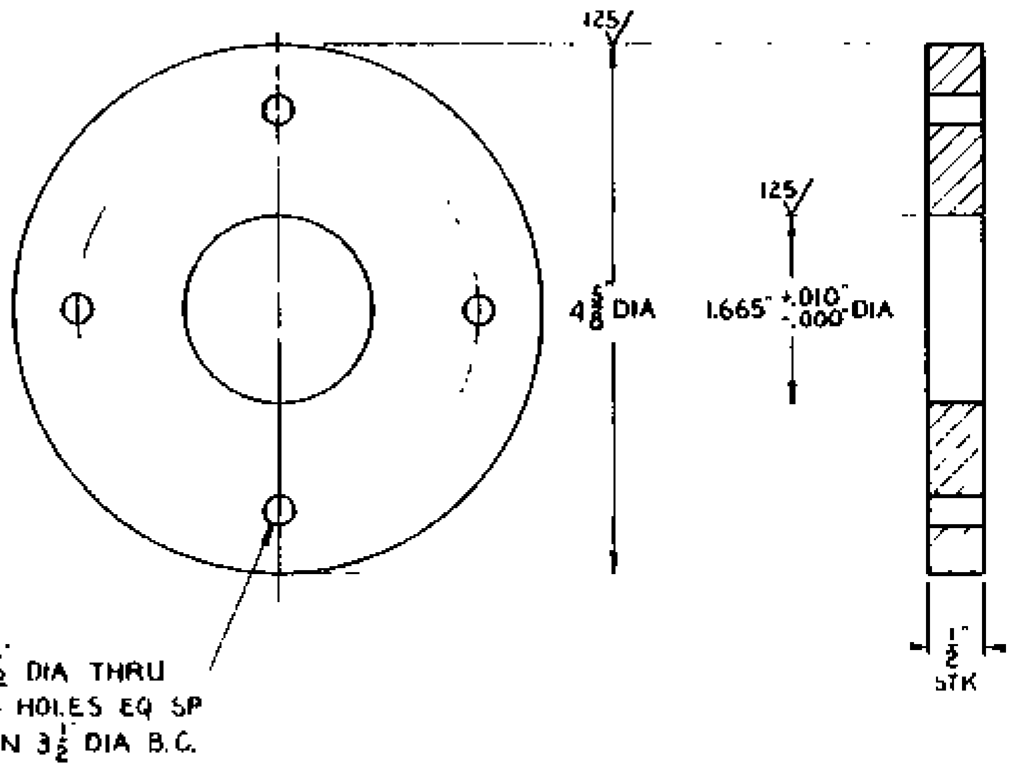
| | | | |
|---|---|---|---|
| TOLERANCES | CARNEGIE MELLON UNIVERSITY PITTSBURGH, PA. | | |
| DECIMAL ~ | TOP SEAL PLATE | SCALE FULL | DRAWN BY RRF |
| FRACTIONAL 1/64" | TITLE O.T.E.C. HEAT TRANSFER MONITOR | | |
| ANGULAR 2° | DATE 2-17-77 | DRAWING NUMBER B-200 | REV. |

## LIST OF MATERIAL

| ITEM | NO REQD | ORDERING INFORMATION | MATERIAL | SPEC | VENDOR - PART NO | REMARKS | WT |
|---|---|---|---|---|---|---|---|
| 1 | 1 | BOTTOM SEAL PLATE | LUCITE | COM'L. | | | |

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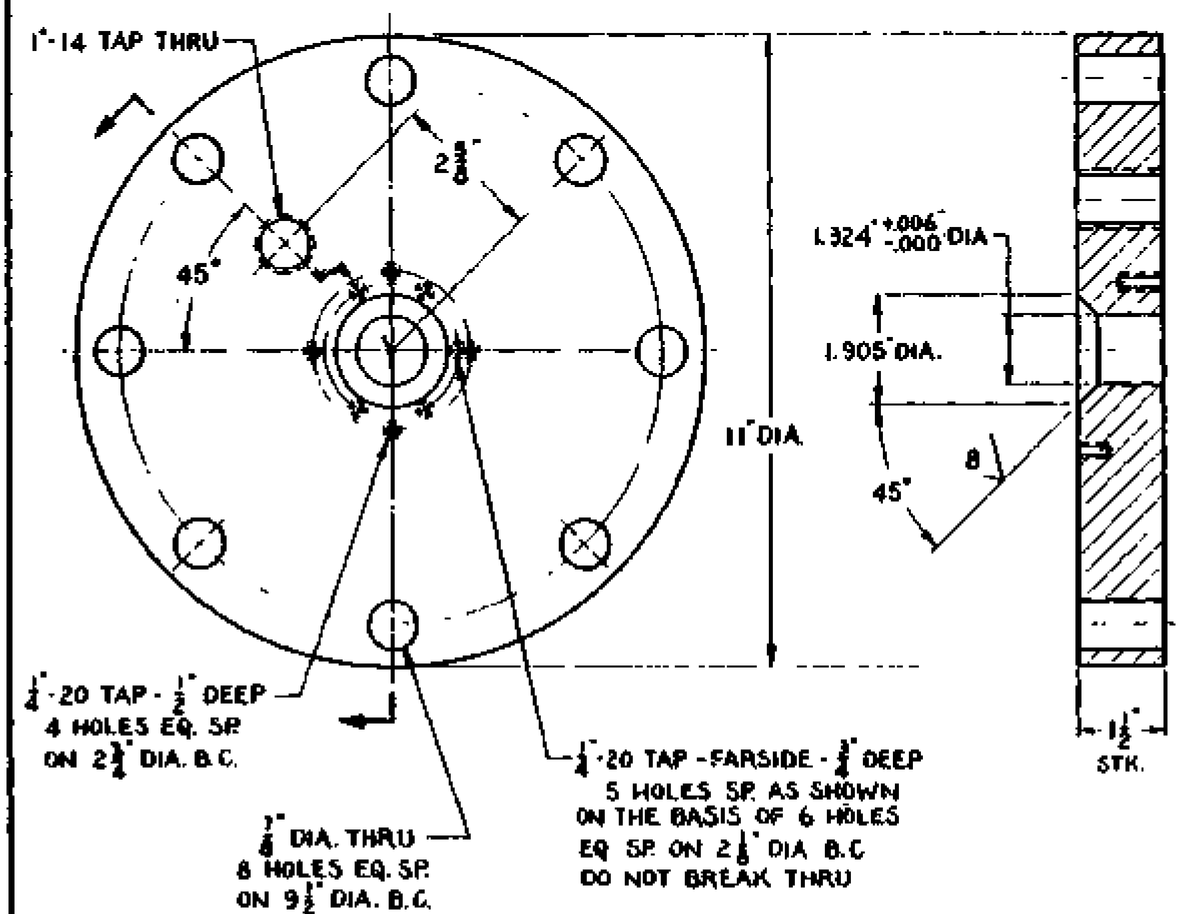
PITTSBURGH, PA

| | | | |
|---|---|---|---|
| DECIMAL: ± | BOTTOM SEAL PLATE | SCALE: FULL | DRAWN BY: RRF |
| FRACTIONAL: ± $\frac{1}{64}$ | TITLE: OTEC HEAT TRANSFER MONITOR | | |
| ANGULAR: ± 2° | DATE: 2 17 77 | DRAWING NUMBER: B-201 | REV |

## LIST OF MATERIAL

| ITEM | NO. REQD. | ORDERING INFORMATION | MATERIAL | SPEC. | VENDOR - PART NO. | REMARKS | WT. |
|---|---|---|---|---|---|---|---|
| 1 | 1 | TOP PVC PLATE | PVC | COM'L. | | | |



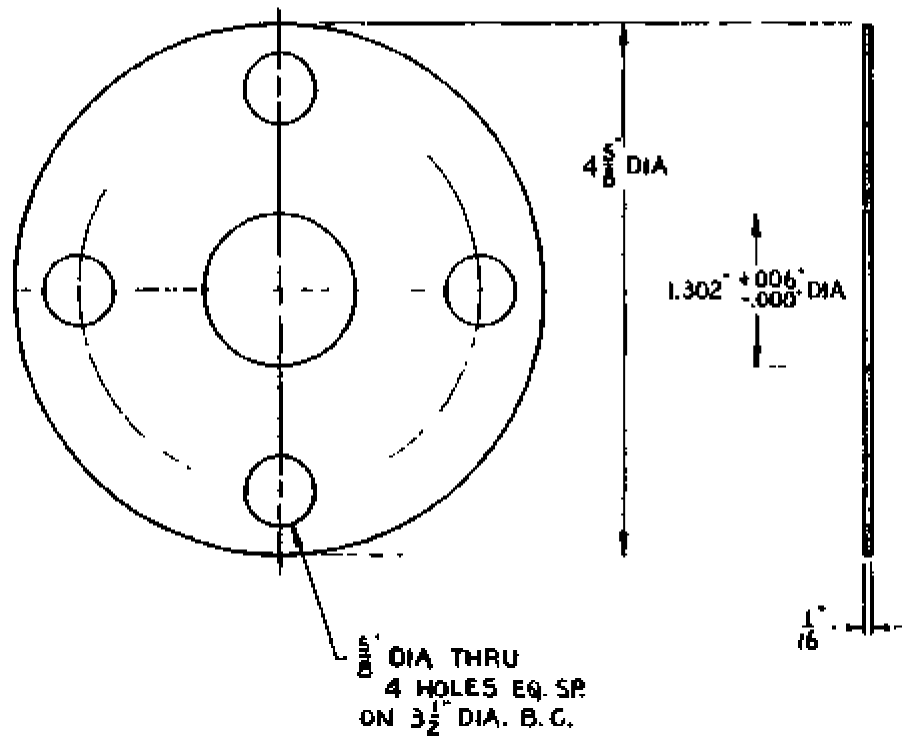

**NOTE**

1. FINISH 125√ ALL MACHINED SURFACES EXCEPT AS NOTED.

| | | | |
|---|---|---|---|
| TOLERANCES | CARNEGIE MELLON UNIVERSITY PITTSBURGH, PA. | | |
| DECIMAL ± .005" | TOP PVC PLATE | SCALE 1/2" = 1" | DRAWN BY RRF / APPROVED BY |
| FRACTIONAL ± 1/64 | TITLE: OTEC HEAT TRANSFER MONITOR | | |
| ANGULAR ± 2° | DATE 2-17-77 | DRAWING NUMBER B-202 | REV |

## LIST OF MATERIAL

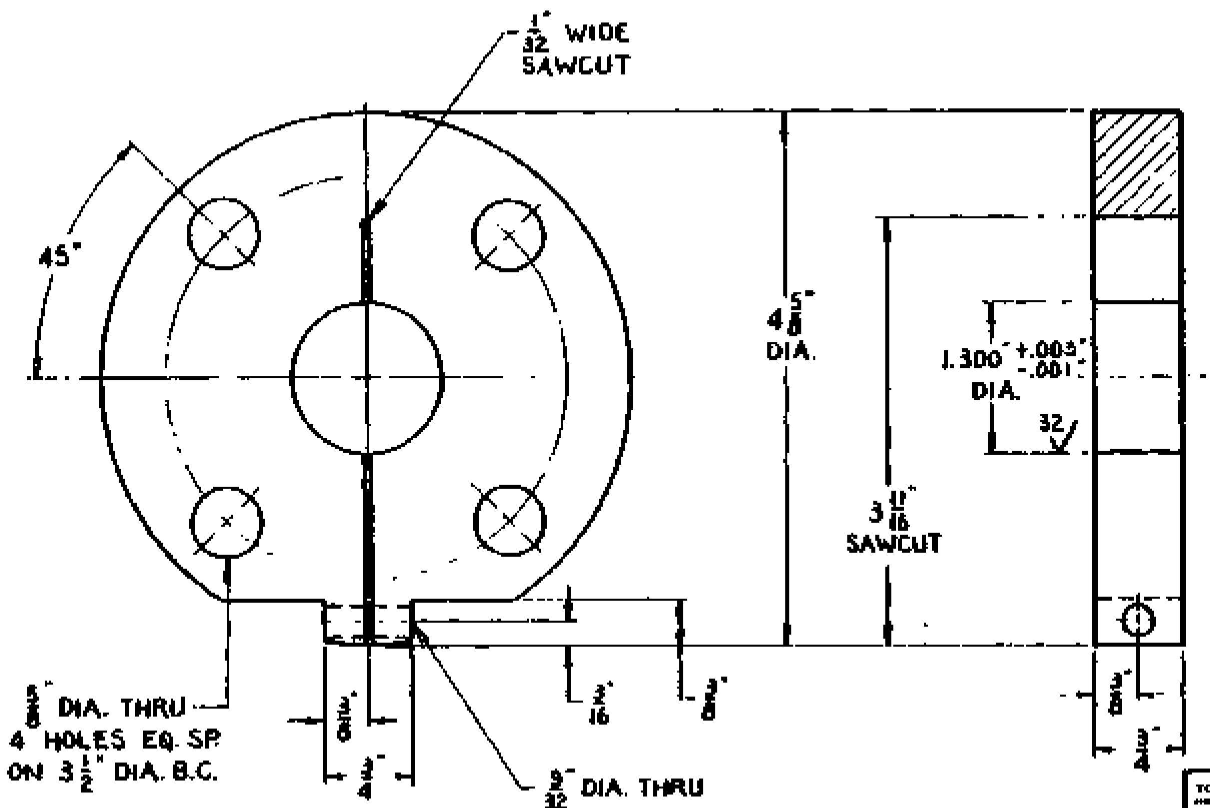
| ITEM | NO REQD | ORDERING INFORMATION | MATERIAL | SPEC | VENDOR-PART NO | REMARKS | WT |
|---|---|---|---|---|---|---|---|
| 1 | 1 | DISC | MICARTA | | | | |




| | | | |
|---|---|---|---|
| TOLERANCES | CARNEGIE MELLON UNIVERSITY PITTSBURGH, PA | | |
| DECIMAL ±/ | MICARTA DISC | SCALE FULL | DRAWN BY RRF / APPROVED BY |
| FRACTIONAL $\frac{1}{64}$" | TITLE OTEC HEAT TRANSFER MONITOR | | |
| ANGULAR 2° | DATE 2-18-77 | DRAWING NUMBER B-203 | REV |

LIST OF MATERIAL

| ITEM | NO. REQD. | ORDERING INFORMATION | MATERIAL | SPEC. | VENDOR-PART NO. | REMARKS | WT. |
|---|---|---|---|---|---|---|---|
| 1 | 1 | CLAMP RING | ALUM. | COM'L. | | | |



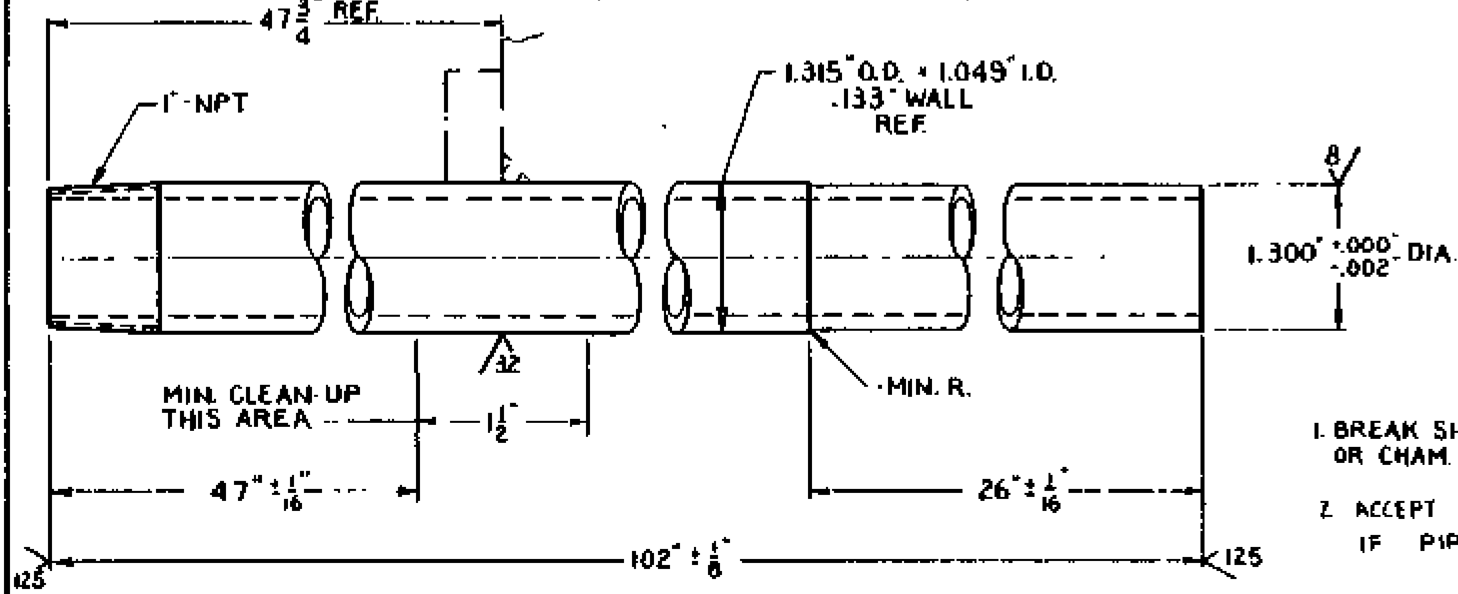

## NOTES

1. FINISH 125 ALL MACHINED SURFACES EXCEPT AS NOTED.
2. BREAK ALL SHARP EDGES-1/64" MAX. RAD. OR CHAM.

| | | | |
|---|---|---|---|
| TOLERANCES | CARNEGIE MELLON UNIVERSITY PITTSBURGH, PA. | | |
| DECIMAL ± | CLAMP RING | SCALE FULL | DRAWN BY RRF |
| FRACTIONAL ± 1/64 | TITLE O.T.E.C. HEAT TRANSFER MONITOR | | |
| ANGULAR ± 2° | DATE 2-21-77 | DRAWING NUMBER B-204 | |

| | | LIST OF MATERIAL | | | | | |
|---|---|---|---|---|---|---|---|
| ITEM | NO REQD | ORDERING INFORMATION | MATERIAL | SPEC. | VENDOR - PART NO. | REMARKS | WT |
| 1 | 1 | 1" SCH. 40 PIPE | TITANIUM | B337-76 | SEE NOTE "A" | | |

"A" - TITANIUM SALES CORP - FAIRFIELD, N.J. 07006 OR APPD. EQUAL




NOTE

1. BREAK SHARP EDGES - 1/64" MAX. RAD. OR CHAM.
2. ACCEPT FOR MACHINING ONLY IF PIPE OD IS 1.315" MIN.

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PITTSBURGH, PA

FLOW PIPE (TITANIUM)

SCALE: FULL

DRAWN BY: RRF

TITLE: OTEC HEAT TRANSFER MONITOR

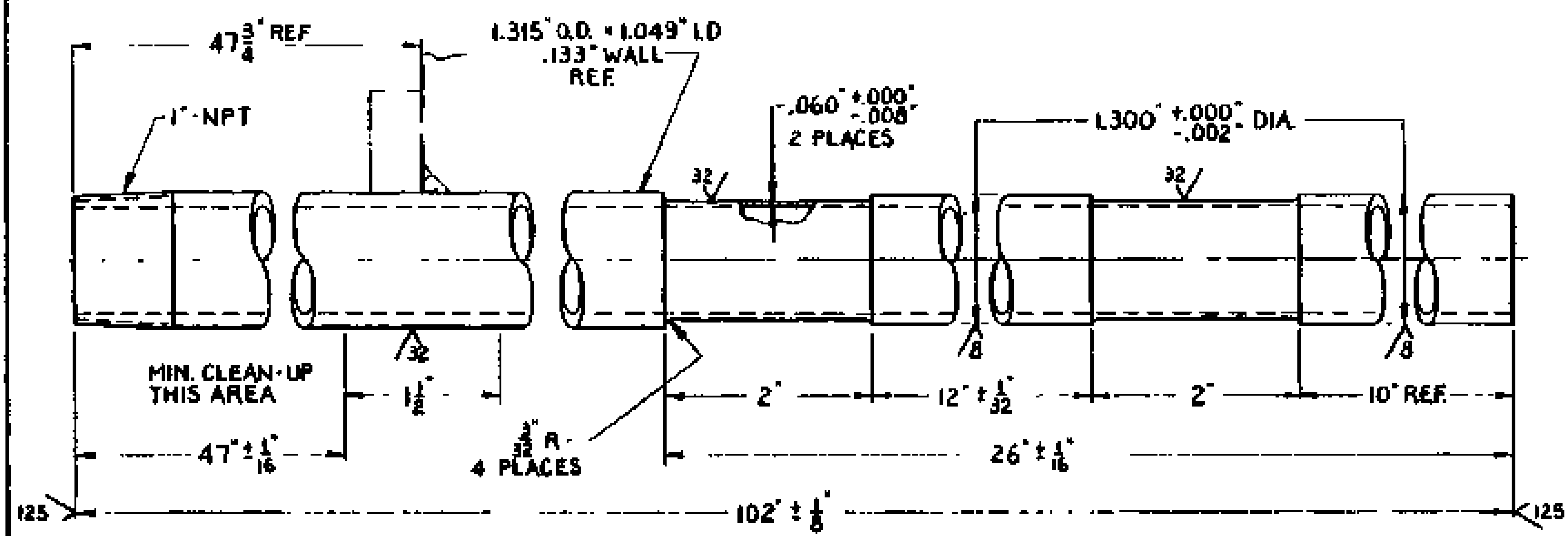
FRACTIONAL: ± 1/64"

DATE: 2-21-77

DRAWING NUMBER: B-205

## LIST OF MATERIAL

| ITEM | NO. REQD. | ORDERING INFORMATION | MATERIAL | SPEC. | VENDOR - PART NO. | REMARKS | WT. |
|---|---|---|---|---|---|---|---|
| 1 | 1 | 1" SCH. 40 PIPE | ALUM. | COML. | | COMP. 6061-T6 | |

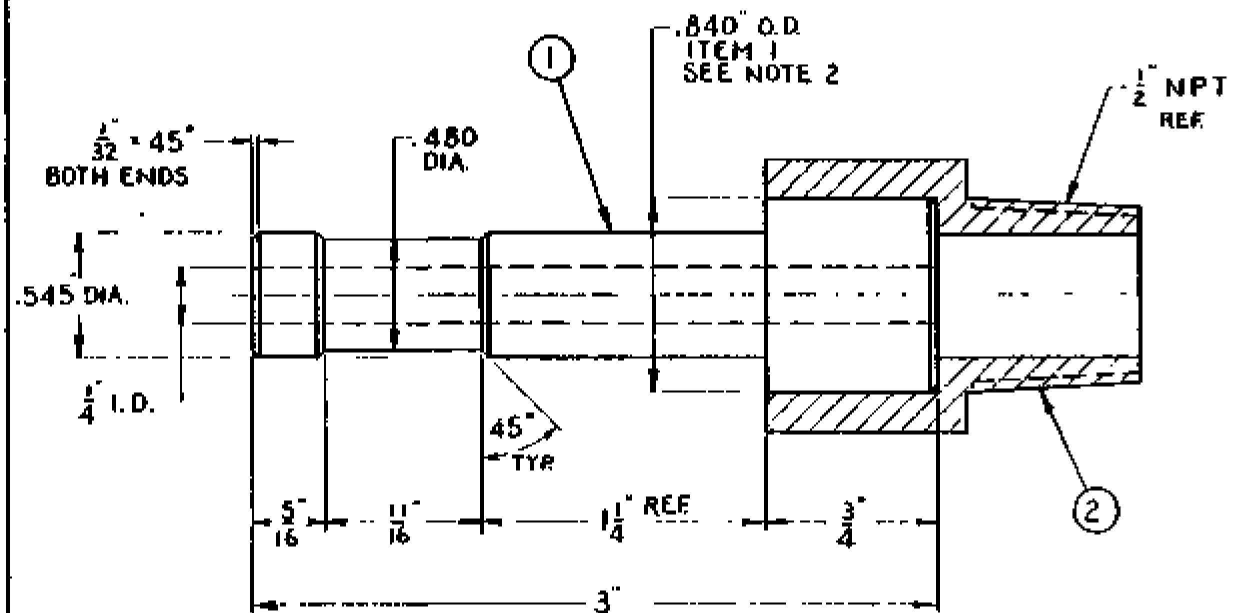



**NOTE**

1. BREAK SHARP EDGES - $\frac{1}{64}$" MAX. RAD. OR CHAM.
2. ACCEPT FOR MACHINING ONLY IF PIPE OD IS 1.315" MIN

| | | | | |
|---|---|---|---|---|
| TOLERANCES | CARNEGIE MELLON UNIVERSITY PITTSBURGH, PA. | | | |
| DECIMAL ~ | FLOW PIPE (ALUMINUM) | SCALE FULL | DRAWN BY RRF | APPROVED BY |
| FRACTIONAL $\frac{1}{64}$ | TITLE OTEC HEAT TRANSFER MONITOR | | | |
| ANGULAR ~ | DATE 2-21-77 | DRAWING NUMBER B-206 | | REV |

| LIST OF MATERIAL | | | | | | | |
|---|---|---|---|---|---|---|---|
| ITEM | NO. REQD | ORDERING INFORMATION | MATERIAL | SPECIFICATION | VENDOR - PART NO. | REMARKS | WT. |
| 1 | 1 | CONNECTOR | PVC | COM'L. | | | |
| 2 | 1 | ½" MALE ADAPTER | PVC | COM'L. | | ½" I.P.S/ ½" NPT | |

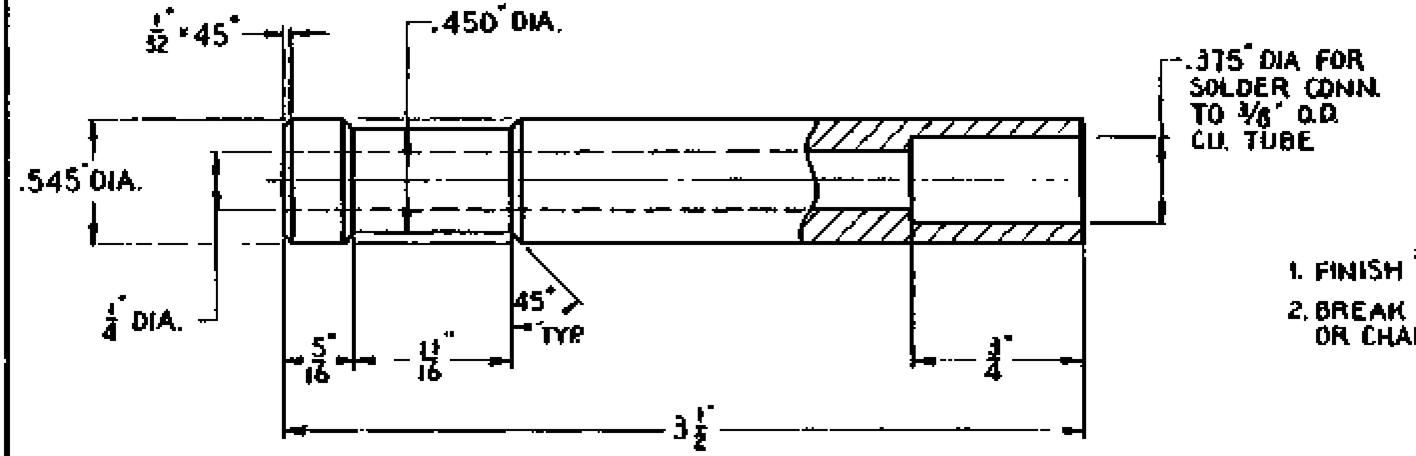



## NOTES

1. FINISH 32√ ALL MACHINED SURFACES.
2. CEMENTED JOINTS SHALL BE WATERTIGHT. THIS UNIT IS INTENDED TO BE USED IN SEA WATER AT 100 FT. DEPTH. (APPROX 50 P.S.I EXTERNAL PRESSURE.)

| | | | |
|---|---|---|---|
| TOLERANCES | CARNEGIE MELLON UNIVERSITY PITTSBURGH, PA | | |
| DECIMAL .005" | PVC NIPPLE | SCALE 2"-1 | DRAWN BY RRF |
| FRACTIONAL 1/64" | DOTEC HEAT TRANSFER MONITOR | | |
| ANGULAR 2° | DATE 2-23-77 | DRAWING NUMBER B-207 | REV. |

| LIST OF MATERIAL | | | | | | | |
|---|---|---|---|---|---|---|---|
| ITEM | NO. REQD | ORDERING INFORMATION | MATERIAL | SPECIFICATION | VENDOR · PART NO. | REMARKS | WT. |
| 1 | 1 | NIPPLE | BRASS | | | | |




## NOTES

1. FINISH 32√ ALL MACHINED SURFACES
2. BREAK SHARP EDGES 1/64" MAX. RAD. OR CHAMFER.

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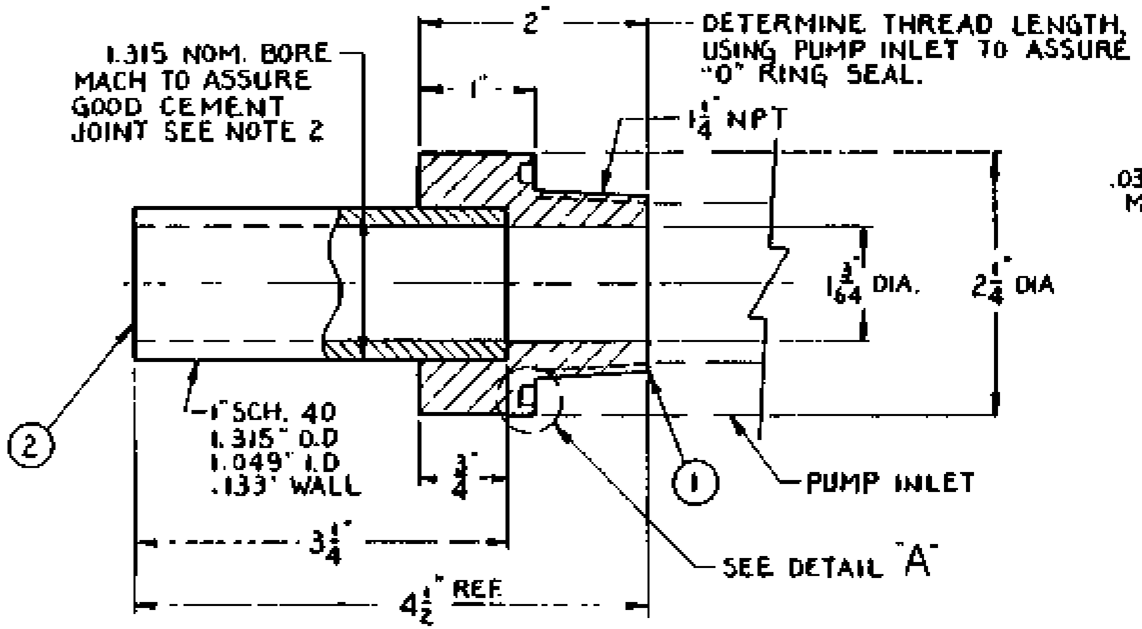
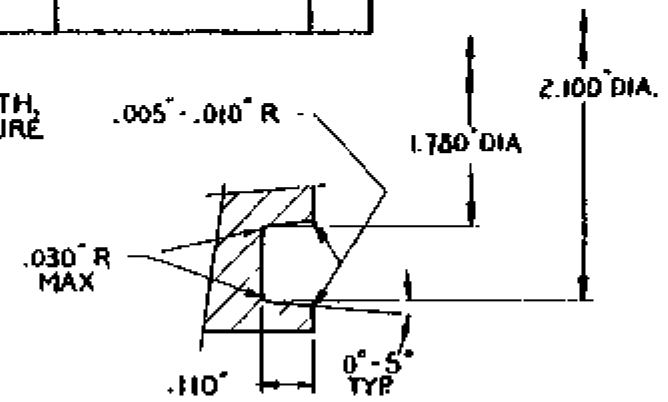
| TOLERANCES | CARNEGIE MELLON UNIVERSITY PITTSBURGH, PA. | | | |
|---|---|---|---|---|
| DECIMAL ±.005" | BRASS NIPPLE | SCALE 2" = 1" | DRAWN BY ARF | APPROVED BY |
| FRACTIONAL ±1/64 | TITLE OTEC HEAT TRANSFER MONITOR | | | |
| ANGULAR ±2° | DATE 2-23-77 | DRAWING NUMBER B-208 | | REV |

H·E ENGINEERING STANDARD FORM

## LIST OF MATERIAL

| ITEM | NO REQD | ORDERING INFORMATION | MATERIAL | SPECIFICATION | VENDOR-PART NO | REMARKS | WT. |
|---|---|---|---|---|---|---|---|
| 1 | 1 | ADAPTER | PVC | COM'L | | | |
| 2 | 1 | NIPPLE - 1" SCH 40 PIPE | PVC | COM'L | | | |




DETAIL "A"
SCALE 4" : 1"

NOTES

1. FINISH 32/√ ALL MACHINED SURFACES
2. CEMENTED JOINTS SHALL BE WATERTIGHT THIS UNIT IS INTENDED TO BE USED IN SEA WATER AT 100 FT DEPTH. (APPROX 50 P.S.I. EXTERNAL PRESSURE)

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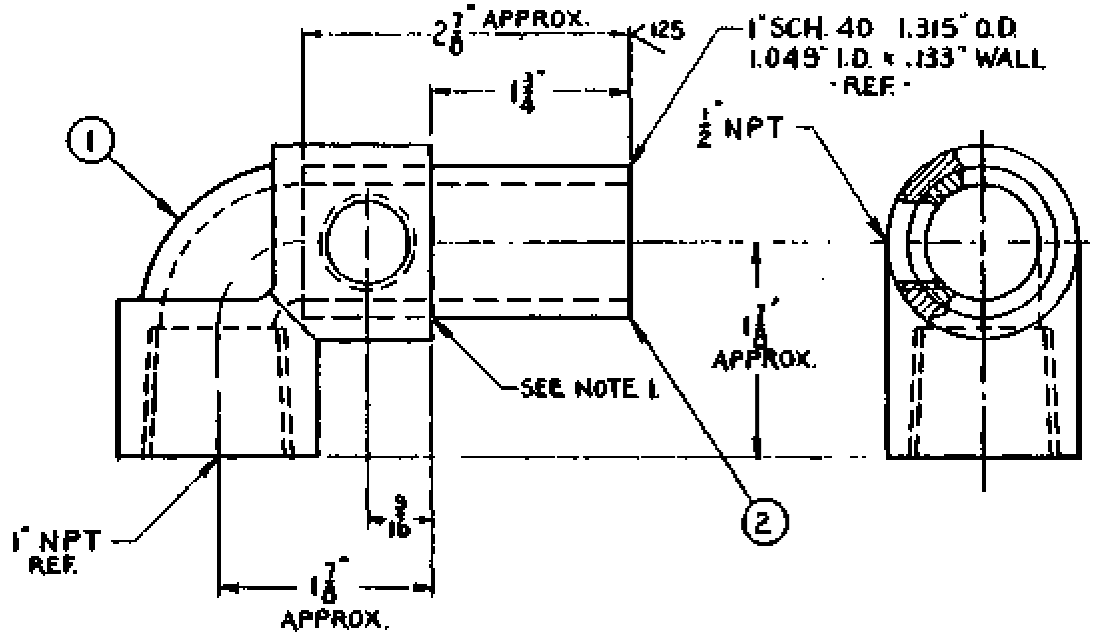
| | | | |
|---|---|---|---|
| TOLERANCES | CARNEGIE MELLON UNIVERSITY PITTSBURGH, PA | | |
| DECIMAL .005 | PUMP INLET FITTING | SCALE FULL | DRAWN BY RRF / APPROVED BY |
| FRACTIONAL 1/64" | TITLE O.T.E.C. HEAT TRANSFER MONITOR | | |
| ANGULAR ½° | DATE 2-24-77 | DRAWING NUMBER B-209 | REV |

| LIST OF MATERIAL | | | | | | | |
|---|---|---|---|---|---|---|---|
| ITEM | NO. REQD | ORDERING INFORMATION | MATERIAL | SPECIFICATION | VENDOR - PART NO. | REMARKS | WT |
| 1 | 1 | 90° ELBOW - 1" I.P.S. - 1" FEMALE N.P.T. | PVC | COM'L. | | | |
| 2 | 1 | NIPPLE 1" SCH 40 PIPE | PVC | COM'L. | | | |




## NOTES

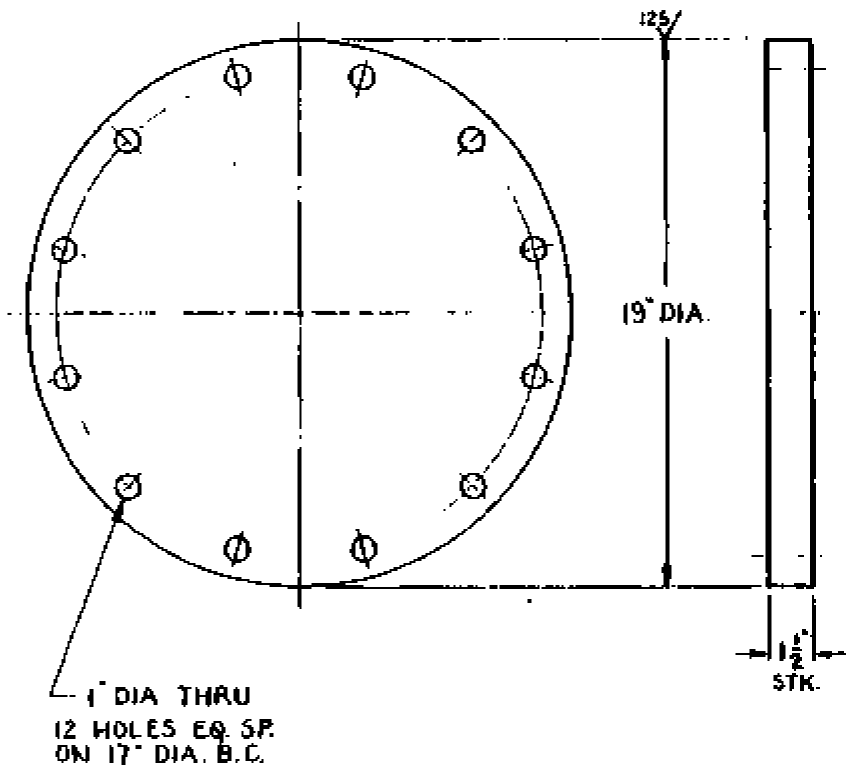
1. CEMENTED JOINTS SHALL BE WATERTIGHT. THIS UNIT IS INTENDED TO BE USED IN SEA WATER AT 100 FT. DEPTH. (APPROX. 50 PSI. EXTERNAL PRESSURE.)



| | | | |
|---|---|---|---|
| TOLERANCES | CARNEGIE MELLON UNIVERSITY PITTSBURGH, PA. | | |
| DECIMAL | PVC ELBOW | SCALE FULL | DRAWN BY RRF |
| FRACTIONAL ± 1/64 | TITLE O.T.E.C HEAT TRANSFER MONITOR | | |
| ANGULAR | DATE 2-24-77 | DRAWING NUMBER B-210 | REV |

## LIST OF MATERIAL

| ITEM | NO. REQD | ORDERING INFORMATION | MATERIAL | SPECIFICATION | VENDOR-PART NO. | REMARKS | WT. |
|---|---|---|---|---|---|---|---|
| 1 | 1 | REAR PLATE | PVC | COM'L. | | | |

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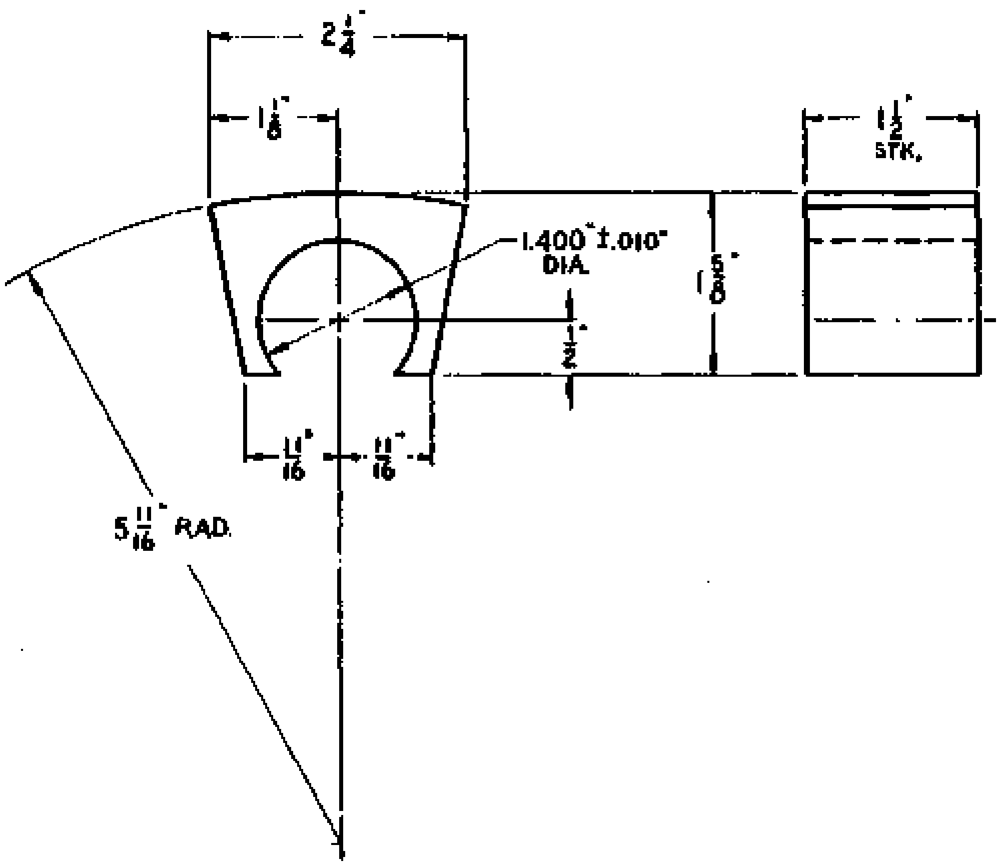
PITTSBURGH, PA.

| | | | |
|---|---|---|---|
| TOLERANCES DECIMAL ± | PUMP HOUSING REAR PLATE | SCALE 1/4" = 1" | DRAWN BY RRF |
| FRACTIONAL ± 1/64 | TITLE O.T.E.C. HEAT TRANSFER MONITOR | | |
| ANGULAR ± | DATE 2-25-77 | DRAWING NUMBER B-211 | REV. |

## LIST OF MATERIAL

| ITEM | NO. REQD. | ORDERING INFORMATION | MATERIAL | SPECIFICATION | VENDOR-PART NO. | REMARKS | WT. |
|---|---|---|---|---|---|---|---|
| 1 | 1 | CAPACITOR MOUNT | PVC | COM'L. | | | |




NOTE

1. FINISH 125/ ALL MACHINED SURFACES.

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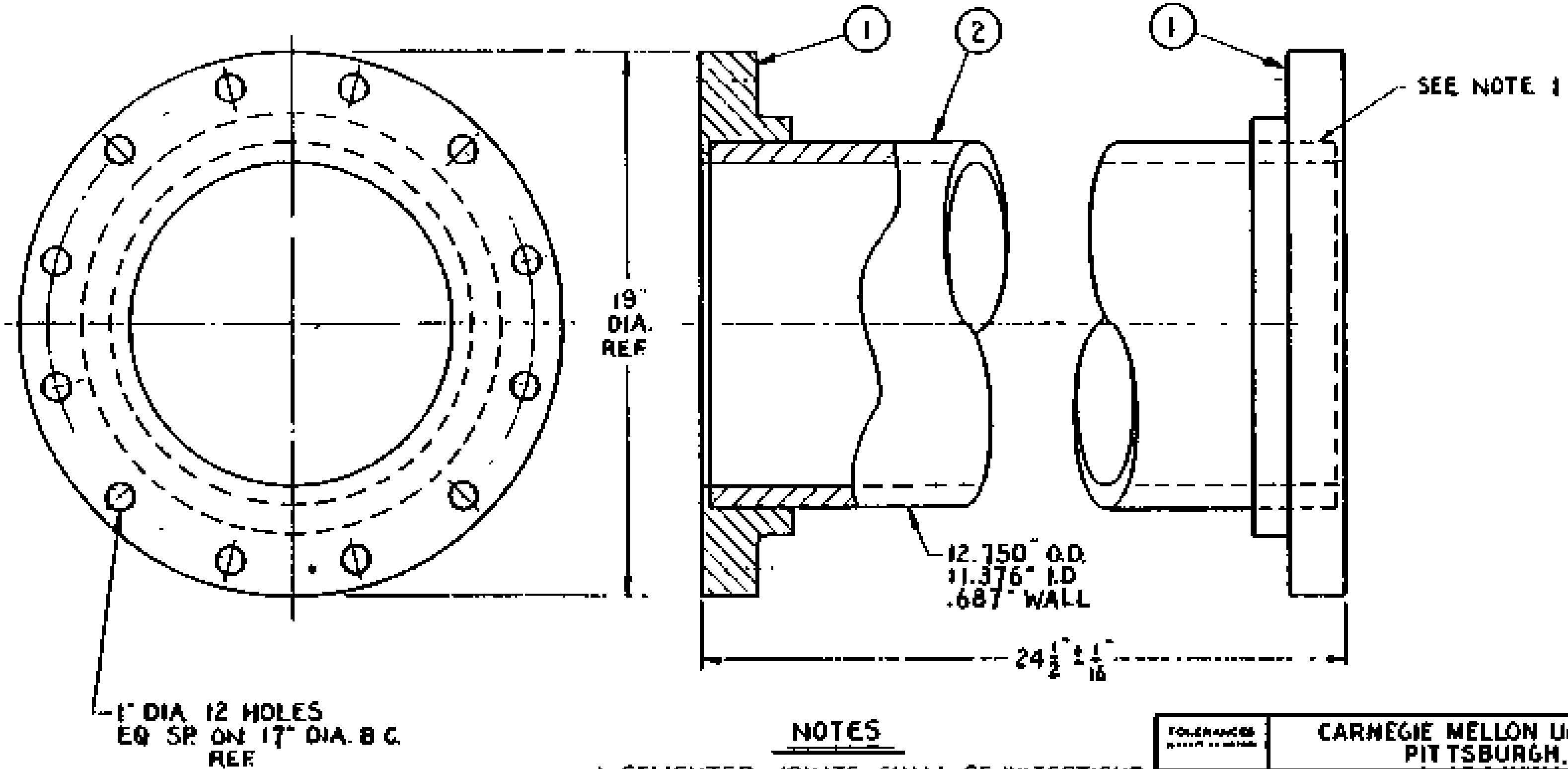
PITTSBURGH, PA

| | | | |
|---|---|---|---|
| TOLERANCES DECIMAL ± — | CAPACITOR MOUNT | SCALE FULL | DRAWN BY RRF |
| FRACTIONAL ± 1/64" | TITLE O.T.E.C. HEAT TRANSFER MONITOR | | |
| ANGULAR ± — | DATE 3-1-77 | DRAWING NUMBER B-212 | REV |

| LIST OF MATERIAL | | | | | | | |
|---|---|---|---|---|---|---|---|
| ITEM | NO. REQD | ORDERING INFORMATION | MATERIAL | SPECIFICATION | VENDOR · PART NO. | REMARKS | WT |
| 1 | 2 | 12"-150# SOCKET FLANGE | PVC | COM'L. | | | |
| 2 | 1 | 12" SCH. 80 PIPE | PVC | COM'L. | | | |



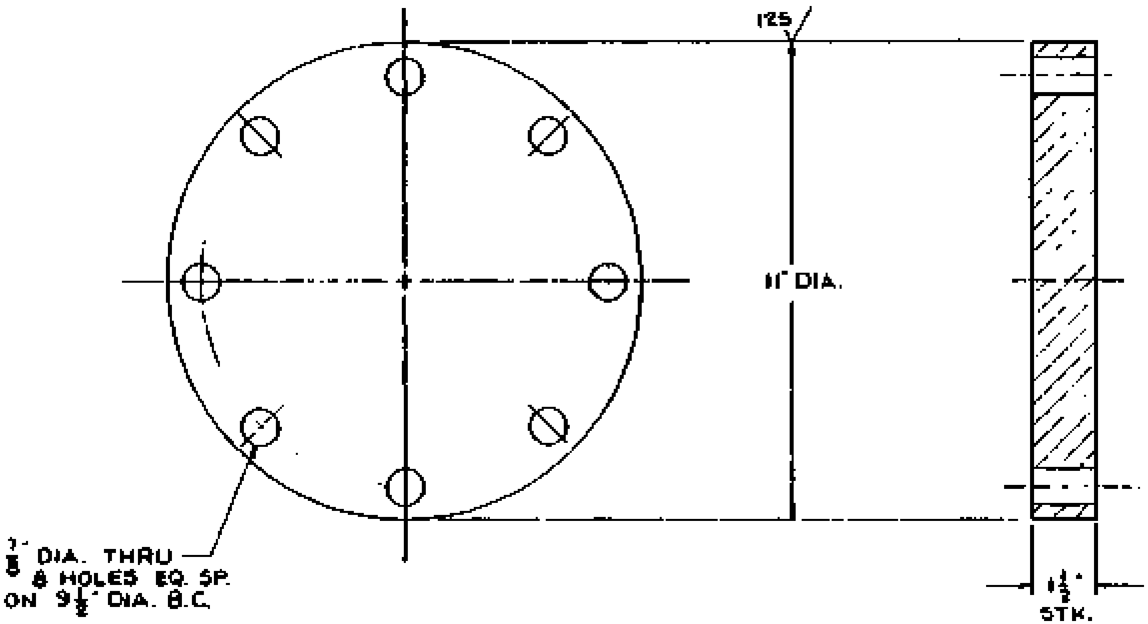

## NOTES

1. CEMENTED JOINTS SHALL BE WATERTIGHT. THIS UNIT IS INTENDED TO BE USED IN SEA WATER AT 100 FT DEPTH. (APPROX 50 P.S.I. EXTERNAL PRESSURE)

| | | | |
|---|---|---|---|
| TOLERANCES | CARNEGIE MELLON UNIVERSITY PITTSBURGH, PA | | |
| DECIMAL ± | PUMP HOUSING | SCALE $\frac{1}{4}" = 1"$ | DRAWN BY RRF / APPROVED BY |
| FRACTIONAL ± | TITLE OTEC HEAT TRANSFER MONITOR | | |
| ANGULAR ± | DATE 3-1-77 | DRAWING NUMBER B-213 | REV |

## LIST OF MATERIAL

| ITEM | NO. REQ'D. | ORDERING INFORMATION | MATERIAL | SPEC. | VENDOR - PART NO. | REMARKS | WT. |
|---|---|---|---|---|---|---|---|
| 1 | 1 | SIDE PVC PLATE | PVC | COM'L. | | | |




CARNEGIE MELLON UNIVERSITY
PITTSBURGH, PA.

SIDE PVC PLATE

SCALE: 3/8" : 1"

DRAWN BY: B.J.H.

APPROVED BY:

TOLERANCES: DECIMAL ±; FRACTIONAL ±1/64"; ANGULAR ±2°

TITLE: O.T.E.C. HEAT TRANSFER MONITOR

DATE: 2-17-77

DRAWING NUMBER: B-214

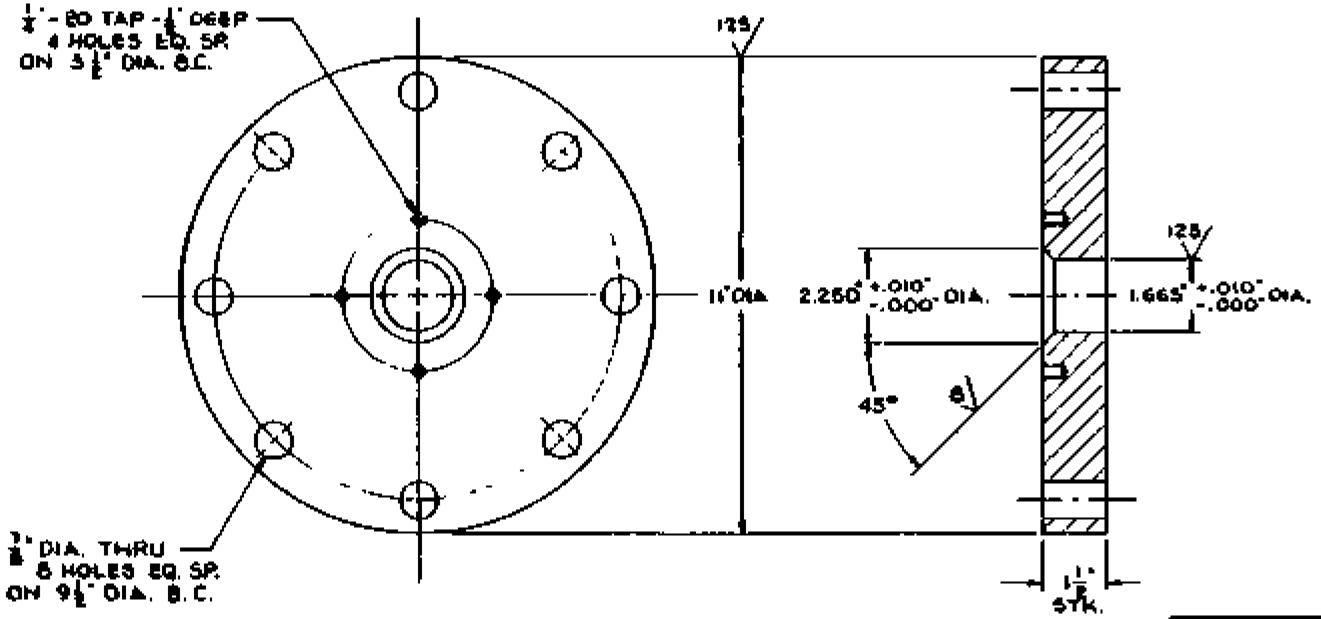
REV.

K+E

MADE IN U.S.A.

LIST OF MATERIAL

| ITEM | NO. REQ'D. | ORDERING INFORMATION | MATERIAL | SPEC. | VENDOR - PART NO. | REMARKS | WT. |
|---|---|---|---|---|---|---|---|
| 1 | 1 | BOTTOM PVC PLATE | PVC | COM'L. | | | |

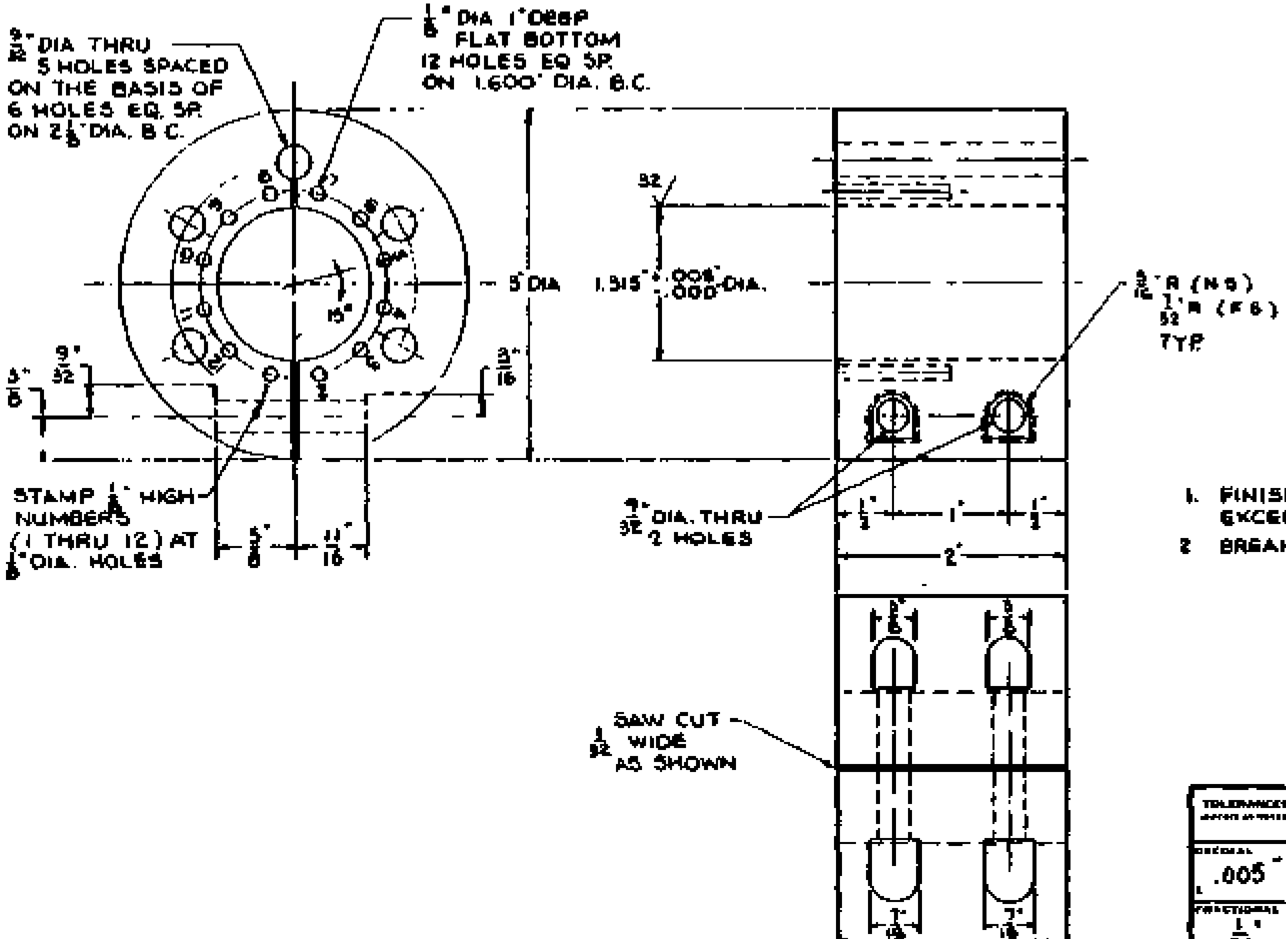



CARNEGIE MELLON UNIVERSITY
PITTSBURGH, PA.

| | | | |
|---|---|---|---|
| TOLERANCES DECIMAL ± .X | BOTTOM PVC PLATE | SCALE 1/8" = 1" | DRAWN BY B.J.H. |
| FRACTIONAL ± 1/64" | TITLE O.T.E.C. HEAT TRANSFER MONITOR | | |
| ANGULAR ± 2° | DATE 2-17-77 | DRAWING NUMBER B-215 | REV. |

## LIST OF MATERIAL

| ITEM | NO. REQ'D. | ORDERING INFORMATION | MATERIAL | SPEC. | VENDOR - PART NO. | REMARKS | WT. |
|---|---|---|---|---|---|---|---|
| 1 | 1 | COPPER REFERENCE BLOCK | COPPER | COML. | | | |



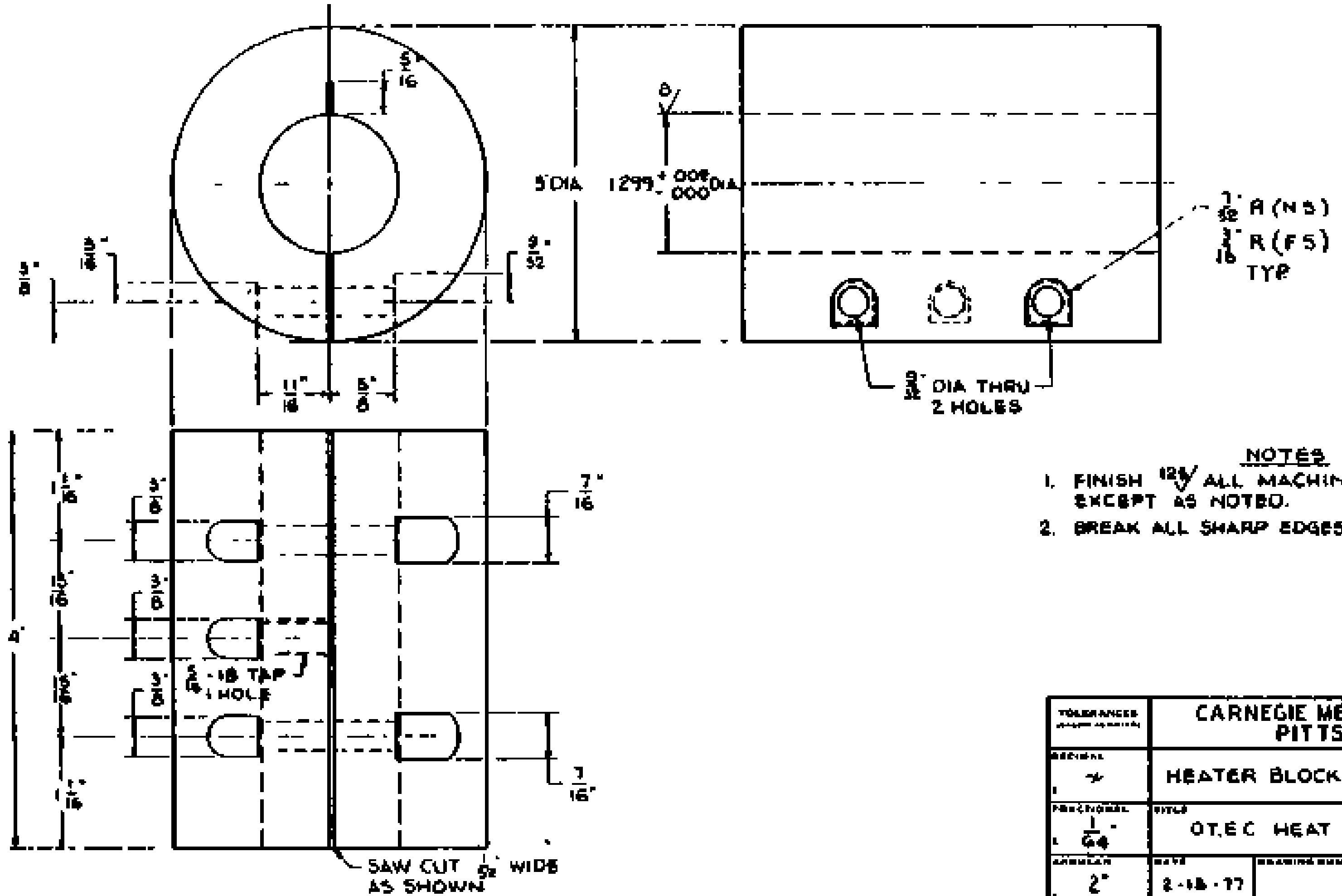

### NOTES

1. FINISH 125/ ALL MACHINED SURFACES EXCEPT AS NOTED.
2. BREAK SHARP EDGES 1/64" MAX. R. OR CHAM.

| | | | |
|---|---|---|---|
| TOLERANCES | CARNEGIE MELLON UNIVERSITY PITTSBURGH, PA. | | |
| DECIMAL ± .005" | CU. REFERENCE BLOCK | SCALE FULL | DRAWN BY B.J.H. |
| FRACTIONAL ± 1/64" | TITLE O.T.E.C. HEAT TRANSFER MONITOR | | |
| ANGULAR ± 2° | DATE 2-17-77 | DRAWING NUMBER B-216 | REV |

LIST OF MATERIAL

| ITEM | NO. REQ'D | ORDERING INFORMATION | MATERIAL | SPEC. | VENDOR - PART NO. | REMARKS | WT |
|---|---|---|---|---|---|---|---|
| 1 | 2 | HEATER BLOCK | COPPER | COML | | | |



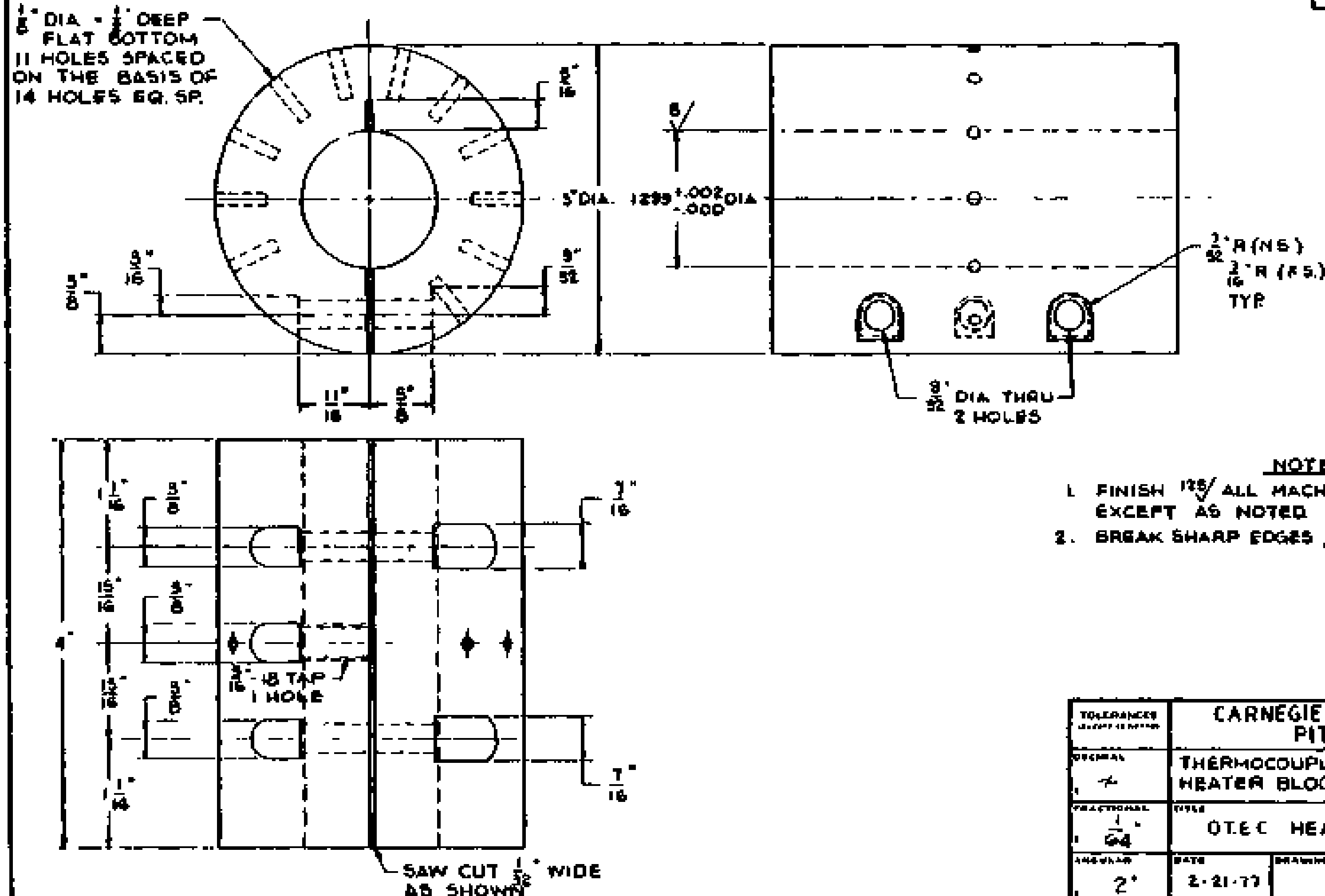

NOTES

1. FINISH 125√ ALL MACHINED SURFACES EXCEPT AS NOTED.
2. BREAK ALL SHARP EDGES 1/64" MAX R OR CHAM.

| | | | | |
|---|---|---|---|---|
| TOLERANCES | CARNEGIE MELLON UNIVERSITY PITTSBURGH, PA | | | |
| DECIMAL ± | HEATER BLOCK | SCALE FULL | DRAWN BY B.J.H. | APPROVED BY |
| FRACTIONAL ± 1/64" | TITLE OT.E.C. HEAT TRANSFER MONITOR | | | |
| ANGULAR ± 2° | DATE 2-16-77 | DRAWING NUMBER B-217 | | REV |

## LIST OF MATERIAL

| ITEM | NO REQ'D. | ORDERING INFORMATION | MATERIAL | SPEC. | VENDOR - PART NO. | REMARKS | WT. |
|---|---|---|---|---|---|---|---|
| 1 | 1 | THERMOCOUPLE HEATER BLOCK | COPPER | COML | | | |




**NOTES**

1. FINISH 125/ ALL MACHINED SURFACED EXCEPT AS NOTED
2. BREAK SHARP EDGES 1/64" MAX. R. OR CHAM.

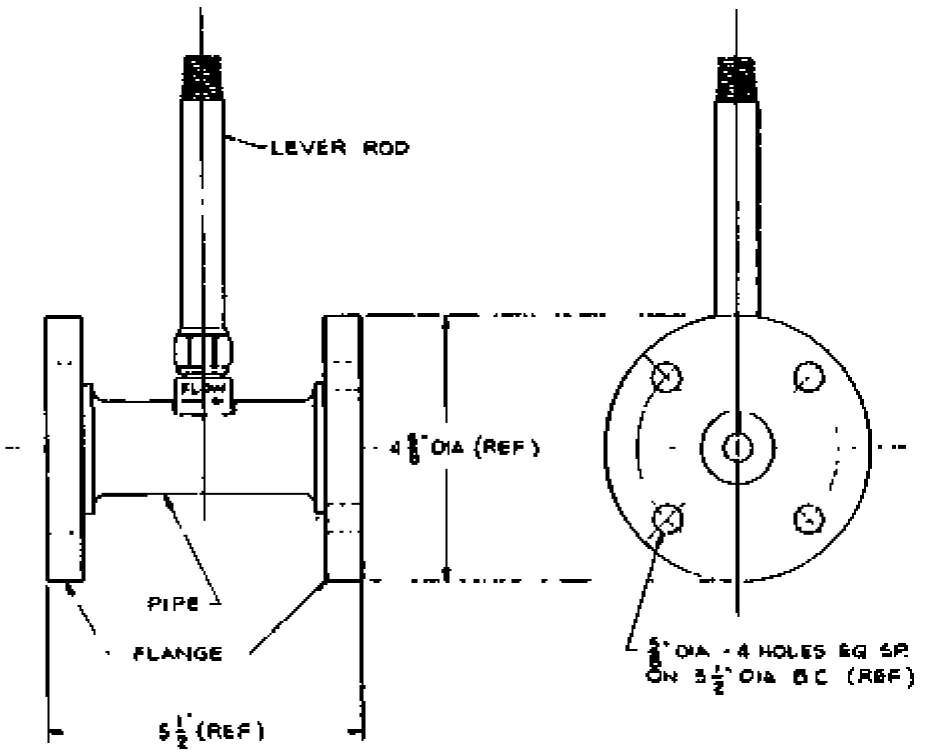
| TOLERANCES | CARNEGIE MELLON UNIVERSITY PITTSBURGH, PA | | |
|---|---|---|---|
| DECIMAL ± | THERMOCOUPLE HEATER BLOCK | SCALE FULL | DRAWN BY B.J.H. |
| FRACTIONAL ± 1/64" | TITLE OT.E.C HEAT TRANSFER MONITOR | | |
| ANGULAR ± 2° | DATE 2-21-77 | DRAWING NUMBER B-218 | REV. |

H-E

LIST OF MATERIAL

| ITEM | NO REQ'D | ORDERING INFORMATION | MATERIAL | SPEC | VENDOR - PART NO. | REMARKS | WT |
|---|---|---|---|---|---|---|---|
| 1 | 1 | FLOW METER | | | | | |

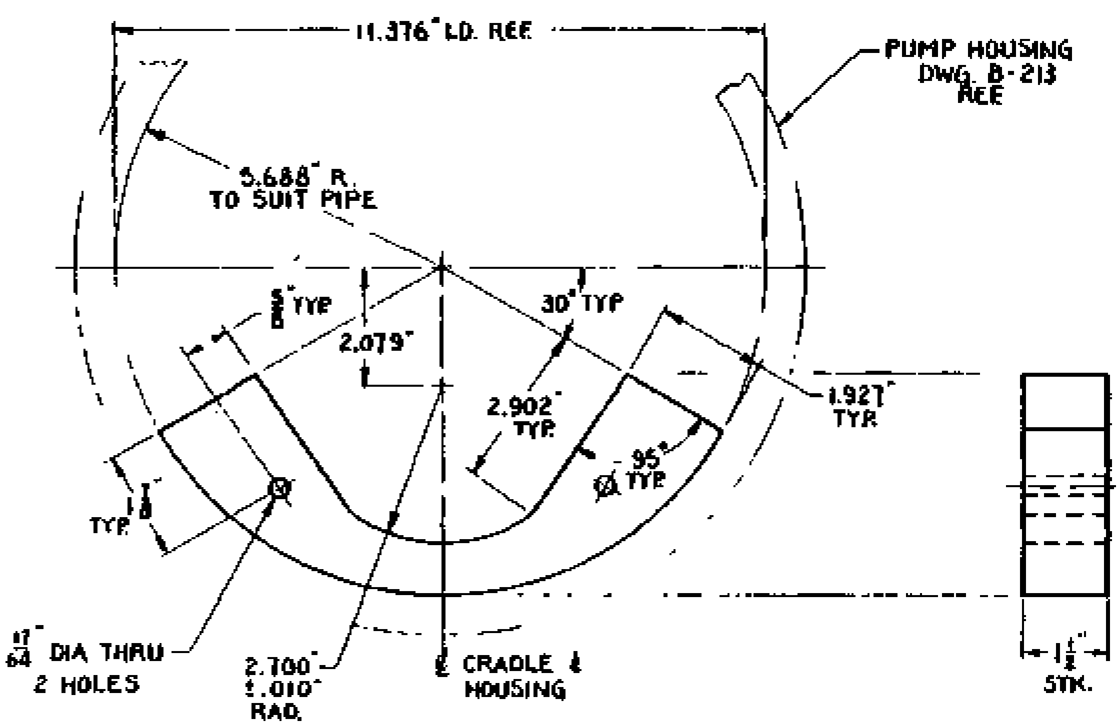
VENDOR: RAMAPO INSTRUMENT COMPANY, INC (DWG 31050)
MONTVILLE, NEW JERSEY 07045
MODEL : MARK V - 1¼" - 5FY
SERIAL NO : 4030
LINE SIZE : 1¼"
SCHEDULE : 40 PIPE
FLOW RATE : 4.4 - 44 GPM
FLANGE : 1¼" - 150# ANSI
MATERIALS
FLANGE : T316 S.S (PVC IN FUTURE)
PIPE : T316 S.S (PVC IN FUTURE)
SENSING ELEMENT : T 316 S.S (HASTELLOY "C" IN FUT
LEVER ROD : T316 S.S (HASTELLOY "C" IN FUTURE)
OTHER : T316 S.S




| | |
|---|---|
| TOLERANCES | CARNEGIE MELLON UNIVERSITY PITTSBURGH PA |
| DECIMAL | FLOW METER — SCALE 1/2" = 1" — DRAWN BY B J H — APPROVED BY |
| FRACTIONAL | TITLE: OTEC HEAT TRANSFER MONITOR |
| ANGULAR | DATE 2-25-77 — DRAWING NUMBER B-219 — REV |

## LIST OF MATERIAL

| ITEM | NO. REQD | ORDERING INFORMATION | MATERIAL | SPECIFICATION | VENDOR- PART NO. | REMARKS | WT. |
|---|---|---|---|---|---|---|---|
| 1 | 1 | PUMP CRADLE | PVC | COM'L. | | | |



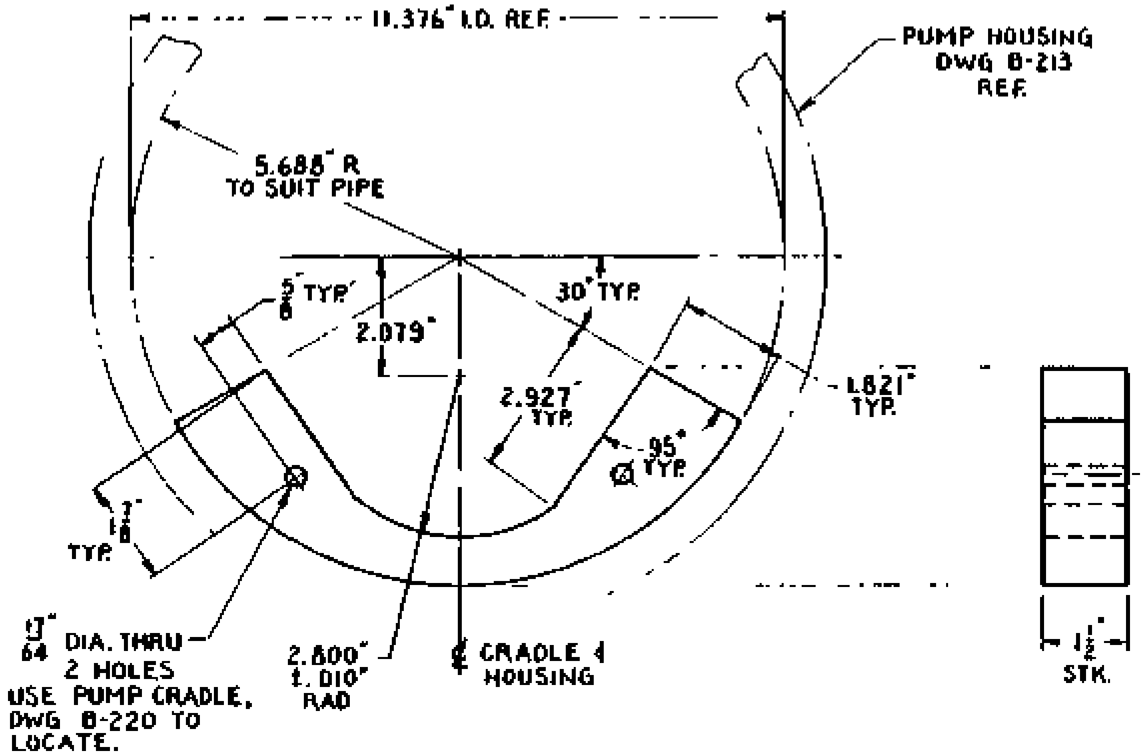

NOTE

1. FINISH 125√ ALL MACHINED SURFACES

| TOLERANCES | CARNEGIE MELLON UNIVERSITY PITTSBURGH, PA. | | |
|---|---|---|---|
| DECIMAL .005 | PUMP CRADLE | SCALE 1/2" = 1" | DRAWN BY RRF |
| FRACTIONAL ± 1/64 | TITLE QTEC HEAT TRANSFER MONITOR | | |
| ANGULAR ± 2° | DATE 3-1-77 | DRAWING NUMBER B-220 | REV. |

## LIST OF MATERIAL

| ITEM | NO REQD | ORDERING INFORMATION | MATERIAL | SPECIFICATION | VENDOR-PART NO. | REMARKS | WT. |
|---|---|---|---|---|---|---|---|
| 1 | 1 | MOTOR CRADLE | PVC | COM'L. | | | |




### NOTE

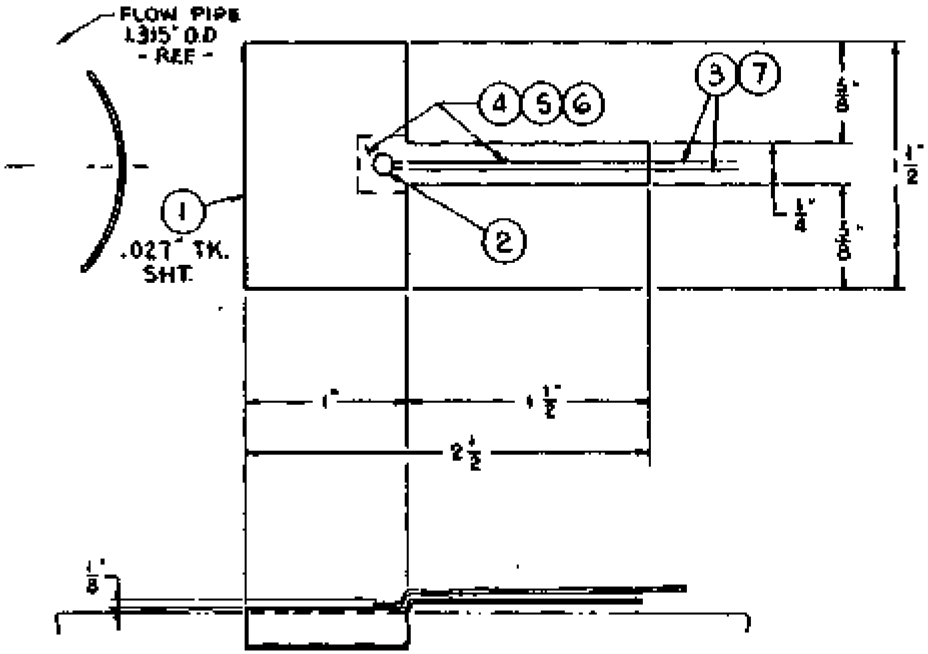
1. FINISH 125√ ALL MACHINED SURFACES.

94.

| | |
|---|---|
| TOLERANCES | CARNEGIE MELLON UNIVERSITY PITTSBURGH, PA |
| DECIMAL ±.005" | MOTOR CRADLE — SCALE 1/2" : 1" — DRAWN BY RRF — APPROVED BY |
| FRACTIONAL ±1/64" | TITLE: OTEC HEAT TRANSFER MONITOR |
| ANGULAR ±2° | DATE 3-1-77 — DRAWING NUMBER B-221 — REV |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| LIST OF MATERIALS | | | | | | | |
| ITEM | NT REQ'D | ORDERING INFORMATION | MATERIAL | SPEC. | VENDOR - PART NO. | REMARKS | WT. |
| 1 | 1 | THERMISTOR MOUNT | COPPER | COM'L. | | | |
| 2 | 1 | THERMISTOR | | | VECO - 31E2 | SEE NOTE "A" | |
| 3 | 2 | ENAMELED WIRE - 5" | COPPER | | BELDEN - 8051 | SEE NOTE "B" | |
| 4 | 1 SET | RESIN AND HARDENER | EPOXY | | DELTA BOND - 153 - K - A | SEE NOTE "C" | |
| 5 | 1 SET | ADHESIVE AND HARDENER | EPOXY | | MILLER STEPHENSON 907 | SEE NOTE "D" | |
| 6 | 1 SET | ELECTRICAL COATING | | | 3 M - SKOTCHKOTE | SEE NOTE "E" | |

| SYM | DN | REVISION RECORD | AUTH | DR | CK |
|---|---|---|---|---|---|
| | | | | | |



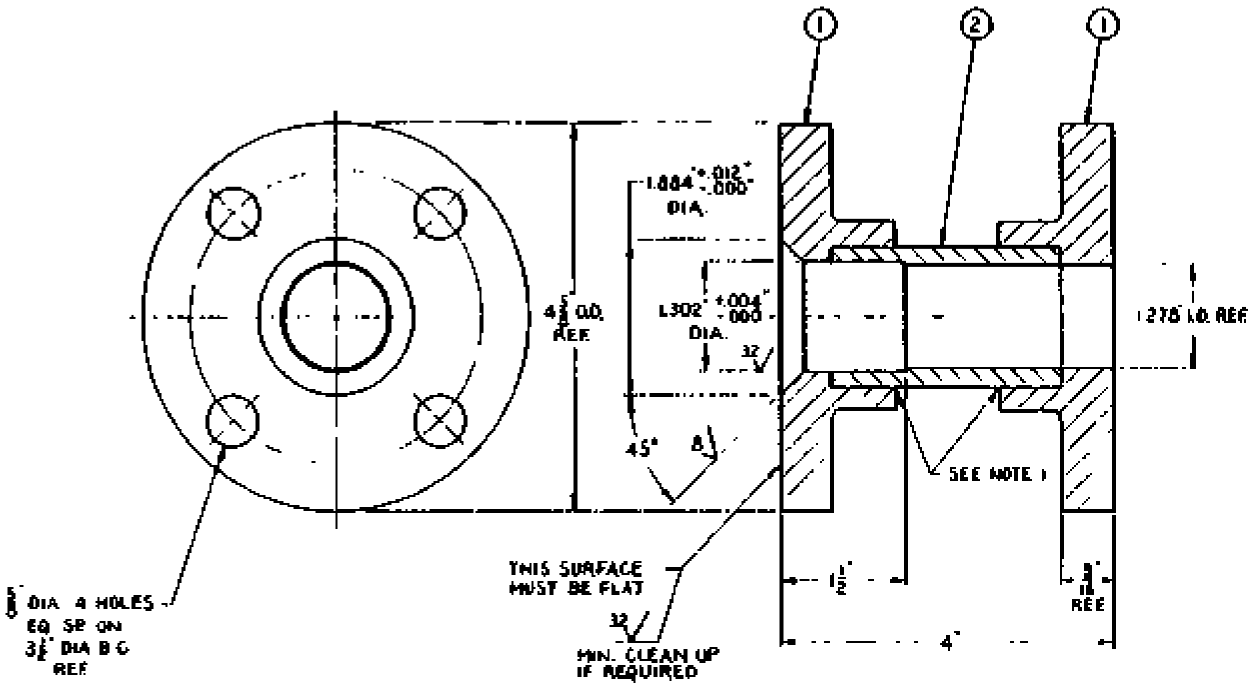

## PROCEDURE

1. FORM ① TO THE CIRCULAR SHAPE OF THE FLOW PIPE AS SHOWN ON DWGS B-205 & B-206.
2. ETCH ① WITH WEAK ACID SOLUTION OF HYDROCHLORIC OR NITRIC ACID, WASH WITH CLEAR WATER AND DRY.
3. TRIM LEADS OF ② TO APPROX. 3/8".
4. MIX ④ (200 PARTS RESIN - 15 PARTS HARDENER)
5. COAT AND POT ② TO ①, BUT NOT THE TIPS OF THE LEADS ON ②, USING ④ ALLOW 24 HOURS TO DRY.
6. SOLDER ③ TO ② AS SHOWN.
7. MIX ⑤ (EQUAL PARTS ADHESIVE AND HARDENER)
8. COAT LEADS AND STRIP WITH ⑤. ATTACH LEADS TO STRIP. COVER LEADS AND THERMISTOR WITH ⑤.
9. CHECK FOR ELECTRICAL SHORTS
10. COAT LEADS WITH ⑥.

"A" - TECHNICAL ELECTRONIC DISTRIBUTORS - BERGENFIELD, N.J. 07621
"B" - BELDEN CORP. - CHICAGO, ILL. 60644
"C" - WAKEFIELD ENGINEERING INC. - WAKEFIELD, MASS. 01880
"D" - MILLER-STEPHENSON CHEMICAL CO. INC. - CHICAGO, ILL. 60626
"E" - ELECTRO-PRODUCTS DIV. 3 M CO. - ST PAUL, MINN. 55101
} OR APPD. EQUAL

| | | | | | |
|---|---|---|---|---|---|
| TOLERANCES | CARNEGIE MELLON UNIVERSITY PITTSBURGH, PA. | | | | |
| DECIMAL ± | THERMISTOR MOUNT | SCALE $1\frac{1}{2}$" = 1" | DRAWN BY B.J.H. | APPROVED BY | |
| FRACTIONAL ± 1/64 | TITLE O.T.E.C HEAT TRANSFER MONITOR | | | | |
| ANGULAR ± | DATE 3-2-77 | DRAWING NUMBER B-222 | | | REV. |

| LIST OF MATERIAL | | | | | | | |
|---|---|---|---|---|---|---|---|
| ITEM | NO. REQ'D | ORDERING INFORMATION | MATERIAL | SPEC. | VENDOR - PART NO. | REMARKS | WT |
| 1 | 2 | 1¼"-150# SOCKET FLANGE | PVC | COM'L. | | | |
| 2 | 1 | 1¼"-SCH. 80 PIPE | PVC | COM'L. | | | |

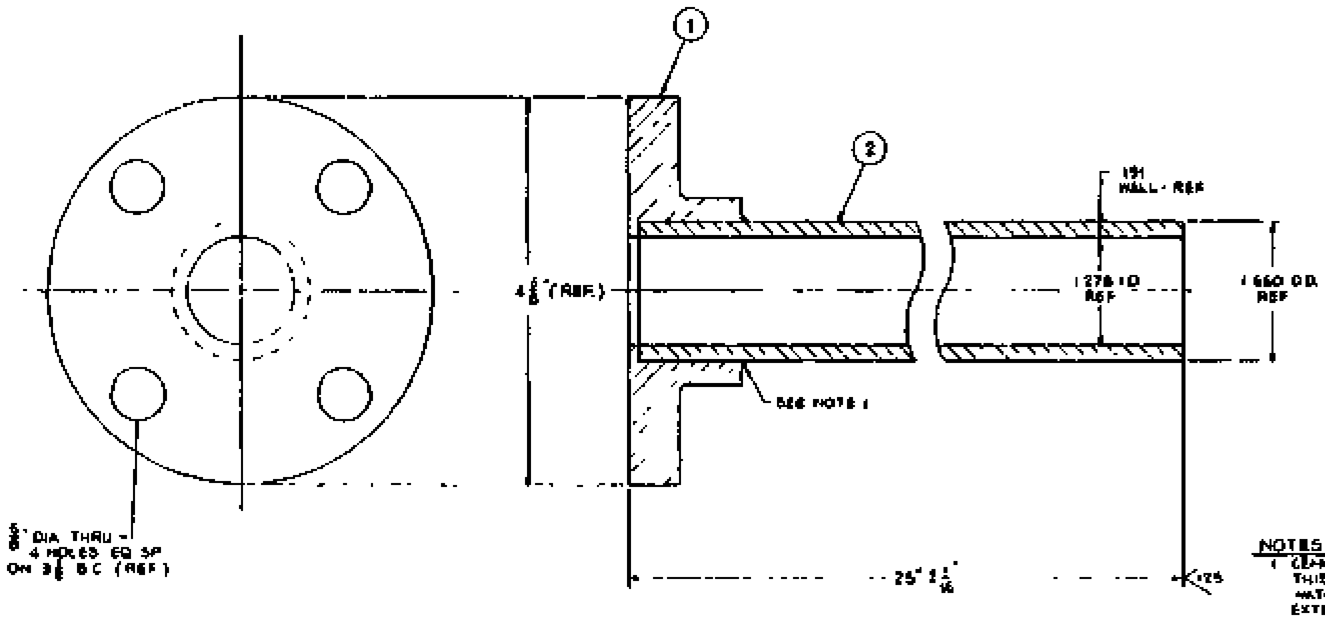



NOTE

1. CEMENTED JOINTS SHALL BE WATER TIGHT. THIS UNIT IS INTENDED TO BE USED IN SEA WATER AT 100 FT. DEPTH. (APPROX. 50 PSI EXTERNAL PRESSURE)

| | |
|---|---|
| | CARNEGIE MELLON UNIVERSITY PITTSBURGH, PA |
| -/- | FLOW PIPE CONN. FULL RRP |
| 1/64 | OTEC HEAT TRANSFER MONITOR |
| 2° | 2-21-77 C-300 |

| LIST OF MATERIALS | | | | | | | |
|---|---|---|---|---|---|---|---|
| ITEM | Nº REQD | ORDERING INFORMATION | MATERIAL | SPEC | VENDOR - PART Nº | REMARKS | WT |
| 1 | 1 | 1¼" - 150# SOCKET FLANGE | PVC | COM'L | | | |
| 2 | 1 | 1¼" SCHEDULE 80 PIPE | PVC | COM'L. | | | |




NOTES
1. CEMENTED JOINTS SHALL BE WATERTIGHT. THIS UNIT IS INTENDED TO BE USED IN SEA WATER AT 100 FT DEPTH (APPROX 50 PSI EXTERNAL PRESSURE)

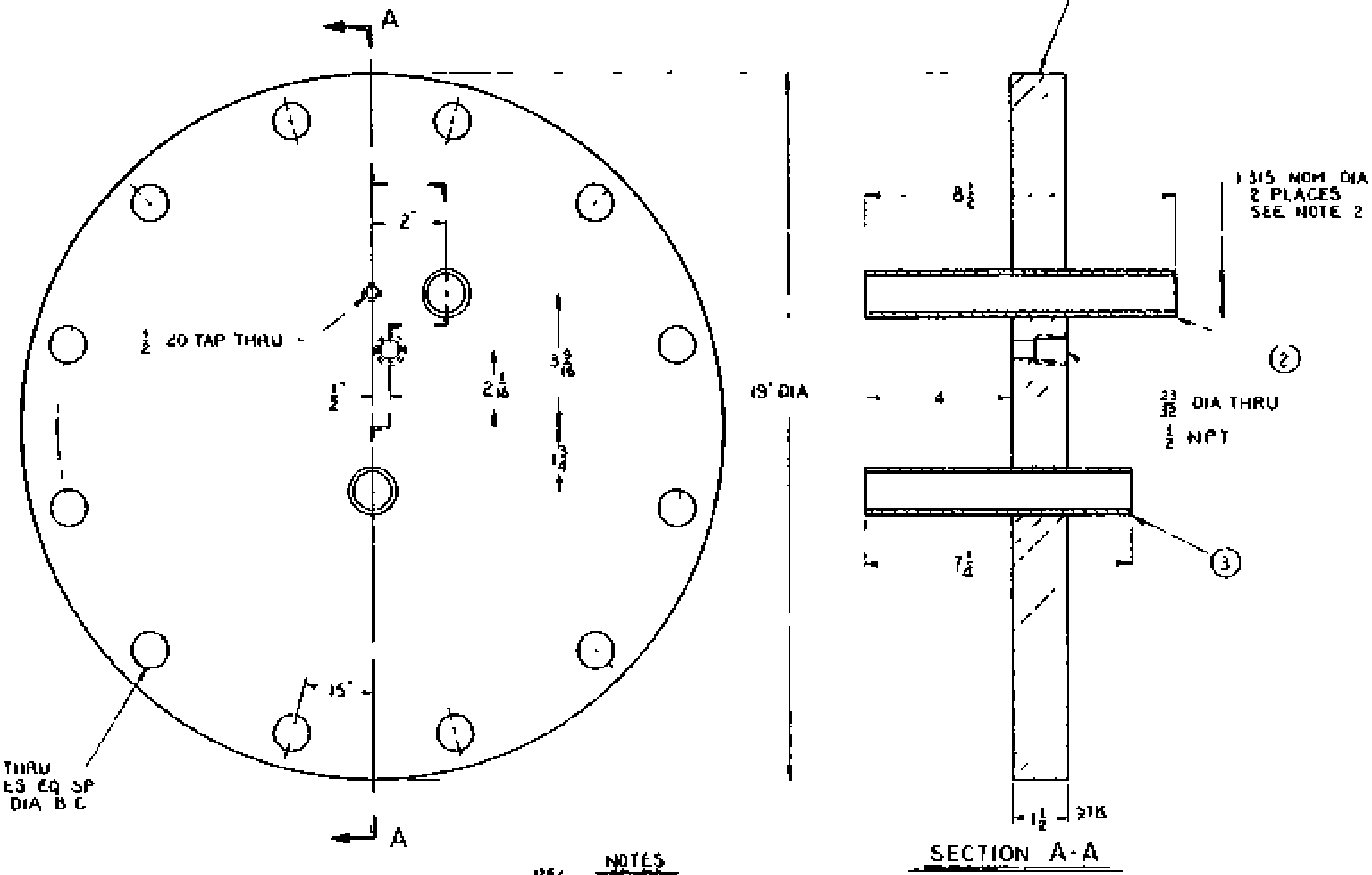
CARNEGIE MELLON UNIVERSITY
PITTSBURGH, PA

PIPE ASSEMBLY | FULL | G J H

OTEC HEAT TRANSFER MONITOR

2 16 77 | C-301

| LIST OF MATERIAL | | | | | | | |
|---|---|---|---|---|---|---|---|
| ITEM | NO. REQ'D | ORDERING INFORMATION | MATERIAL | SPECIFICATION | VENDOR PART NO | REMARKS | WT |
| 1 | 1 | FRONT PLATE | PVC | COM'L | | | |
| 2 | 1 | DISCHARGE 1" SCH 40 PIPE | PVC | COM'L | | | |
| 3 | 1 | SUCTION 1" SCH 40 PIPE | PVC | COM'L | | | |




NOTES

1. FINISH 125/√ ALL MACHINED SURFACES
2. CEMENTED JOINTS SHALL BE WATERTIGHT. THIS UNIT IS INTENDED TO BE USED IN SEA WATER AT 100 FT. DEPTH (APPROX 50 PSI EXTERNAL PRESSURE)

CARNEGIE MELLON UNIVERSITY
PITTSBURGH PA

PUMP HOUSING
FRONT PLATE

RRF

OTEC HEAT TRANSFER MONITOR

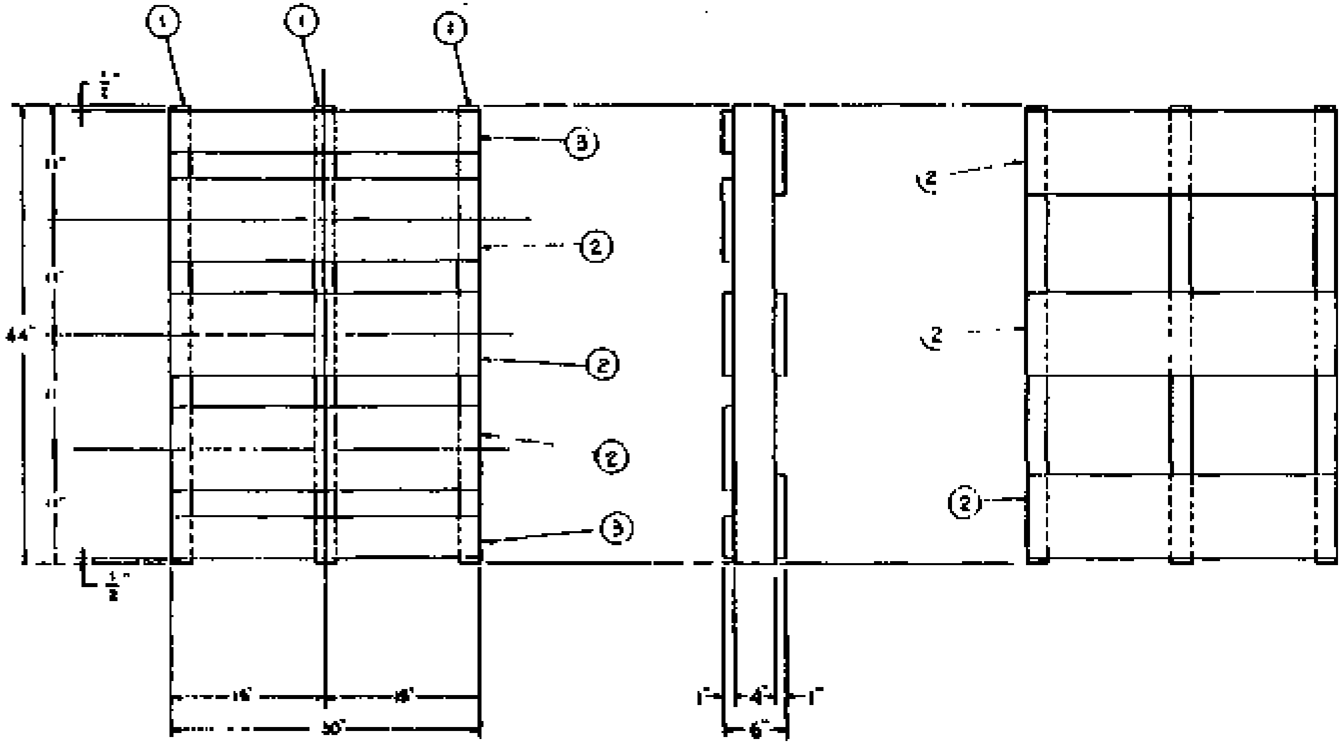
1/64

2"

2 25 77

C-302

| LIST OF MATERIAL | | | | | | | |
|---|---|---|---|---|---|---|---|
| ITEM | NO. REQ'D | ORDERING INFORMATION | MATERIAL | SPEC | VENDOR - PART NO | REMARKS | WT. |
| 1 | 5 | LUMBER - 2" × 4" × 44" | | | | | |
| 2 | 6 | LUMBER - 1" × 8" × 50" | | | | | |
| 3 | 2 | LUMBER - 1" × 4" × 50" | | | | | |




CARNEGIE MELLON UNIVERSITY
PITTSBURGH PA

PUMP HOUSING PALLET

B.J.H.

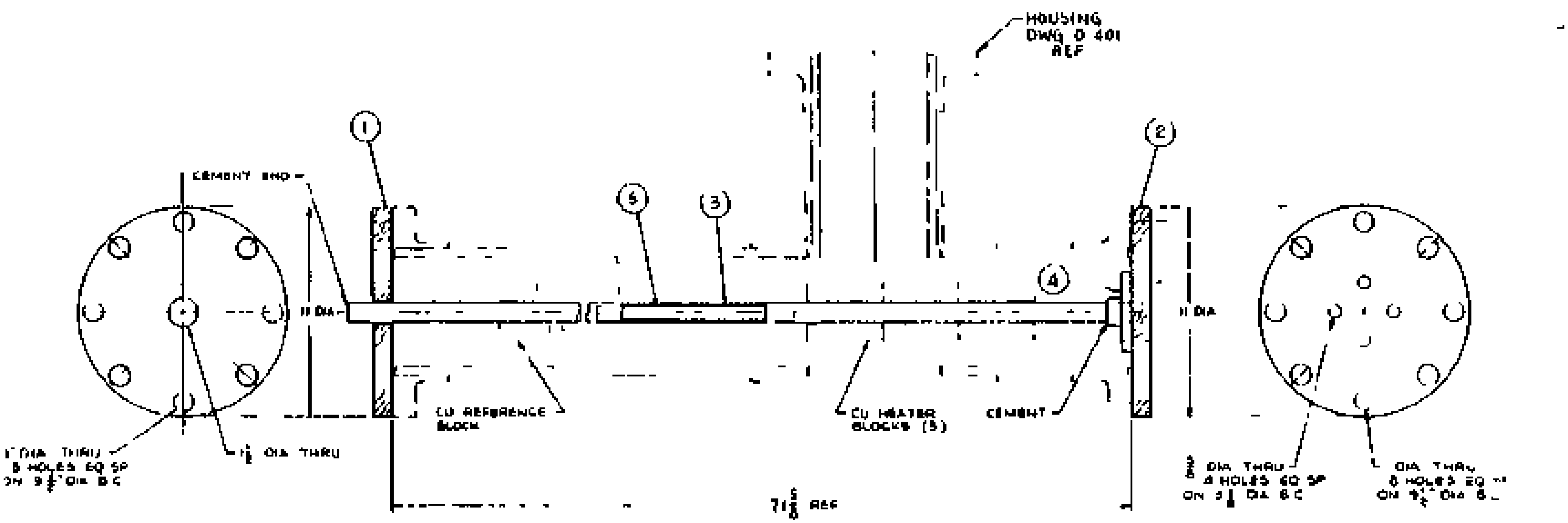
OT&C HEAT TRANSFER MONITOR

5-1-77

C-303

LIST OF MATERIALS

| ITEM | NO REQD | ORDERING INFORMATION | MATERIAL | SPEC | VENDOR - PART NO | REMARKS | WT |
|---|---|---|---|---|---|---|---|
| 1 | 1 | FLANGE ¾ THK - 11" DIA | PLYWOOD | | | | |
| 2 | 1 | FLANGE ¾ THK - 11 DIA | PLYWOOD | | | | |
| 3 | 1 | 1" SCHEDULE 80 PIPE - 74 LG | PVC | COM L | | | |
| 4 | 1 | 1 150# SOCKET FLANGE | PVC | COM L | | | |
| 5 | 1 | ½" SCHEDULE 40 PIPE - 14" LG | STL | COM L | | | |




NOTE

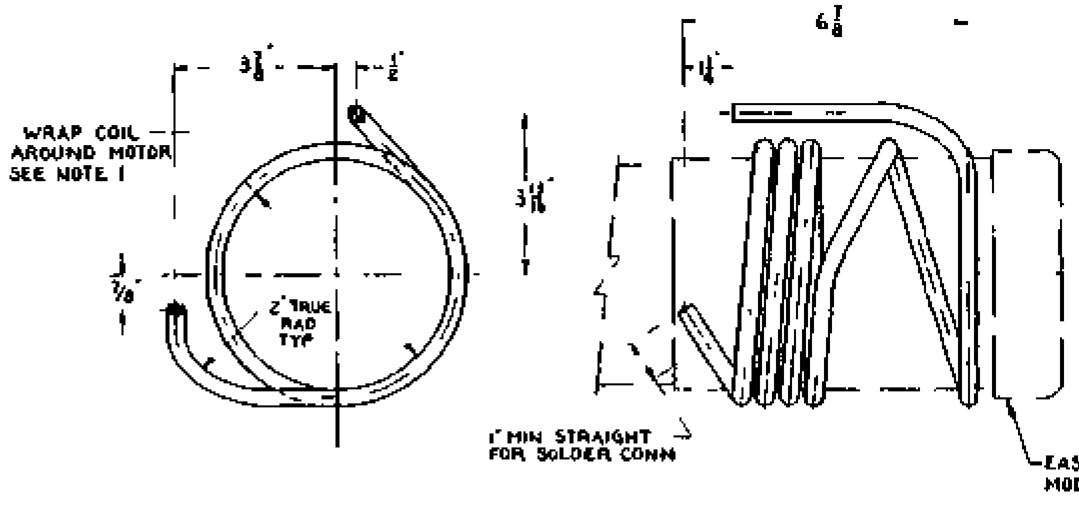
1 USE EXISTING HARDWARE TO SECURE FLANGES
2 MACHINE [illegible] PVC PIPE FROM [illegible] .300 DIA [illegible] LENGTH FROM FREE END
3 [illegible]

CARNEGIE MELLON UNIVERSITY
PITTSBURGH PA

OTEC HEAT TRANSFER MONITOR

C-304

| LIST OF MATERIAL | | | | | | | |
|---|---|---|---|---|---|---|---|
| ITEM | NO REQD | ORDERING INFORMATION | MATERIAL | SPECIFICATION | VENDOR PART NO | REMARKS | WT |
| 1 | 1 | COOLING COIL 5/8 OD × 1/2 ID - 10'LG | COPPER | COML | | | |




NOTE

1 SCRAPE PAINT FROM THE OUTSIDE OF THE MOTOR HOUSING. WRAP COIL TIGHTLY, AS SHOWN AROUND THE HOUSING. SOFT SOLDER COIL SECURELY IN PLACE & REPAINT

2 COIL IS POSITIONED ON MOTOR SO AS NOT TO INTERFERE WITH HOSE CLAMPS AT ASSY SEE ITEM 15, DWG D 403



CARNEGIE MELLON UNIVERSITY
PITTSBURGH PA

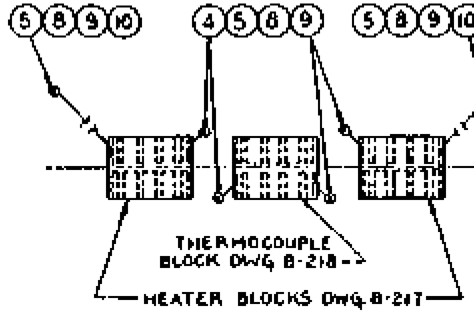
COOLING COIL — SCALE $\frac{1}{2}$" - 1 — RRF

OTEC HEAT TRANSFER MONITOR

3 3 77 — C-305

| LIST OF MATERIAL | | | | | | | |
|---|---|---|---|---|---|---|---|
| ITEM | NO. REQD | ORDERING INFORMATION | MATERIAL | SPEC | VENDOR-PART NO. | REMARKS | WT |
| 1 | 13 FT | POLYESTER TAPE 3/4" WIDE × .004" TK | POLYESTER | | SCOTCH BRAND ELEC TAPE | SEE NOTE "A" | |
| 2 | 13 FT | NICHROME WIRE 1/16" WIDE × .004" TK | 80% Ni 20% Cr | | W.B DRIVER - TOPHET "A" | SEE NOTE "B" | |
| 3 | 6 IN | JUMPER WIRE # 16 A.W.G. SOLID | COPPER | COML | | | |
| 4 | 1 FT | LEAD WIRE # 16 A.W.G. - STRANDED | COPPER | COML | | 4 REQD - EACH 2 1/2" LG | |
| 5 | 6 | CRIMP-ON CONN 22-18 # 4 | CU.-TIN PL | COML | | | |
| 6 | 1 PT | INSULATING ENAMEL - RED | GLYPTAL | | GENERAL ELEC 1201 | SEE NOTE "C" | |
| 7 | A.R. | SOLDER & FLUX | | | EUTEC ROD 157 B (SOLDER), 157 (FLUX) NOTE "D" | | |
| 8 | 2 | # 4 40 RD HD MACH SCR 1/4" LG | STN STL | COML | | | |
| 9 | 2 | # 4 40 HEX. NUT | STN STL | COML | | | |
| 10 | 4 1/2 FT | LEAD WIRE # 16 A.W.G. - STRANDED | COPPER | COML. | | 2 REQD EACH 25" LG | |
| 11 | A.R. | EPOXY RESIN | | | EPON RESIN 815 | SEE NOTE "E" | |
| 12 | A.R. | EPOXY HARDENER | | | EPON CURING AGENT U | SEE NOTE "E" | |

A - [illegible] ELECTRICAL PROD DIV 3M CO. - ST PAUL, MINN 55101 OR APPD EQUAL
([illegible] POLYESTER FILM - THERMOSETTING - PRESSURE SENSITIVE ADHESIVE)
B - W. [illegible] & [illegible] CO - NEWARK, N.J. 07104 OR APPD EQUAL
C - GENERAL ELECTRIC CORP - SCHENECTADY, N.Y. 12345 OR APPD EQUAL
D - EUTECTIC CORP - FLUSHING, N.Y. 11358 OR APPD EQUAL
E - MILLER - STEPHENSON CHEMICAL CO INC - CHICAGO, ILL 60626 OR APPD EQUAL



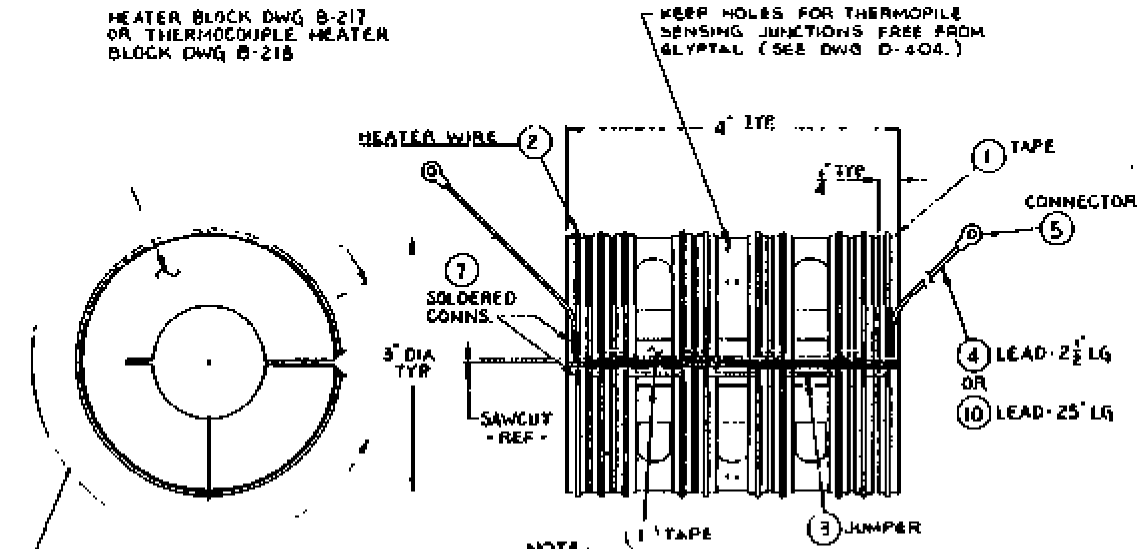

LEAD ARRGT.

WINDING PROCEDURE

1. PLACE STRIPS OF ITEM 1 ON HEATER BLOCK AS SHOWN. 12 STRIPS ARE REQUIRED : 1 ON EACH SIDE OF SAW CUT FOR JUMPER WIRE INSULATION AND 10 FOR HEATER STRIP INSULATION.
2. CUT ITEM 2, HEATER WIRE, INTO 10 EQUAL LENGTHS APPROX 9 1/4" LONG
3. TIN BOTH ENDS OF HEATER WIRES - ONE SIDE ONLY - USING ITEM 7
4. THOROUGHLY CLEAN THE FLUX FROM HEATER WIRES
5. PLACE THE HEATER WIRES (CENTERED ON TAPE) AS SHOWN WITH THE TINNED SIDE UP TEMPORARILY HOLD IN PLACE WITH MASKING TAPE AT BOTH ENDS
6. COAT THE STRIPS (EXCEPT TINNED ENDS) AND BLOCK (EXCEPT FLAT END FACES) WITH GLYPTAL.
7. SOLDER JUMPER WIRES IN POSITION PROTECT TAPE FROM HEAT WHILE SOLDERING
8. SOLDER HEATER LEADS, ITEMS 4 OR 10 AND ITEM 5 IN PLACE WITH HEATER LEAD RUNNING ANTIPARALLEL TO CORRESPONDING HEATER STRIP, AS SHOWN AT LEFT ANCHOR EACH HEATER LEAD TO THE BLOCK FOR A LENGTH OF 1 1/4" BY MEANS OF A GENEROUS COATING OF EPOXY USE 5 PARTS EPON RESIN 815 (ITEM 11) TO 1 PART CURING AGENT U (ITEM 12) BY WEIGHT.
9. USE SPECIAL JIG TO HOLD WIRES FIRMLY AGAINST BLOCK & COAT WITH GLYPTAL
10. APPLY A FINAL COAT OF GLYPTAL OVER THE ENTIRE OUTER CURVED SURFACE OF THE BLOCK

102

HEATER BLOCK DWG B-217 OR THERMOCOUPLE HEATER BLOCK DWG B-218




(6) GLYPTAL - APPLY ONE COAT IN THIS AREA BEFORE SOLDERING JUMPERS. SEE WINDING PROCEDURE.

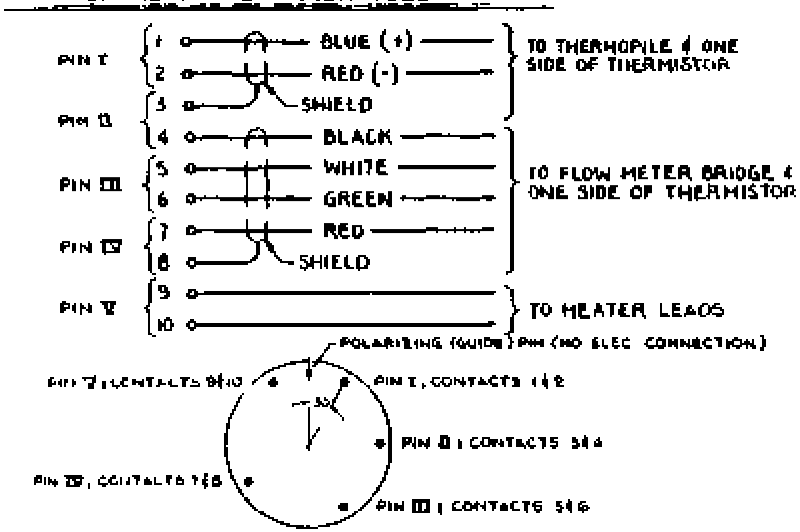
NOTE:
WHEREVER POSSIBLE THE SPACING BETWEEN HEATER STRIPS IS KEPT UNIFORM AT 0.4 IN. DEVIATION FROM UNIFORM SPACING OCCURS ONLY AS NECESSARY FOR HEATER STRIPS TO AVOID DEPRESSIONS IN COPPER BLOCKS.

| | |
|---|---|
| CARNEGIE MELLON UNIVERSITY PITTSBURGH, PA | |
| HEATER WINDING | RRF |
| O.T.E.C HEAT TRANSFER MONITOR | |
| 3 15 77 | C-306 |

WIRE TABLE

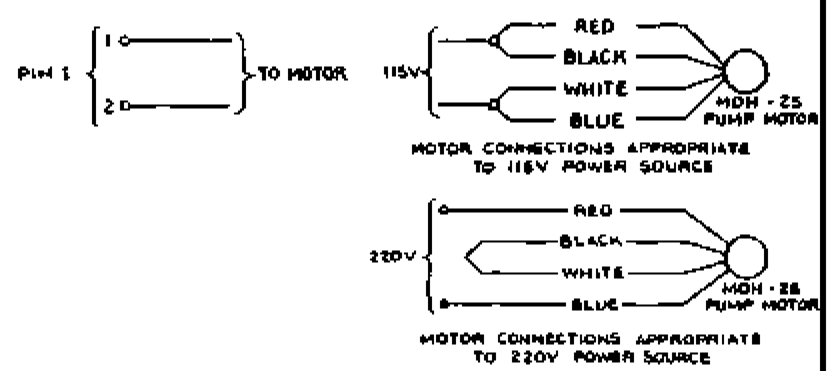
| FROM | TO | CONDUCTOR | LENGTH |
|---|---|---|---|
| ELECTRO 5 PIN CONN | THERMOPILE | 2/C #22 STRD W/SHLD | 7 FT |
| | FLOW METER | 4/C #22 STRD W/SHLD | 7 FT |
| | HEATERS | 2-1/C #16 STRD | 7 FT |
| ELECTRO 1 PIN CONN | PUMP MOTOR | 2-1/C #16 STRD | 7 FT |

ELECTRO CONNECTION DIAGRAM FOR HEAT EXCHANGER TUBE

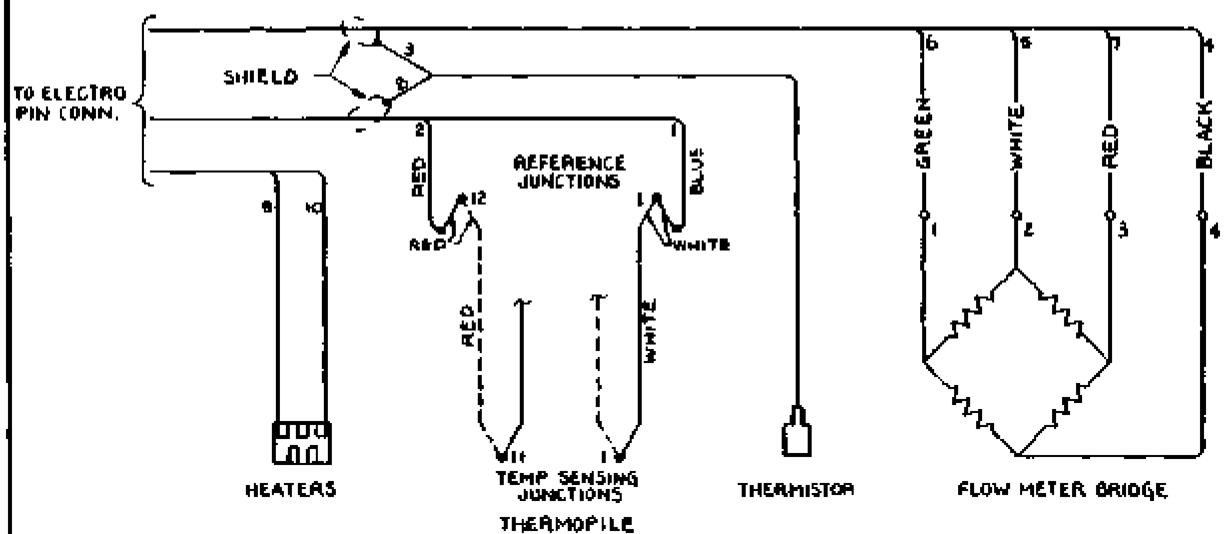



NOTE: 2 CONTACTS PER PIN, EVEN NUMBERED CONTACTS ARE THOSE NEAREST TO THE BODY OF THE CONNECTOR

NUMBERING SCHEME FOR CONTACTS ON ELECTRO TUBE CONNECTOR (VIEW WITH PINS UP)

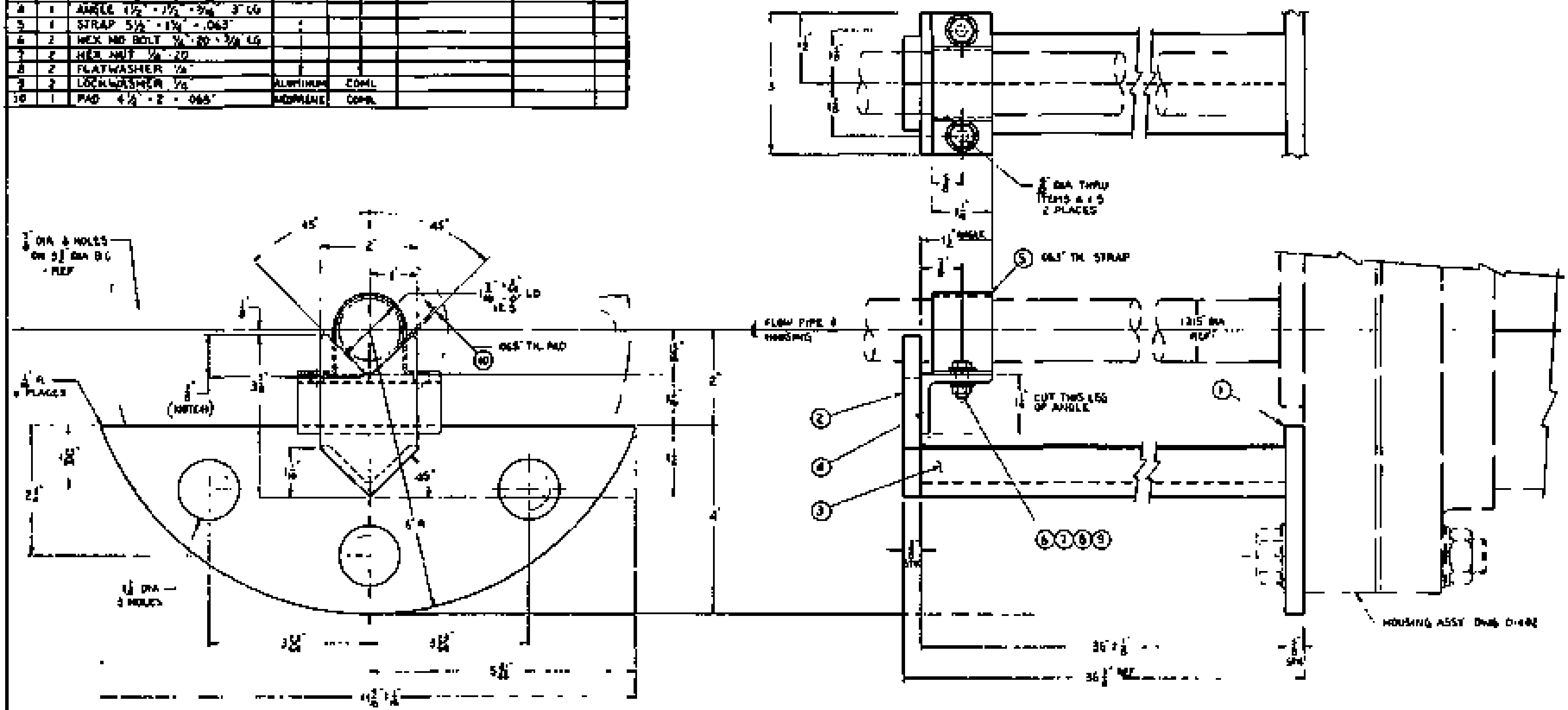



ELECTRO CONNECTION DIAGRAM FOR PUMP HOUSING




| | |
|---|---|
| CARNEGIE MELLON UNIVERSITY PITTSBURGH, PA | |
| CONNECTION DIAGRAM | RRF |
| Q.T.E.C HEAT TRANSFER MONITOR | |
| 3 16 77 | C-307 |

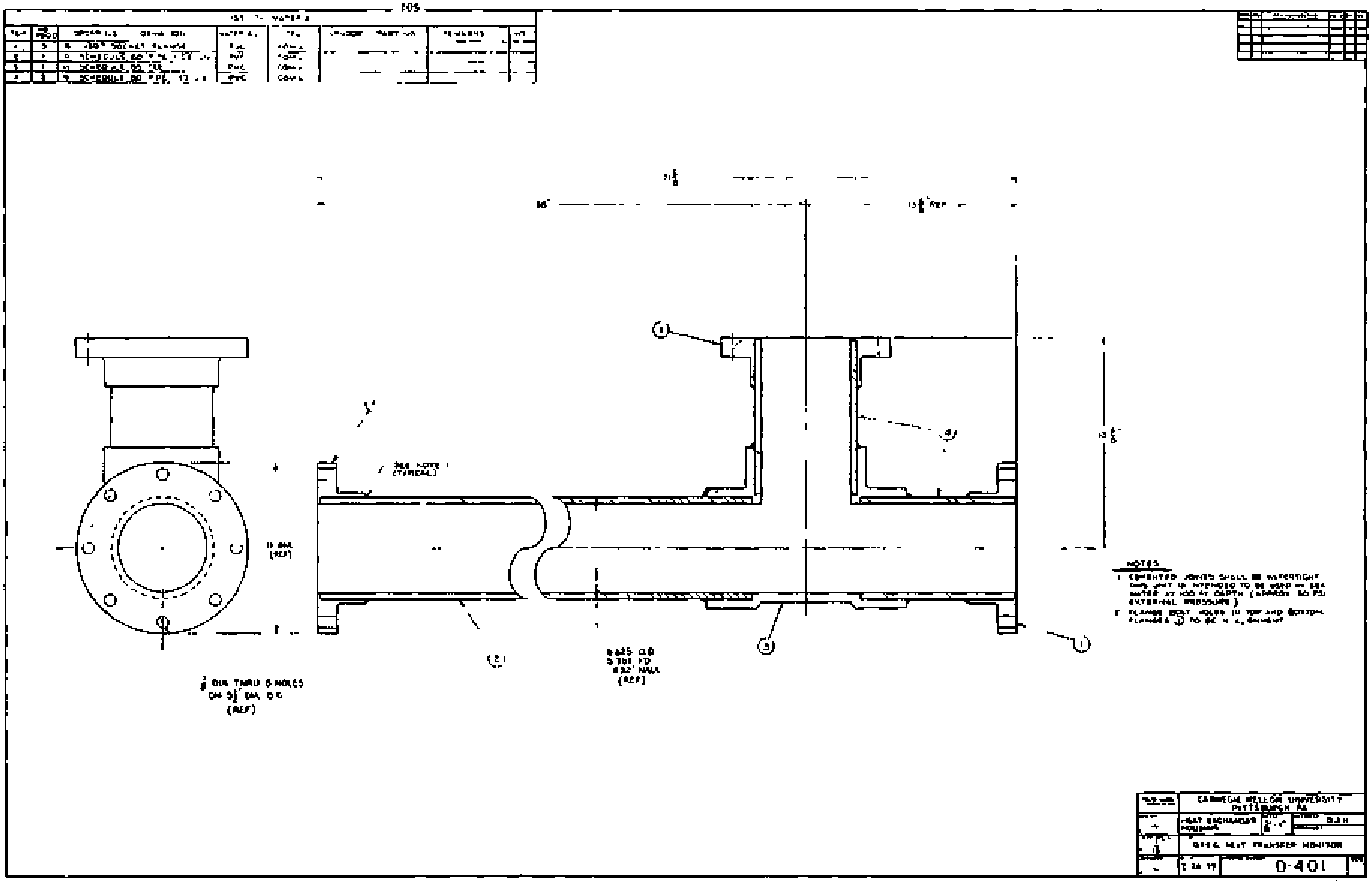
| LIST OF MATERIAL | | | | | | | |
|---|---|---|---|---|---|---|---|
| ITEM | NO. REQ'D | ORDERING INFORMATION | MATERIAL | SPECIFICATION | VENDOR - PART NO | REMARKS | WT |
| 1 | 1 | PLATE 1 13/16" × 4" × 5/8" | ALUMINUM | COML | | | |
| 2 | 1 | SUPPORT 3" × 2" × 1/8" | | | | | |
| 3 | 1 | ANGLE 1½" × 1½" × 3/16" - 36" LG | | | | | |
| 4 | 1 | ANGLE 1½" × 1½" × 3/16" 3" LG | | | | | |
| 5 | 1 | STRAP 5½" × 1¼" × .063" | | | | | |
| 6 | 2 | HEX HD BOLT 1/4"-20 × 3/4 LG | | | | | |
| 7 | 2 | HEX NUT 1/4"-20 | | | | | |
| 8 | 2 | FLATWASHER 1/4" | | | | | |
| 9 | 2 | LOCKWASHER 1/4" | ALUMINUM | COML | | | |
| 10 | 1 | PAD 4½" × 2" × .065" | NEOPRENE | COML | | | |




NOTES

1. ALL WELDED CONSTRUCTION USING 1/8" CONTINUOUS FILLET
2. FINISH 125/ ALL MACHINED SURFACES
3. BREAK ALL SHARP EDGES 1/64" MAX RADIUS OR CHAMFER

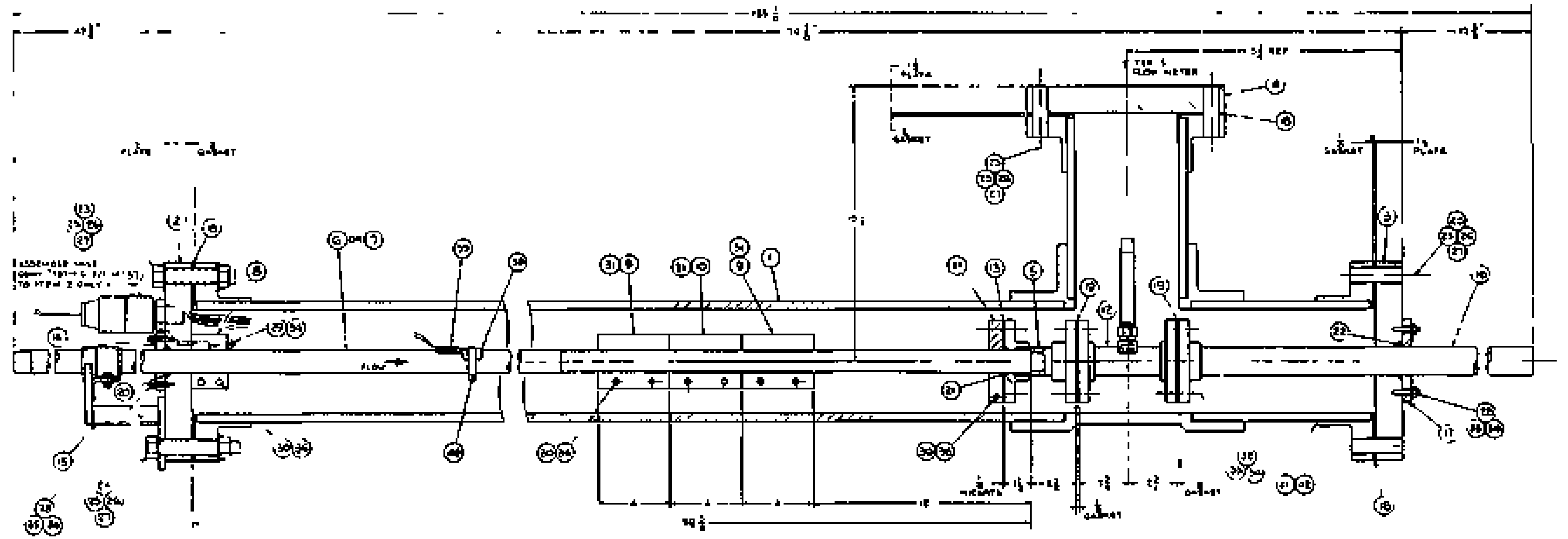
| | |
|---|---|
| | CARNEGIE MELLON UNIVERSITY PITTSBURGH PA |
| | FLOW PIPE SUPPORT ASSY — FULL — RAF |
| | OTEC HEAT TRANSFER MONITOR |
| | D-400 |


NOTES
SEE NOTE 1 (TYPICAL)
(REF)
6.625 O.D
(REF)
CARNEGIE MELLON UNIVERSITY
PITTSBURGH PA
HEAT EXCHANGER HOUSING
OTEC HEAT TRANSFER MONITOR
D-401

LIST OF MATERIAL

| ITEM | NO. REQ'D | ORDERING INFORMATION | MATERIAL | SPEC | DETAIL DWG NO | VENDOR PART NO | REMARKS | WT |
|---|---|---|---|---|---|---|---|---|
| 1 | 1 | HEAT EXCHANGER HOUSING | | | D 401 | | | |
| 2 | 1 | TOP PVC PLATE (UP STREAM) | | | B 202 | | | |
| 3 | 1 | BOTTOM PVC PLATE | | | B 216 | | | |
| 4 | | SIDE PVC PLATE | | | B [illegible] | | | |
| 5 | 1 | FLOW PIPE CONNECTOR | | | C 300 | | | |
| 6 | 1 | FLOW PIPE TITANIUM | | | B 204 | | | |
| 7 | 1 | FLOW PIPE ALUMINUM | | | B 206 | | | |
| 8 | 1 | COPPER REFERENCE 5 DIA | | | B [illegible] | | | |
| 9 | 8 | HEATER BLOCK | | | B [illegible] | | | |
| 10 | 4 | THERMOCOUPLE CENTER BLOCK | | | B [illegible] | | | |
| 11 | 1 | CLAMP RING | | | B [illegible] | | | |
| 12 | 1 | FLOW METER | | | B [illegible] | | | |
| 13 | 1 | MICARTA DISC | | | B [illegible] | | | |
| 14 | 1 | TOP SEAL PLATE | | | B [illegible] | | | |
| 15 | 1 | [illegible] SUPPORT ASSEMBLY | | | D [illegible] | | | |
| 16 | 1 | PIPE ASSEMBLY | | | C [illegible] | | | |
| 17 | 1 | BOTTOM SEAL PLATE | | | B [illegible] | | | |
| 18 | 2 | GASKET [illegible] THICK | NEOPRENE | COML | — | PLASTIC PIPING SYSTEMS [illegible] | SEE NOTE A | |
| 19 | 2 | GASKET [illegible] THICK | NEOPRENE | COML | — | PLASTIC PIPING SYSTEMS [illegible] | SEE NOTE A | |
| 20 | 1 | O-RING [illegible] | BUNA N | COML | — | PARKER [illegible] 325 | SEE NOTE B | |
| 21 | 1 | O-RING [illegible] | BUNA N | COML | — | PARKER [illegible] 322 | SEE NOTE B | |
| 22 | 1 | O-RING [illegible] | BUNA N | COML | — | PARKER [illegible] 326 | SEE NOTE B | |

| ITEM | NO. REQ'D | ORDERING INFORMATION | MATERIAL | SPEC | DETAIL DWG NO | VENDOR PART NO | REMARKS | WT |
|---|---|---|---|---|---|---|---|---|
| 23 | 21 | [illegible] HEX HD BOLT | STN STL | COML | — | | | |
| 24 | 1 | [illegible] HEX HD BOLT | STN STL | COML | — | | | |
| 25 | 24 | [illegible] HEX NUT | STN STL | COML | — | | | |
| 26 | 20 | [illegible] LOCKWASHER | STN STL | COML | — | | | |
| 27 | 48 | [illegible] FLATWASHER | STN STL | COML | — | | | |
| 28 | 8 | [illegible] THREADED ROD | STN STL | COML | — | | | |
| 29 | [illegible] | [illegible] THREADED ROD | STN STL | COML | — | | | |
| 30 | [illegible] | [illegible] SOC HD CAP SCR | STN STL | COML | — | | | |
| 31 | 5 | [illegible] SOC HD CAP SCR | STN STL | COML | — | | | |
| 32 | [illegible] | [illegible] HEX HD BOLT | STN STL | COML | — | | | |
| 33 | [illegible] | [illegible] HEX NUT | STN STL | COML | — | | | |
| 34 | [illegible] | [illegible] FLATWASHER | STN STL | COML | — | | | |
| 35 | 8 | [illegible] FLATWASHER | STN STL | COML | — | | | |
| 36 | 22 | [illegible] HEX NUT | STN STL | COML | — | | | |
| 37 | 1 | PIN CONNECTOR | | | | | SEE NOTE C | |
| 38 | 1 | THERMISTOR MOUNT | | | B [illegible] | | | |
| 39 | 1 | THERMISTOR | | | C [illegible] | | | |
| 40 | 1 | HOSE CLAMP [illegible] | STN STL | COML | — | | | |
| 41 | A.R. | PVC PRIMER | | | | [illegible] WELD | SEE NOTE D | |
| 42 | A.R. | PVC CEMENT | | | | [illegible] WELD | SEE NOTE D | |




NOTES

A PLASTIC PIPING SYSTEMS [illegible] N.J. 07060 OR APPD EQUAL
B PARKER SEAL COMPANY, CULVER CITY, CALIF 90230 OR APPD EQUAL
C ELECTRO PARAMOUNT [illegible] OR APPD EQUAL [illegible]
D [illegible] INDUSTRIES INC [illegible] OR APPD EQUAL

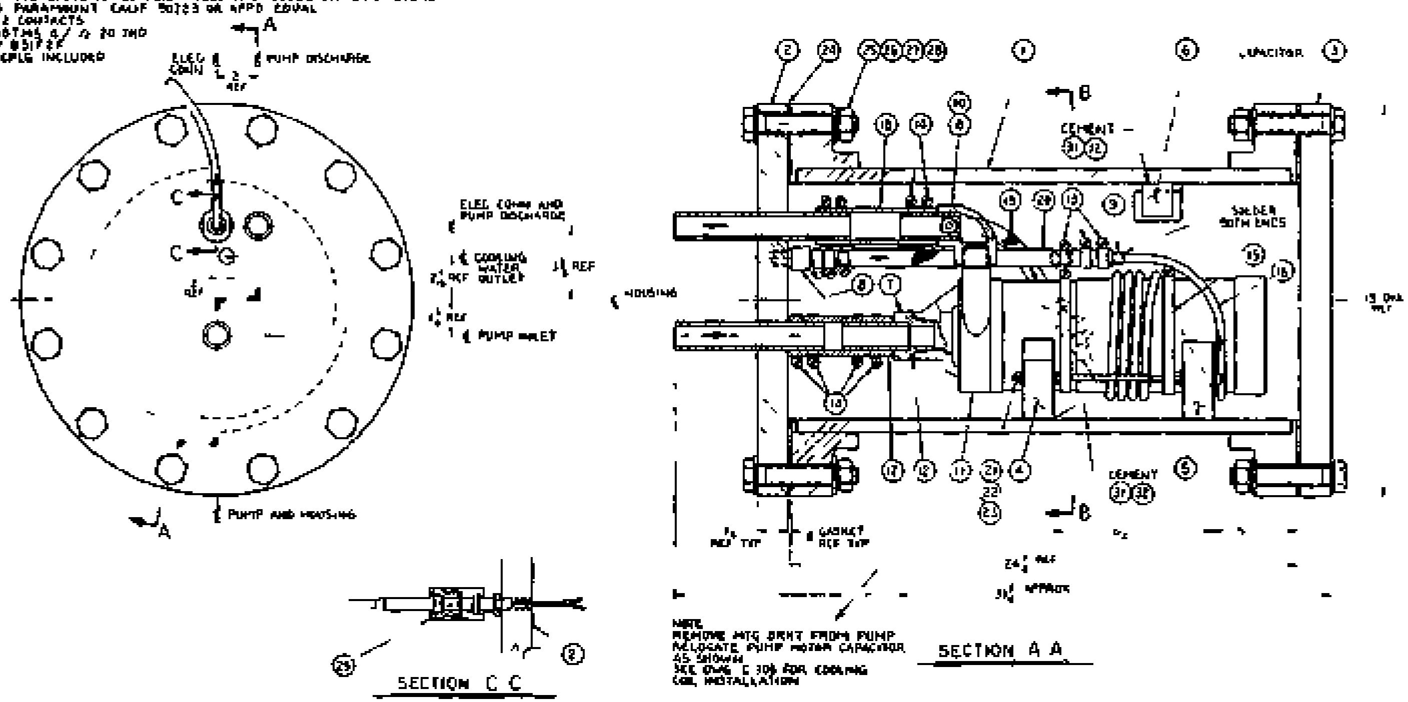
CARNEGIE MELLON UNIVERSITY PITTSBURGH PA
HEAT EXCHANGER ASSEMBLY
[illegible] HEAT TRANSFER [illegible]
D-402

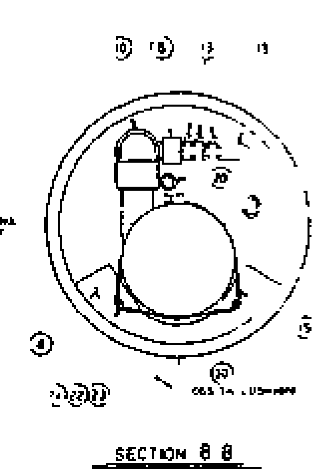
TO2

LIST OF MATERIAL

| ITEM | NO REQD | ORDERING INFORMATION | MATERIAL | SPEC | DETAIL DWG NO | VENDOR PART NO | REMARKS | WT | ITEM | NO REQD | ORDERING INFORMATION | MATERIAL | SPEC | DETAIL DWG NO | VENDOR PART NO | REMARKS | WT |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 | PUMP HOUSING | | | B 211 | | | | 21 | 2 | ROD ½ 20 × 34 LG ALL THD | STN STL | COML | | | | |
| 2 | 1 | FRONT PLATE | | | L 104 | | | | 22 | 8 | HEX NUT ½ 20 | STN STL | COML | | | | |
| 3 | 1 | REAR PLATE | | | B 211 | | | | 23 | 8 | FLATWASHER ½ STD | STN STL | COML | | | | |
| 4 | 1 | PUMP CRADLE | | | B 220 | | | | 24 | 2 | GASKET 2 IPS ⅛ TH | NEOPRENE | | | PLAS PIPE SYS # M122 | SEE NOTE D | |
| 5 | 1 | MOTOR CRADLE | | | B 221 | | | | 25 | 24 | HEX HD BLT ⅜ 9 5½ LG | STN STL | COML | | | | |
| 6 | 1 | CAPACITOR MOUNT | | | B 212 | | | | 26 | 24 | HEX NUT ⅜ 9 | STN STL | COML | | | | |
| 7 | 1 | PUMP INLET FITTING | | | B 209 | | | | 27 | 48 | FLATWASHER ⅜ STD | STN STL | COML | | | | |
| 8 | 2 | PVC NIPPLE | | | B 207 | | | | 28 | 24 | LOCKWASHER ⅜ STD | STN STL | COML | | | | |
| 9 | 2 | BRASS NIPPLE | | | B 208 | | | | 29 | 1 | PW CONNECTOR | | | | | SEE NOTE E | |
| 10 | 1 | PVC ELBOW | | | B 210 | | | | 30 | 4 | CUSHION 1/8 3 .065 TH | NEOPRENE | COML | | | | |
| 11 | 1 | MAGNETIC DRIVE PUMP | | | | EASTERN IND MDH 25 | SEE NOTE A | | 31 | A R | PCV PRIMER | | | | E Z WELD | SEE NOTE F | |
| 12 | 1 | O RING 1.734 ID .139 W DE | BUNA N | | | PARKER # 04 224 | SEE NOTE B | | 32 | A R | PCV CEMENT | | | | E Z WELD | SEE NOTE F | |
| 13 | 12 | HOSE CLAMP # 10 | STN STL | COML | | | | | | | | | | | | | |
| 14 | 8 | HOSE CLAMP # 24 | STN STL | COML | | | | | | | | | | | | | |
| 15 | 2 | HOSE CLAMP # 64 | STN STL | COML | | | | | | | | | | | | | |
| 16 | 1 | COPPER COOLING COIL | | | C 305 | | | | | | | | | | | | |
| 17 | 1 | TUBING 1⅛ FD ⅛ WALL | TYGON | COML | | | 5 ⅛ LONG | | | | | | | | | | |
| 18 | 1 | TUBING 1⅛ ID ⅛ WALL | TYGON | COML | | | 5⅝ LONG | | | | | | | | | | |
| 19 | 1 | TUBING ⅜ ID 3⁄32 WALL | BRAID TYGON | COML | | | 12 LG NOTE C | | | | | | | | | | |
| 20 | 1 | TUBING ½ ID 3⁄32 WALL | BRAID TYGON | COML | | | MIN LG NOTE C | | | | | | | | | | |

A. EASTERN INDUSTRIES HAMDEN CONN 06514 OR APPD EQUAL
B. PARKER SEAL CO CULVER CITY CALIF 90230 OR APPD EQUAL
C. NORTON CO AKRON OHIO 44305 OR APPD EQUAL
D. PLASTIC PIPING SYSTEMS SO PLAINFIELD N J 07080 OR APPD EQUAL
E. ELECTRO PARAMOUNT CALIF 90723 OR APPD EQUAL
PW PM 2 CONTACTS
MALE # 50TMS 6/ 32 THD
FEMALE # 0517 2F
CAPTIVE CPLG INCLUDED
F. PCI INDUSTRIES INC RIVIERA BEACH FLA OR APPD EQUAL

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PITTSBURGH PA

PUMP HOUSING ASSEMBLY

DTGG HEAT TRANSFER MONITOR

1977 D 403

107

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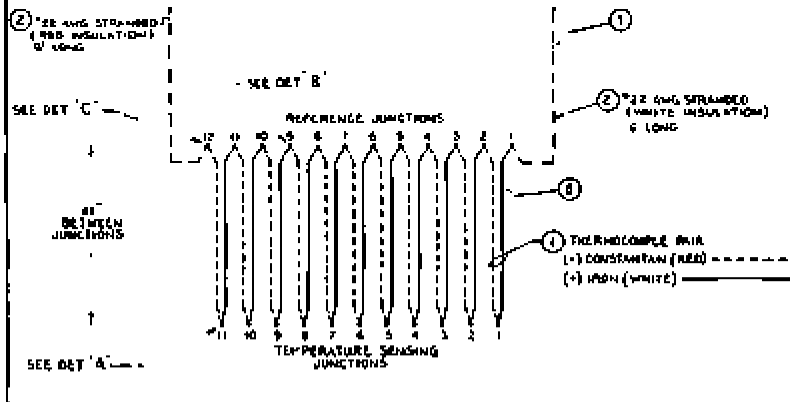
| LIST OF MATERIAL | | | | | | | |
|---|---|---|---|---|---|---|---|
| ITEM | NO REQD | ORDERING INFORMATION | MATERIAL | SPEC | VENDOR PART NO | REMARKS | WT |
| 1 | 50 FT | THERMOCOUPLE WIRE #45 GA #30 | [illegible] | | OMEGA [illegible] TT J 30 | SEE NOTE "A" | |
| 2 | 3 FT | INSULATED STRANDED #22 AWG | COPPER | COML | | RED INSULATION WHITE INSULATION | |
| 3 | A R | SHRINK FIT TUBE 1/16" SEMI RIGID | | [illegible] | ALPHA WIRE FIT 295 1/16 | SEE NOTE "B" | |
| 4 | 1 PT | INSULATING ENAMEL RED | GLYPTAL | | GEN ELEC 1201 | SEE NOTE "C" | |
| 5 | A R | EPOXY | | | EPON 815 | SEE NOTE "D" | |
| 6 | A R | EPOXY HARDENER | | | EPI CURE 855 | SEE NOTE "E" | |
| 7 | 6 FT | BRAIDED SHIELD | COPPER | COML | | 1/16 FLAT WIDTH | |
| 8 | [illegible] | BRAIDED SHIELD | COPPER | COML | | 1/4" FLAT WIDTH | |
| 9 | A R | SOLDER | | | EUTEC ROD 157 [illegible] | SEE NOTE "F" | |
| 10 | A R | FLUX | | | [illegible] | SEE NOTE "G" | |

"A" OMEGA ENGINEERING INC STAMFORD, CONN 06907 OR APPD EQUAL
"B" - ALPHA WIRE CORP ELIZABETH, N J 07202 OR APPD EQUAL
"C" GENERAL ELECTRIC CORP SCHENECTADY, N Y 12345 OR APPD EQUAL
"D" MILLER STEPHENSON CHEMICAL CO INC CHICAGO, ILL 60626 OR APPD EQUAL
"E" CELANESE RESINS LOUISVILLE, KY 40208 OR APPD EQUAL
"F" - EUTECTIC CORP FLUSHING N Y [illegible] OR APPD EQUAL
"G" DIVISION LEAD CO CHICAGO, ILL OR APPD EQUAL




THERMOPILE SCHEMATIC

## ASSEMBLY INSTRUCTIONS

1 CUT ITEM 1 INTO 11 EQUAL LENGTHS SUCH THAT THE FINISHED LENGTH BETWEEN JUNCTIONS IS APPROX 41 IN AS SHOWN

2 STRIP BACK THE OUTER CLEAR JACKET ON BOTH ENDS OF ALL ELEVEN PAIRS

3 STRIP BACK THE RED & WHITE TEFLON INSULATION TO BARE THE IRON & CONSTANTAN WIRES

4 THE 11 TEMPERATURE SENSING AND 10 REFERENCE JUNCTIONS ARE MADE FROM COMMON AND ADJACENT (+) AND (-) WIRES RESPECTIVELY SEE THERMOPILE SCHEMATIC

5 THE LEAD JUNCTIONS, 1 & 12 ARE MADE FROM THE REMAINING (+) AND (-) WIRES, EACH PAIRED WITH ONE OF ITEM 2 AS SHOWN AND SOLDERED USING ITEMS 9 & 10.

6 ALL JUNCTIONS ARE FORMED AS SHOWN IN DETAILS "A", "B" AND "C", AND AS FOLLOWS
   a CROSS THE JUNCTION WIRES AND SPOT WELD AT THE INTERSECTION. BEND EXCESS PARALLEL TO AND OVER THE INSULATED PORTION OF OPPOSITE WIRES
   b CUT A LENGTH OF ITEM 3 (SHRINK-FIT TUBE) AND SLIP IT OVER THE JUNCTION AND SHRINK ACCORDING TO MANUFACTURER'S INSTRUCTIONS
   c APPLY TWO COATS OF GLYPTAL (ITEM 4) TO THE JUNCTION

7 CHECK FOR CONTINUITY BY MEASURING THE RESISTANCE AND TEST THE FINISHED THERMOPILE IN ACCORDANCE WITH THE SPECIFICATIONS IN SECTION 7.1 OF QUALITY ASSURANCE DOCUMENT

8 MIX 2 PARTS OF ITEM 5 TO 1 PART OF ITEM 6 BY WEIGHT AND FILL A SYRINGE USING A [illegible] NEEDLE, INJECT THE MIXTURE INTO THE 12 HOLES IN THE REFERENCE BLOCK (ITEM 8 DWG [illegible])

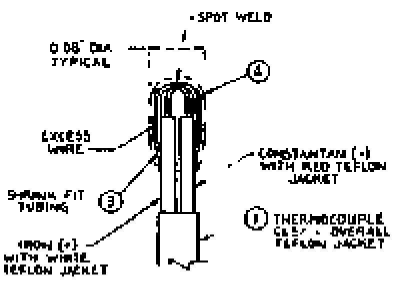
9 INSERT THE 12 REFERENCE JUNCTIONS INTO HOLES PROVIDED IN THE REFERENCE BLOCK AND ALLOW 24 HOURS FOR EPOXY TO CURE. BE SURE JUNCTIONS ARE TOUCHING THE BOTTOM OF THE HOLES

10 INSERT THE THERMOCOUPLE BUNDLE, 11 PAIRS (SENSING JUNCTIONS 1 THRU 11) INTO ITEM 8

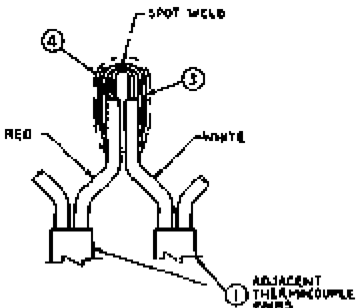
11 INSERT THE LEAD WIRES INTO SHIELD ITEM 7. SOLDER ITEMS 7 & 8 TOGETHER NEAR REFERENCE BLOCK FOR ELECTRICAL CONTINUITY OF THE SHIELD

12 MOUNT THE REFERENCE BLOCK ON A TYPICAL FLOW PIPE ([illegible] DWG [illegible] FOR EXAMPLE) AND MOUNT THE [illegible] HEATER BLOCKS ([illegible] DWGS [illegible]) WITH HEATERS ALREADY IN PLACE ON THE FLOW PIPE, AS SHOWN ON DWG [illegible]. WRAP THE SHIELD CONTAINING THE THERMOCOUPLE BUNDLE (FROM STEP 10) [illegible] AROUND THE FLOW PIPE 5 TIMES AND HOLD TEMPORARILY [illegible] WITH TAPE. WITH THE FLOW PIPE MOUNTED HORIZONTALLY [illegible] LOW VISCOSITY EPOXY (ITEMS 5 & 6) INTO THE UPPERMOST 6 HOLES IN THE HEATER BLOCK AS IN STEP 8. INSERT 6 TEMPERATURE SENSING JUNCTIONS TO THE BOTTOM OF THESE HOLES AND BE SURE THE JUNCTIONS REMAIN IN CONTACT WITH THE BOTTOM DURING THE 24 HOUR CURE TIME. REPEAT FOR THE REMAINING 5 TEMPERATURE SENSING JUNCTIONS

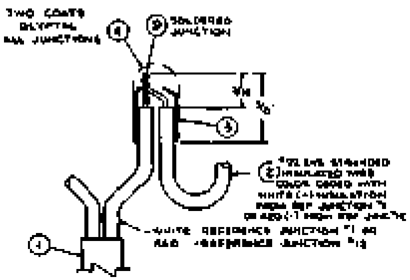
NOTE
BE VERY SURE TO PERFORM REQUIRED CHECKS OF CONTINUITY AND ISOLATION AT APPROPRIATE TIMES AS DESCRIBED IN SECTION 7.1 OF THE QUALITY ASSURANCE DOCUMENT




DETAIL A
TYPICAL FOR TEMPERATURE SENSING JUNCTIONS 1 THRU 11




DETAIL B
TYPICAL FOR REFERENCE JUNCTIONS 2 THRU 11




DETAIL "C"
TYPICAL FOR LEAD JUNCTIONS 1 & 12

CARNEGIE MELLON UNIVERSITY PITTSBURGH PA
GTF & HEAT TRANSFER MONITOR
D-404

# 5. ELECTRONICS DESIGN

## 5.1. Introduction

The study of the effects of fouling on the heat transfer of heat exchangers submerged in ocean water requires instrumentation which will allow not only measurement of several parameters while being submerged, but also allow certain functions to be controlled from a distant location on shore.

The instrumentation system described in this report was designed to measure the thermopile output voltage, the flow velocity of sea water through the tube, the sea water temperature, and eventually, the electrolysis current and voltage for a fouling inhibitor. These measurements may be made in from one to six separate heat exchanger units, each connected to the submarine electronics circuitry by water-proof cables, capable of being connected underwater by divers.

In addition, the electronics system allows the operator on shore to control, by push-button, which one of six heat exchangers is being monitored as to temperature and flow; which pump (one of six) is to be turned off; and which heater (one of six) is energized at a particular time. Furthermore, the heater power to any particular heater can be controlled.

Analog data resulting from the various measured quantities is converted to digital signals which are sent to shore over a 1500 foot submarine cable, where the digital signals are converted to analog voltages and read on a digital voltmeter, whose output is transferred to punched paper tape, for computer analysis.

Provisions are included in the system to allow addition of a microprocessor. The microprocessor will select a particular heat exchanger whose temperature is to be monitored, and will allow the data for that heat exchanger to be analyzed by the microprocessor, thus reducing the raw data output of the system. Since the system will be required to operate for long periods unattended, it is felt that the microprocessor can perform many of the duties now done by a human operator.

The design of the electronics system required particular attention to reliability over long periods, low power consumption, and the problems of measuring low level voltages in the presence of noisy devices such as pumps and relays.

As discussed in Sec. 1, the field experience obtained with this system so far has not included submerged operation with signal transmission through a long (1500 ft.) submarine cable. The system instead was operated on the deck of a moored boat with signals transmitted only through short (less than 25 ft.) wires.

In fact, the system was designed to operate with a cable (the original cable which was found upon examination to be faulty) different from that described in this report (Sec. 5.11). It is recognized that the present cable does not have ideal characteristics for this purpose. It was decided nevertheless to use it for several reasons, in spite of a small probability that it might not work. First, it was expected to be available very quickly and at low cost (through the U.S. Navy). Second, electronics tests on a short piece of cable (~5 feet) indicated it should work. Third, even if the small likelihood of electronics problems with this cable materialized, it was expected that fairly minor modifications of the electronics system would solve the problems.

It should be noted that in dockside tests, this electronics system was tested and found to work using a long submarine cable (a 400 foot piece of the original cable).

In many future applications of this system, the test instruments will not be remote from the control electronics (for example in dockside operation or operation from manned, moored surface platform). In such cases, the complex multiplexing feature of the electronics design will not be required, and it would be preferable to use a correspondingly simpler system. With this in mind, we have described in Appendix D another electronics system. This is one we have used in laboratory tests of the apparatus.

5.2. Description of Basic Systems

The system consists of two separate units. One of these (Buoy Unit) is submerged in the ocean and held in place by an anchored buoy. The other is housed in a shelter on the beach (The Beach Control). The two units are connected electrically by a submarine cable carrying power and signal lines.

The Beach Control, in addition to the indicator lights which continuously show the status of the Buoy Unit, contains the necessary circuitry to:

a) Select (in the Buoy Unit) one of six thermopiles from which to extract temperature data.

b) Select one of six flowmeters from which to obtain water flow velocity data. (This operation simultaneously selects the corresponding thermistor which reads the absolute water temperature).

c) Select one of six pumps to be shut down, reducing the water flow in a particular heat exchanger to zero.

d) Select one of six heaters to be energized or de-energized, at either of two power levels, allowing control of the copper block temperature.

The Beach Control contains the circuitry necessary to send control and function signals, in digital form, to the Buoy Unit, to convert the digital signals arriving from the Buoy Unit to analog voltages, and the timing circuitry to provide a precision reference clock for the frequency-to-voltage converters in the Beach Control and the voltage-to-frequency converters in the Buoy Unit.

The Buoy Unit is electronically a slave to the Beach Control, in that it makes measurements and performs duties as a result of Control and Function pulses sent from the Beach Control.

The Buoy Unit electronics is contained in a watertight box to which is connected the submarine cables to the heat exchanger units ( up to six in number) and carrying the thermopile voltage, flow-meter signals, heater current, and pump power for these heat exchanger units. Provision is also made for an electrolysis power supply (not used at present) and for measuring the resistance of thermistors mounted on the heat exchanger pipes.

Low level D.C. voltages from the thermopiles are multiplexed to a single chopper amplifier via dry-reed relays with low thermal e.m.f. contacts. The amplifier output is converted to a digital signal using a voltage-to-frequency converter and sent to the Beach Control on one of the signal pairs in the connecting cable. Flowmeter bridge voltages are handled in the same way, with a second chopper amplifier. A third chopper amplifier is used for the voltages from the electrolysis power supply and from the thermistors used for water temperature measurement.

## 5.3. General Design Considerations

The design of the electronic circuitry required that primary concern be directed towards a system that could operate reliably for long periods without attention, and be as immune as possible from the effects of vibration and motion, and from the electrical noise produced by the opening and closing of relay contacts carrying alternating current. Furthermore, it was desired that the power supply drain be small, to avoid the line loss in a long length of sumarine cable.

For these reasons, CMOS logic was used wherever possible, to give a high noise immunity and low power consumption.

The relays handling the low level signals (thermopile and flowmeter voltages) are dry-reed relays with contacts built to develop very small thermal voltages.

The operational amplifiers to amplify the low level signals are high quality chopper types for long term stability.

Ground loops had to be avoided, and special care is taken to see that the low level signals have their signal grounds at only one point.

5.4. The Beach Control

Four printed circuit cards make up the Beach Control logic along with the logic power supply, the indicating LED lamps, and the front panel controls.

As can be seen from the block diagrams (Drawings 5-5, 5-6, and 5-8) the Beach Control consists of several ring counters, with indicator lights, arranged so that an initial setting of one bit in each counter will allow the operator to advance the single bit around the ring, much like a rotary switch. Corresponding ring counters in the Buoy Unit, stepping in sequence upon operator command, provide the signals to open and close relays which select the measurements to be made by the Buoy Unit, and change the parameters that affect these measurements, such as heater power, water flow velocity, and others.

An operator at the Beach Control can cause the logic in the Buoy Unit to read (a) Any one of 6 thermopile output voltages, (b) any one of 6 flowmeter voltages, (c) any one of 6 thermistor bridge voltages, (d) any one of 6 electrolysis power supply currents, (e) the output of a single thermistor bridge monitoring the sea water temperature at the buoy.

The operator can also control (a) which pump (one of six) is turned off, (b) which heater (one of six) is energized, (c) and which heater power (high or low) is used to energize the heaters.

Drawing 5-25 shows the power supplies for the logic circuits used in the Beach Control, and typical lamp driver circuits for the 47 LED's which serve as the indicators for the status of the Buoy logic.

5.5. Beach Control Card #1 - Master Clock (Dwg. 5-11)

The Master Clock generates the 10 Khz square wave used as a reference signal for the voltage-to-frequency converters and the frequency-to-voltage converters. This 10 Khz signal is obtained from a 100 Khz crystal oscillator by a divide-by-10 counter.

Further division produces a one pulse-per-second output, a pulse-per-2 second output, a pulse-per-4 second output, and a pulse-per-10 second output, all derived from the crystal oscillator.

Any one of these signals can be selected by a switch, "Select Interval", which supplies the pulse to advance the scanner, to enable the DVM to read sequential inputs.

Also available are a pulse-per-10-minutes, and a pulse-per-one-minute, to be used as an auto-advance for the F.M. multiplexor.

A "Power Clear" pulse is generated on power-up of the system, which provides a master reset pulse to both the Beach Control and the Buoy Unit, setting all multiplexor counters and registers to their initial starting condition.

5.6. Beach Control Card # 2 - Function, Control and Reset (Dwg. 5-9)

This P.C. card contains the circuitry which allows the operator at the Beach Control to:

a) Reset all multiplex counters in the Buoy Unit to their "Reset" state, as well as the corresponding counters in the Beach Control, which drive the LED indicators. This insures that the Buoy Unit, as a slave to the Beach Control, is started in exact synchronism with the Beach Control indicators.

b) Select which of the four types of registers are to be involved when the "Step" push-button is pushed.

c) Send to the Buoy Unit, over the submarine cable, pulses which will either advance the thermopile multiplexor, (Step Thermocouple) advance the flowmeter multiplexor (Step Flowmeter), advance the Electrolysis-Miscellaneous multiplexor (Step Function), or Control pulses which will determine which electrolysis voltage is to be applied, which pump is to be turned off, which level of heater power is to be used, or which Pipe Thermistor bridge is to be measured.

This card also contains the three differential line drivers which carry the "Step Thermocouple and Function" pulses, the "Step Flowmeter and Control" pulses, and the "Reset and Clock" pulses. The Reset pulse to the Buoy Unit is superimposed on the 10 Khz clock line as a one millisecond gap in the clock pulse train, which is extracted as a reset pulse at the Buoy electronics. This does not interfere with the normal operation of the clock signals.

## 5.7. Beach Control Card #3 - Thermopile and Flowmeter Monitor (Dwg. 5-7)

On this P.C. card, the conversion of the thermocouple (thermopile) data from digital to analog form is done, as well as the conversion of the flowmeter data. These conversions are done by Hybrid Systems Corp. DV-611 frequency - to voltage converters which use the 10 Khz reference clock signal which is also used by the voltage-to-frequency converters in the Buoy Unit, ensuring complete synchronization of the conversion.

Also on this card is the 19 bit ring counter to which a similar ring counter in the Buoy Unit is a slave. The ring counter in the Beach Control is used as a lamp driver to indicate the corresponding status of the slave counter in the Buoy Unit. A reset pulse sets this counter to its starting position, with the leftmost bit set to a one, all others cleared, and the same reset pulse sent to the Buoy Unit ensures that both counters start at the same position (the "Test" position) and are advanced in step by means of the "Step Thermocouple" pulse.

A similar ring counter (six bits) for the flowmeter has its corresponding slave in the Buoy Unit, and is advanced in like manner by the "Step-Flowmeter" pulse.

The Pulser Switch on the front panel of the Beach Control allows the operator to either advance the flowmeter multiplexor in the Buoy Unit manually, or to let it advance automatically at either one-minute, or ten-minute intervals.

5.8. Beach Control - Electrolysis - Miscellaneous Monitors Card #4 (Dwg. S-10)

This P.C. board contains the line receiver for the Miscellaneous data arriving from the Buoy Unit in digital form, and the frequency-to-voltage converter to convert the data to analog form, suitable for read-out in a conventional digital voltmeter.

This card also contains the "Function" register, a "Pumps" register, and an "Electrolysis" register, each of which is a ring counter driving LED lamps, so that continuous monitoring of the corresponding slave ring counters in the Buoy Unit is possible.

The "Function" register is advanced through its seven possible states by means of the "Step" push-button (if the step selector is in the "Step Function" position) and at the same time, in the Buoy Unit, a similar ring counter is being advanced in synchronism. The seven states of the Function register are:

A - Electrolysis Current

B - Electrolysis Voltage

C - Pumps

D - Heater Power

E - Ball

F - Pipe Thermistor

H - Buoy Thermistor

States A, B and E apply to hardware not yet installed, and are not presently used. State C (Pumps) allows the operator to turn off any one of six pumps corresponding to one of six heat exchanger units connected to the Buoy Unit. Likewise, state F allows the operator to read, via the Miscellaneous data line, the temperature of the water at any one of six heat exchanger pipes, using a thermistor bridge.

State H allows the operator to observe, also on the Miscellaneous data line, the temperature of the water at the Buoy Unit itself, using another thermistor bridge.

The "Heater Power" registor is also on this card, and allows application of two different heater voltages to the 53 ohm heaters attached to the heat exchanger units. The two different voltages, allows a heater power of either 134 watts (low power) or 272 watts (high power) to energize the heaters.

### 5.9. Beach Control Interconnections (Dwg. 5-12)

The interconnections between the P.C. boards in the Beach Control is shown in Drawing 5-12, as well as the connections to bring out the analog data lines to the digital voltmeter.

### 5.10. Beach Control - Data Output

The analog data representing temperature and flow velocity which has been converted from digital to analog form in the Beach Control, is brought out on a multiwire cable to a commercial digital voltmeter, scanner and sequencer. The scanner allows many different inputs to be read out on one DVM. The scanner can be advanced by the operator to the thermocouple data, the thermistor data, or the flowmeter data to be read at any time. The sequencer generates the necessary control pulses for scanning and punching.

The ouput of the DVM, while being displayed as a visual number, also is processed and fed thru a commercial coupler to a papaer tape punch. The coupler is the interface between the DVM and the punch, giving the operator the ability to retain the data for later analysis by a computer.

The beach control signal outputs were designed to be compatible with a Consolidated Control Corporations Model 90GP93 Datalogger. This Datalogger was used because it was on hand and not otherwise employed. It had been built to special order. A brief description of this machine and instructions for its operation are given in appendix E. Basically it is a low voltage scanner, digital voltmeter and paper tape punch all contained in one electronics rack. While this system performed very well aboard Noi'i, its use has veen discontinued. Since much more modern versions of the same apparatus are now available, it would not be used in any future experiments with this appratus.

We currently use the system described in appendix D for data taking of this type. This system is more reliable than the system used on Noi'i and since it uses a teletype to punch the paper type, identifying marks can be put on the tape as it is generated. These identifying marks are very helpful in data analysis.

### 5.11. Submarine Cable

The cable from the Beach Control to the Buoy Unit is a high-strength armored submarine cable, about 1500 feet long containing

(a) 3 power lines (#8 copper)

(b) 3 signal pairs (twisted pairs #20 with each pair shielded)

(c) 6 signal wires (#20, not twisted or shielded)

The 3 power lines are used to bring 240 volts, 60 hz, single phase, center tapped to the Buoy Unit. 240 volt power is required for the pumps. The logic power and the heaters are run from the 120 volt taps.

The three signal pairs are used to carry the thermocouple data, the flowmeter data, and the miscellaneous data to the beach.

The six signal wires are organized into 3 pairs, each pair being driven by a differential driver at the beach, with a differential receiver at the buoy, and handle the command pulses sent to the Buoy Unit. One pair carries the Reset and Clock pulses, one the "Step Flowmeter" and "Step Control" pulses, and the third pair the "Step Thermocouple" and "Step Function" pulses. The ability to use each pair of wires for two kinds of signals reduces the cost and size of the submarine cable significantly.

## 5.12. The Buoy Unit

The logic and control electronics for the Buoy Unit is made up on 10 printed circuit cards in a shielded card cage. Power supplies and relays carrying high currents (as for pump and heater power) are mounted external to the card cage, on the inside walls of the Buoy Unit.

As seen from the block diagrams (Drwgs. 5-1, 5-2, 5-3 and 5-4) the logic for the Buoy Unit acts as a slave to the Beach Control logic, with the ring counters in the Buoy Unit duplicating those in the Beach Control, so that both master and slave counters can be advanced in step with each other thus ensuring that the operator at the beach can know at any time the states of the counters in the Buoy Unit by observing the indicator lamps at the Beach Control.

Interconnections between the Buoy Unit printed circuit cards, the associated relays, and the Buoy power supplies are shown on Drawings 5-13 and 5-14.

5.13. Buoy Thermocouple Multiplexor (Dwgs. 5-15, 5-16, and 5-28)

Low level voltages from the thermocouples (thermopiles) are multiplexed to a low drift chopper operational amplifier, (Analog Devices 260-K) using dry-reed relays with low-thermal e.m.f. contacts (Coto-coil CR-3202-12-701). The reed relays are closed, one-at-a-time, as the single bit, that was initially set into the 19 bit ring counter on reset, advances along the counter for each "Step-Thermocouple" pulse.

The initial condition of the 19 bit ring counter, after "Reset", is with a "one" set into the left-most bit, and all other bits cleared. In this position of the ring counter, relay K-0 is energized, which connects a small test voltage to the amplifier, enabling the operator at the Beach Control to verify that the system is reset and that the thermocouple measuring circuitry is functioning.

The other 18 bits of the ring counter are divided into 6 groups of 3 bits each. As the bit is stepped to the first of these groups of three, the reed relay for thermopile number 1 is energized, but the heater relay (Dwg. 5-24) for number one is de-energized, allowing temperature measurement with no heater power applied. As the bit is stepped to the next position, the heater relay for unit one is then energized, and current flows in the heater of unit one, allowing measurement of temperature with heat applied. The next step T.C. pulse turns the heater off, allowing temperature decay measurements to be read. The other 5 units can be monitored in the same way, as the bit is stepped along the ring counter, with each unit's temperature being measured in a heater-off, heater-on, heater-off sequence. The single bit is returned to the reset position (test position) after all units have been monitored. The operator at the Beach Control can position the bit in the ring counter to any unit by having the "Step-Selector" switch set on "Step T.C.", and pressing the "Step" push-button the necessary number of times.

Provision is made for the microprocessor to advance the ring counter, when it is installed.

The amplified thermopile analog signal is converted to a digital signal, by a voltage to frequency converter (Hybrid Systems Corp. Model DV-610) whose output is sent to a TTL line driver and then to the Beach Control via the submarine cable. A reference clock signal is brought to the V-F converter, allowing synchronism with the corresponding frequency-to-voltage converter in the Beach Control, so that transmission can be accurate even in high noise environments.

On Dwg. 5-28, the circuitry is shown which separates the 10 khz clock and the "Reset" pulse, both of which arrive on one signal pair via the submarine cable from the Beach Control. The "Reset" pulse is presented to the Buoy Unit as a one millisecond gap in the 10 Khz clock pulse train. This gap does not interfere with the normal operation of the voltage-to-frequency converters, yet allows the two signals to be sent down one pair of wires. Integrated circuit B-1 (dual one-shot) separates the "Reset" pulse from the 10 Khz clock, and sends the "Reset" pulse to the rest of the Buoy Unit logic.

Also on Dwg. 5-28 is the Heater Power register, which is a single flip-flop which can be alternately set or cleared by "Step Control" pulses by the operator at the Beach Control, providing that the "Function" register (Dwg. 5-20) is set to the "Heater Power" position.

Also shown on Dwg. 5-28 are the relay drivers for the heater relays shown on Dwg. 5-24.

5.14. Buoy Flowmeter Multiplexor (Dwgs. 5-17 and 5-18)

Outputs from up to six strain-gage-bridge type flowmeters are multiplexed to a second low-drift chopper amplifier (Analog Device 260-K) by means of dry reed relays, again with low thermal e.m.f. contacts (Coto-coil CR-3202-12-701).

The relays are energized sequentially by a six bit ring counter which is initialized at "Reset" to have the left-most bit set to "one" and all others cleared. The operator at the Beach Control can select any of the six flowmeters to be monitored by advancing the bit to the correct position using the "Step" push-button with the "Step Selector" in the "Step-Flowmeter" position.

The same relay drivers that energize the flowmeter relays K-101 thru K-106 also energize the corresponding Pipe Thermistor relays (K-401 thru K406) on Drawing 5-30. This allows the monitoring of the Pipe Thermistors via the Electrolysis-Miscellaneous Amplifier at the same time the corresponding flowmeter for that particular pipe is being monitored.

Also on Dwg. 5-18 is the the necessary decoding to separate the "Step Flowmeter" and "Step Control" pulses which are sent from the Beach Control on one pair of lines.

The differential line receiver (75115) delivers these pulses as a one millisecond wide pulse ("Step Flowmeter") and a five millisecond wide pulse ("Step Control") on the same line to the decoder. The decoder (two one-shots and two gates) sorts out the widths and distributes the "Step Flowmeter" pulses to the flowmeter ring counter and the "Step Control" pulses to another part of the Buoy logic.

5.15 Buoy Electrolysis and Miscellaneous Miltiplexer (Dwgs. 5-19, 5-20 and 5-21)

A third low-drift chopper operational amplifier is used to measure several miscellaneous signals, including the current and voltage applied by a proposed fouling inhibitor (electrolysis) power supply (not yet in use), the voltage from any one of six thermistor bridges (Pipe Thermistor) measuring the water temperature at the buoy electronics and/or a voltage which represents the flowmeter bridge power supply voltage, as diagnostic measurement.

These signals are multiplexed by dry-reed relays (Triridge 228-200-12) to the chopper amplifier (Analog Devices 260-K), and the relays are closed sequentially by an eight bit ring counter called the Function Register. The functions are:

A = Electrolysis Current

B = Electrolysis Voltage

C = Pumps

D = Heater Power

E = Ball

F = Pipe Thermistors

H = Buoy Thermistor

J = Spare for expansion

At reset the leftmost bit of the ring counter is set, and all others are cleared, thus initializing the counter to function A. At the present time, measurements are made only at positions C, D, F and H.

The operator at the Beach Control can select any one of the function positions by using the "Step" push-button, with the "Step Selector" in the "Step Function" position.

Setting a particular function then allows the operator, by using the "Step" push-button with the "Step Selector" in the "Step Control" position, to specify:

For function C, which of six pumps, corresponding to the six heat exchanger units, is turned off, or none of the six off, depending on a seven bit ring counter called the "Pumps" Register, (Dwg. 5-20).

For function D, which of two heater voltages is applied to the heaters.

For function F, which of six tube thermistors is to be monitored by the Electrolysis-Miscellaneous multiplexor.

Function H (Buoy Thermistor) allows reading the output of a thermistor bridge which measures the sea-water temperature at the buoy. "Step Control" pulses have no effect on this measurement. Since there is no data to be taken in the "Pumps" position (function C), the reed relay closed for this function is used to connect the Buoy thermistor to the amplifier.

The remaining functions A, B and E have no use at present, since A and B are retained for the Electrolysis power supply (not yet installed) and function E (Ball) is intended for use with another anti-fouling mechanism (not yet installed).

Dwg. 5-20 includes the circuitry (Integrated circuits C4 and C3) for delayed sequential turn-on of the six pumps. Since the starting current for each pump might exceed 12 amperes, a line surge of more than 70 amperes could occur on power-up. The circuits on Dwg. 5-20 allow only two pumps to come on at turn-on time, then two more after 10 seconds, and the final two pumps on after 20 seconds, thus reducing the instantaneous total starting current, and the corresponding voltage drop in the submarine cable resistance.

5.16. Buoy Power Supples (Dwg. 5-23)

The power supplies for the electronics in the Buoy Unit consist of three commercially made power supplies and a non-commercial supply built for the flowmeter bridges, which require a floating 5 volt, one ampere supply.

The commercially built supplies are:

a) A Lambda 12 volt - 3 ampere supply for all relays.

b) An Analog Devices Dual output, ± 15 volts - 200 ma supply for the operational amplifiers and the voltage to frequency converters. The + 10 volts for the CMOS logic is derived from this supply.

c) An Analog Devices 5 volt - 2 ampere supply for the line drivers and other logic requiring +5 volts.

5.17. Buoy Logic Test Card (Dwg. 5-22)

As a trouble-shooting aid, a P.C. card containing LED lamps, which are duplicates of those on the front panel of the Beach Control, is available for insertion into the Buoy logic card cage. Even though this card can only be used for trouble-shooting when the Buoy Unit is withdrawn from the water, it is felt that the time saved by using such a test card makes the use of such a tool worthwhile. Any failure of the Buoy logic to follow the indicators on the Beach Control can pinpoint the circuitry where trouble has developed.

5.18. Buoy Heater Relays (Dwg. 5-24)

Heating of the copper block corresponding to a particular heat exchanger unit is accomplished automatically as the thermocouple multiplexor (Dwgs. 5-15, 5-16 and 5-28) is advanced to the particular thermocouple to be measured. Measurements of the copper block temperature are taken, first with the heater off, then with the heater on, and again with the heater off, allowing measurement of temperature versus time for both heating and cooling of the copper block.

Relay K-7 allows the heater power to be either of two values upon command of the operator at the Beach Control.

5.19. Microprocessor Connections (Dwg. 5-29)

A connector has been installed to provide for the attachment of a microprocessor and its associated electronics to the Beach Control. When connected, the microprocessor will take over some of the operator functions, and will process the raw data from the thermopiles, the flowmeters, and the miscellaneous data, so that much less raw data will have to be stored on paper tape. Depending on the software provided with the microprocessor, various levels of processing can be done, thus reducing the amount of data that must be punched out, as well as allowing various control functions to be taken over by the microprocessor.

5.20. Buoy Flowmeters

The flowmeter bridges are shown schematically on Dwg. 5-27. These bridges are strain gages whose resistance varies with the velocity of water flow. A floating 5 volt D.C. power supply furnishes the excitation for up to six bridges, each one having provision for initially zeroing the bridge output before the Buoy Unit is submerged.

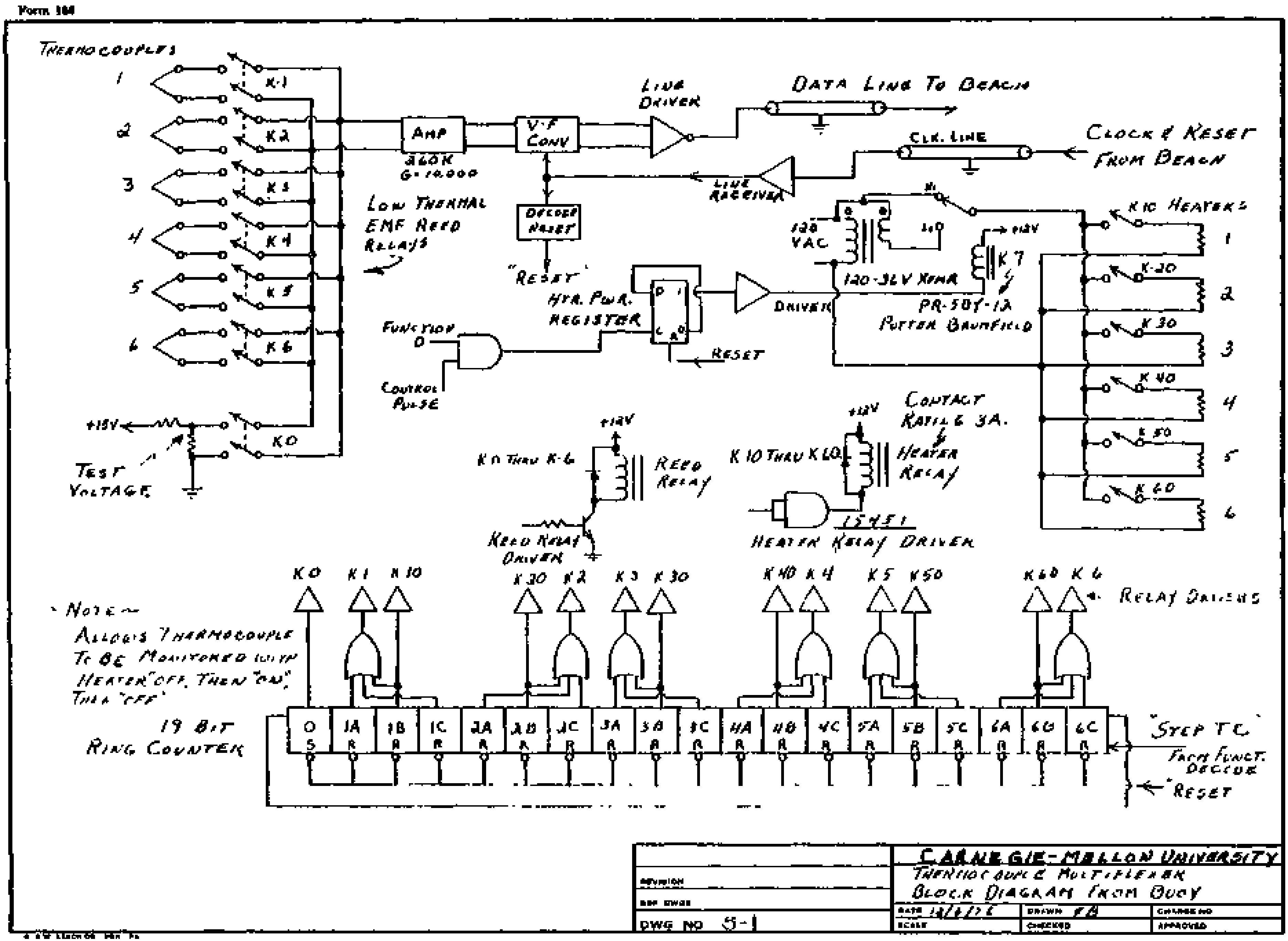
Flowmeter number one has additional connections that allow it to perform the function of a 2 to 1 voltage divider (the strain-gage bridges have approximately 120 ohms resistance in each leg) which can monitor the value of one-half the flowmeter power supply voltage and send it to the Beach Control for read-out. This measurement is done by the Electrolysis-Miscellaneous multiplexor (Dwg. 5-19) using the relay associated with the Heater Power function, since this relay has no other data to switch.

5.21. Buoy Pumps

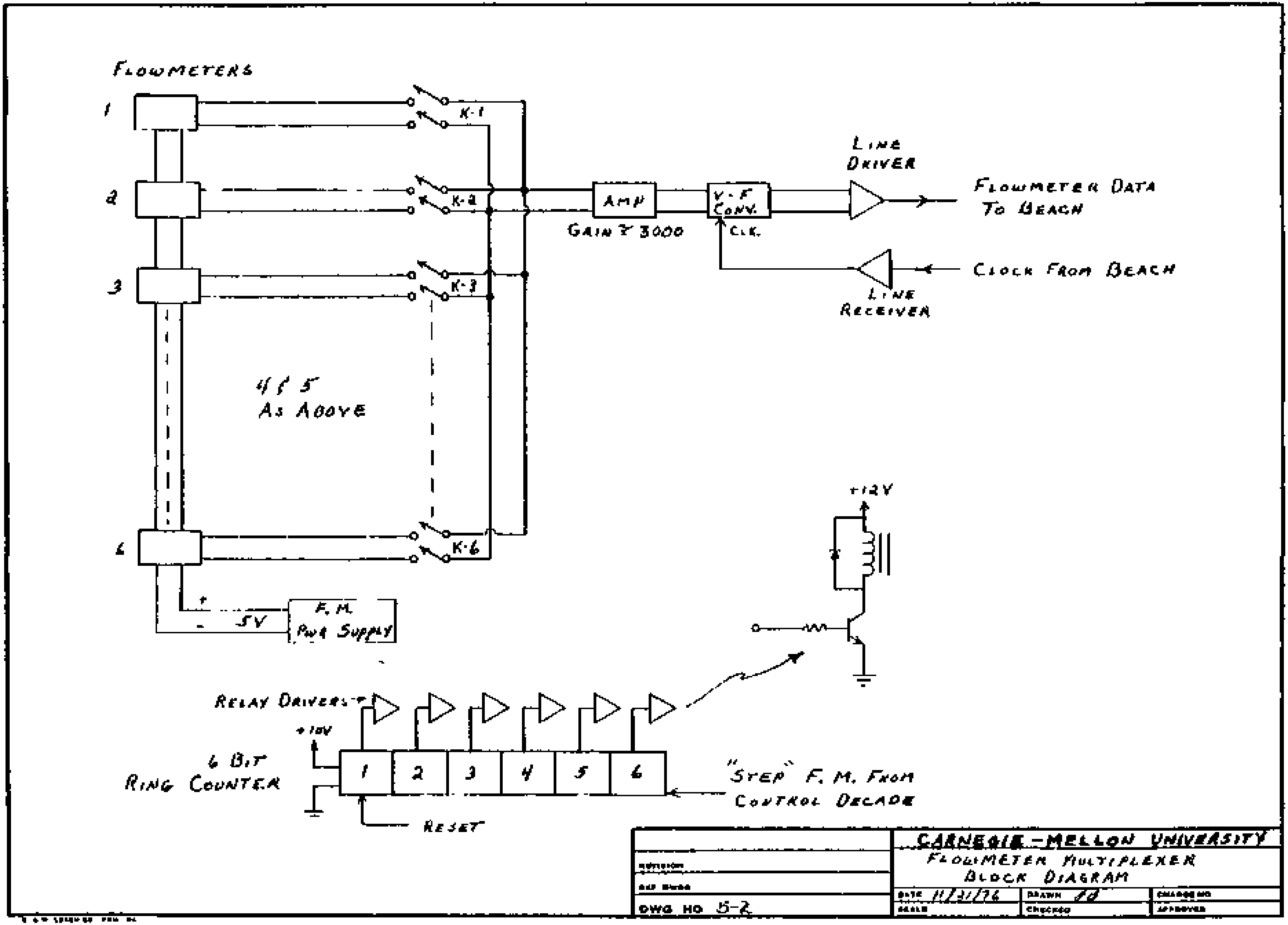
The pumps are controlled by the pump relays (Potter-Brownfield PR5DYO) (Dwg. 5-26) which switch the 240 volts A.C. to the appropriate pumps. The operator can allow all pumps to be on at once (The Reset condition) or can, by pushing the "Step" push-button with the Step Selector in the "Step-Control" position, turn off each pump, one at a time, in sequence, so that the water flow in each heat exchanger unit can be reduced to zero.

5.22. Electronics Drawings

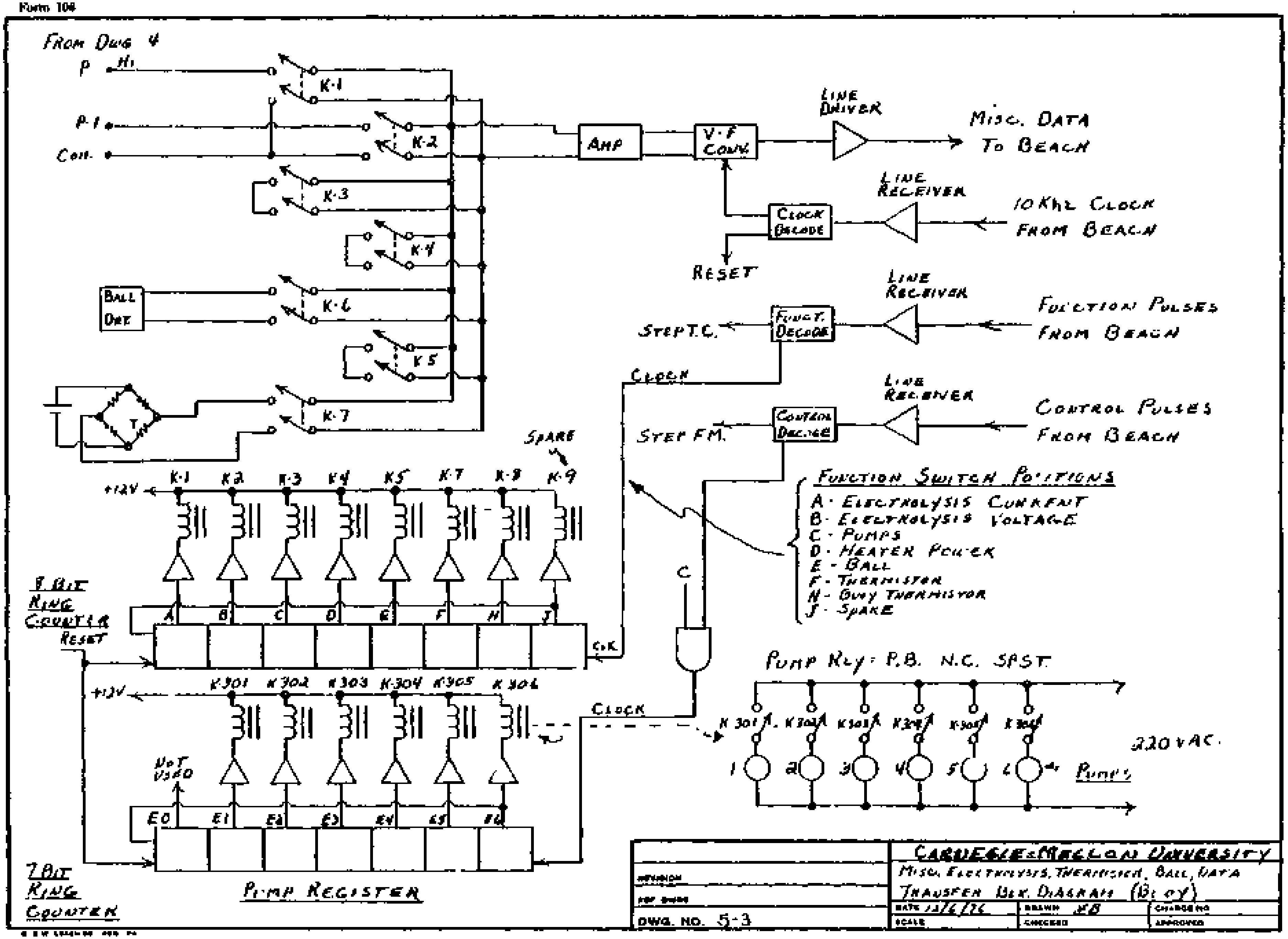
The electronics drawings (No. 5-1 to 5-31) follow.


THERMOCOUPLES
K1
K2
K3
K4
K5
K6
K0
+15V
TEST VOLTAGE
AMP
360K
G=10,000
V-F CONV
LINE DRIVER
DATA LINE TO BEACH
CLK. LINE
CLOCK & RESET FROM BEACH
LINE RECEIVER
DECODE RESET
"RESET"
LOW THERMAL EMF REED RELAYS
HTR. PWR. REGISTER
FUNCTION 0
CONTROL PULSE
RESET
DRIVER
120 VAC
120-36V XFMR
K7
+12V
PR-5DY-12
POTTER BRUMFIELD
K10 HEATERS
K20
K30
K40
K50
K60
K0 THRU K6
REED RELAY
REED RELAY DRIVER
K10 THRU K60
CONTACT RATING 3A.
HEATER RELAY
75451
HEATER RELAY DRIVER
RELAY DRIVERS
NOTE –
ALLOWS THERMOCOUPLE TO BE MONITORED WITH HEATER "OFF", THEN "ON", THEN "OFF"
19 BIT RING COUNTER
"STEP T.C."
FROM FUNCT. DECODE
"RESET"
CARNEGIE-MELLON UNIVERSITY
THERMOCOUPLE MULTIPLEXER
BLOCK DIAGRAM FROM BUOY
REVISION
DRAWN
CHECKED
APPROVED
SCALE
DWG NO 5-1

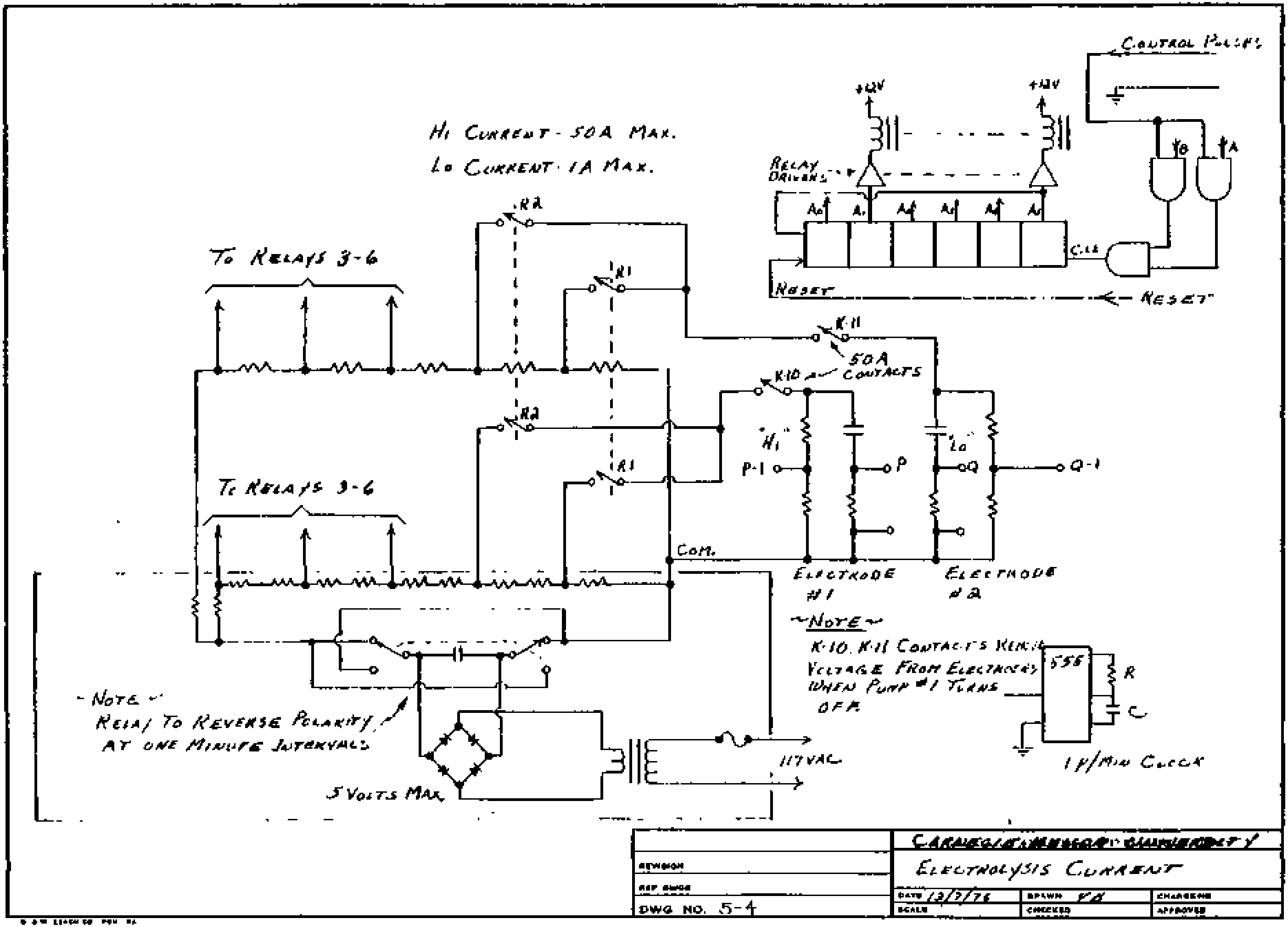
Form 186


FLOWMETERS
1
2
3
6
K-1
K-2
K-3
K-6
4 & 5
AS ABOVE
AMP
GAIN ≅ 3000
V-F
CONV.
CLK.
LINE
DRIVER
FLOWMETER DATA
TO BEACH
CLOCK FROM BEACH
LINE
RECEIVER
+12V
+
-
5V
F. M.
PWR SUPPLY
RELAY DRIVERS
+10V
6 BIT
RING COUNTER
1
2
3
4
5
6
"STEP" F. M. FROM
CONTROL DECADE
RESET
CARNEGIE-MELLON UNIVERSITY
FLOWMETER MULTIPLEXER
BLOCK DIAGRAM
DATE 11/21/76
DRAWN
SCALE
CHECKED
CHANGE NO
APPROVED
REVISION
REF DWGS
DWG NO 5-2

Form 104

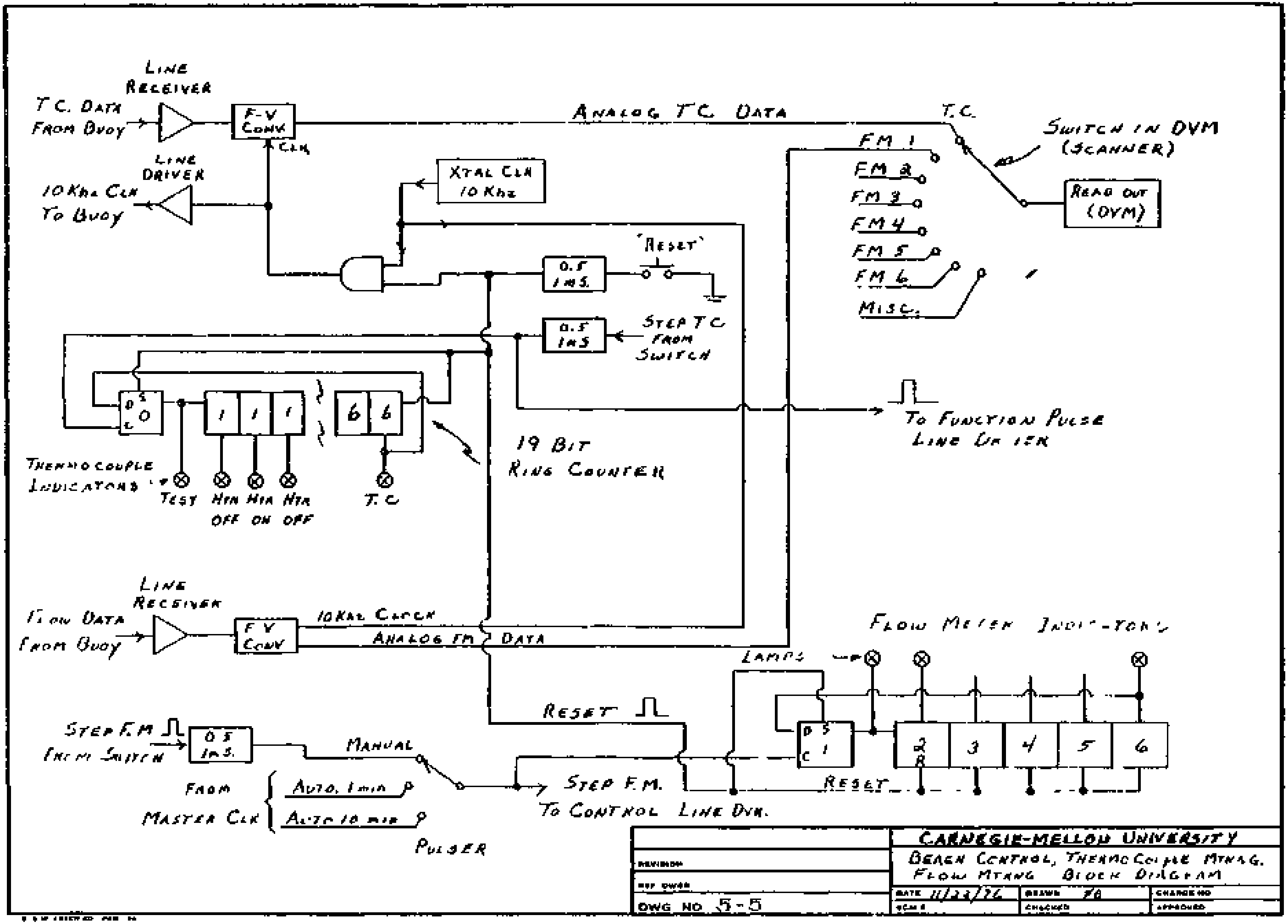

FROM DWG 4
P
Hi
P-1
COM.
K-1
K-2
K-3
K-4
K-6
K-5
K-7
BALL
DET.
T
AMP
V-F
CONV.
LINE
DRIVER
MISC. DATA
TO BEACH
LINE
RECEIVER
CLOCK
DECODE
10 Khz CLOCK
FROM BEACH
RESET
LINE
RECEIVER
FUNCT.
DECODE
STEP T.C.
FUNCTION PULSES
FROM BEACH
CLOCK
LINE
RECEIVER
CONTROL
DECODE
STEP FM.
CONTROL PULSES
FROM BEACH
SPARE
+12V
K-1 K2 K-3 K4 K5 K-7 K-8 K-9
8 BIT
RING
COUNTER
RESET
A B C D E F H J
C-K
FUNCTION SWITCH POSITIONS
A - ELECTROLYSIS CURRENT
B - ELECTROLYSIS VOLTAGE
C - PUMPS
D - HEATER POWER
E - BALL
F - THERMISTOR
H - GUY THERMISTOR
J - SPARE
C
PUMP RLY: P.B. N.C. SPST
+12V
K301 K302 K303 K304 K305 K306
CLOCK
K301 K302 K303 K304 K305 K306
220 VAC.
1 2 3 4 5 6
PUMPS
NOT
USED
E0 E1 E2 E3 E4 E5 E6
7 BIT
RING
COUNTER
PUMP REGISTER
CARNEGIE-MELLON UNIVERSITY
MISC. ELECTROLYSIS, THERMISTOR, BALL, DATA
TRANSFER BLK. DIAGRAM (BUOY)
REVISION
FOR DWGS
DWG. NO. 5-3
DATE
SCALE
DRAWN
CHECKED
CHARGE NO
APPROVED

Form 104

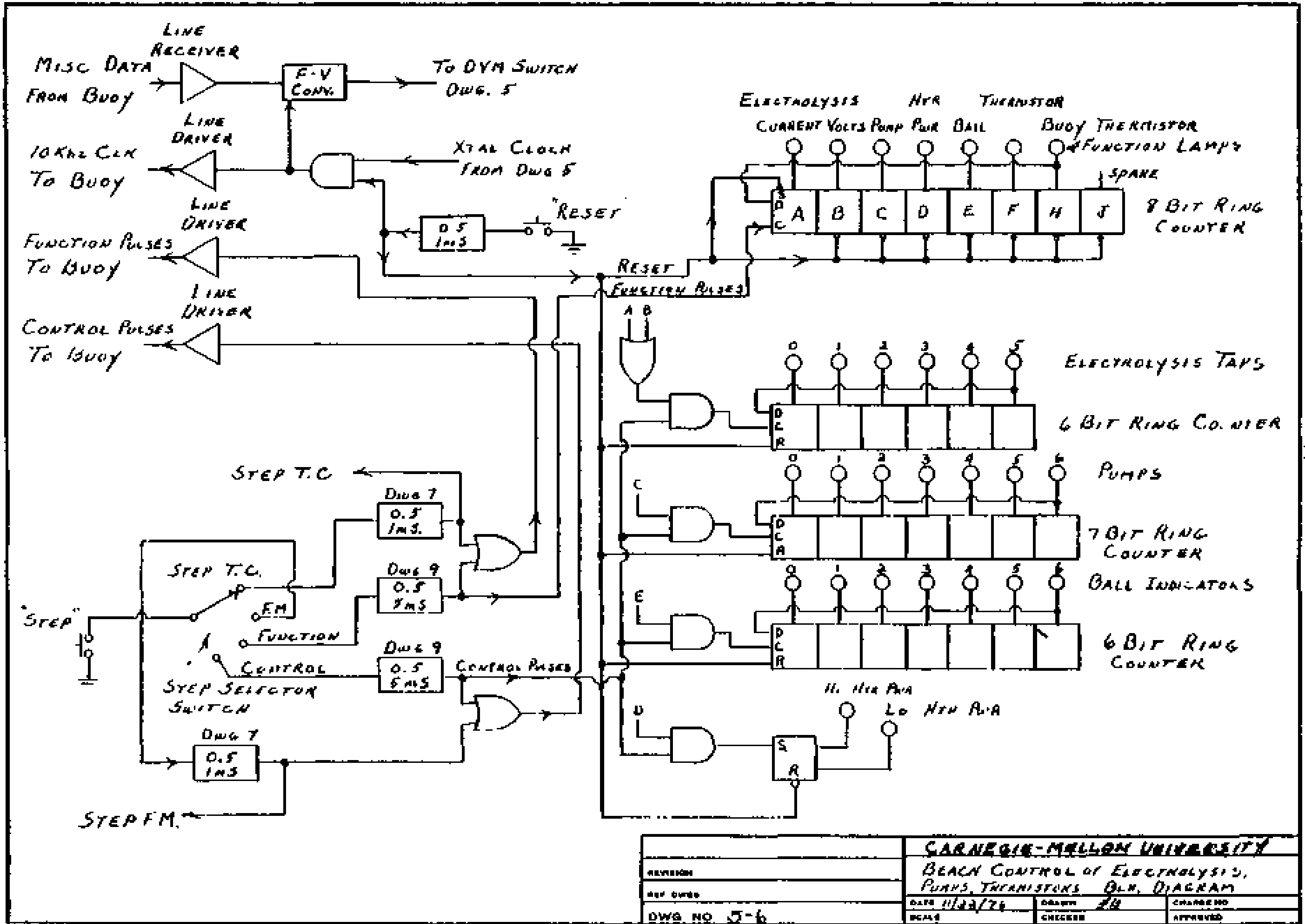


Hi Current - 50A Max.
Lo Current - 1A Max.
To Relays 3-6
To Relays 3-6
R2
R1
R2
R1
K-11
K-10
50A Contacts
"Hi"
"Lo"
P-1
P
Q
Q-1
Com.
Electrode #1
Electrode #2
~Note~
K-10, K-11 Contacts Remove Voltage From Electrodes When Pump #1 Turns Off.
~Note~
Relay To Reverse Polarity At One Minute Intervals
5 Volts Max.
117VAC
Control Pulses
+12V
+12V
Relay Drivers
Reset
Reset
555
R
C
1P/Min Clock
Carnegie-Mellon University
Electrolysis Current
Revision
Ref Dwgs
DWG NO. 5-4
Date 12/7/76
Drawn
Scale
Checked
Changed
Approved

Form 108

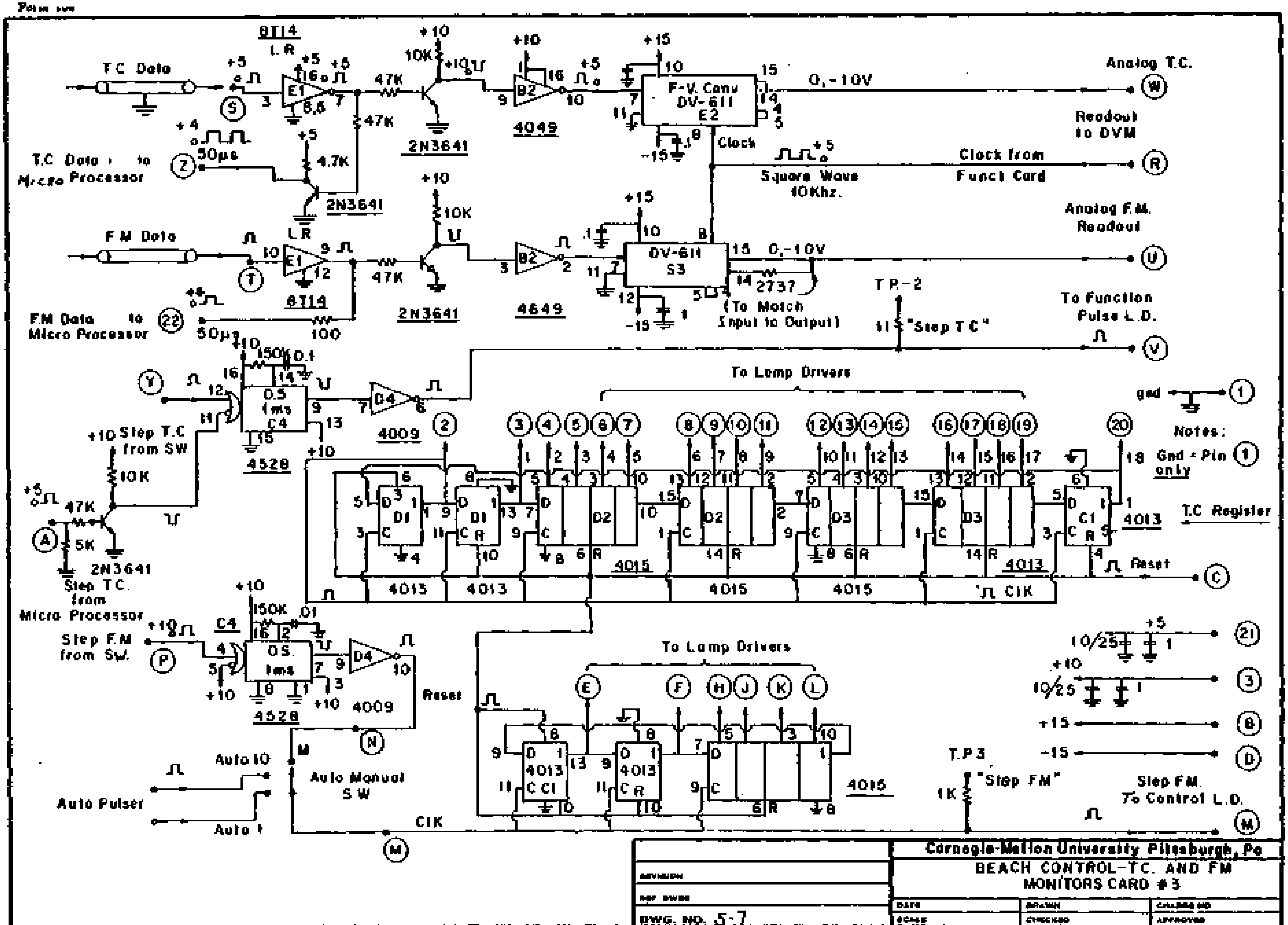

LINE RECEIVER
T.C. DATA FROM BUOY
F-V CONV
CLK
LINE DRIVER
10 KHz CLK TO BUOY
XTAL CLK 10 KHz
ANALOG T.C. DATA
T.C.
SWITCH IN DVM (SCANNER)
FM 1
FM 2
FM 3
FM 4
FM 5
FM 6
MISC.
READ OUT (DVM)
0.5 mS.
'RESET'
STEP T.C. FROM SWITCH
0
1
1
1
6
6
19 BIT RING COUNTER
TO FUNCTION PULSE LINE DRIVER
THERMOCOUPLE INDICATORS
TEST
HTR OFF
HTR ON
HTR OFF
T.C.
LINE RECEIVER
FLOW DATA FROM BUOY
F-V CONV
10 KHz CLOCK
ANALOG FM DATA
FLOW METER INDICATORS
LAMPS
RESET
STEP F.M. FROM SWITCH
0.5 mS.
MANUAL
FROM MASTER CLK
AUTO. 1 min
AUTO 10 min
PULSER
STEP F.M. TO CONTROL LINE DVR.
1
2
3
4
5
6
RESET
CARNEGIE-MELLON UNIVERSITY
BEACH CONTROL, THERMOCOUPLE MTRNG. FLOW MTRNG BLOCK DIAGRAM
REVISION
REF DWGS
DWG NO 5-5
DATE 11/23/76
SCALE
DRAWN
CHECKED
CHARGE NO
APPROVED

Form 101

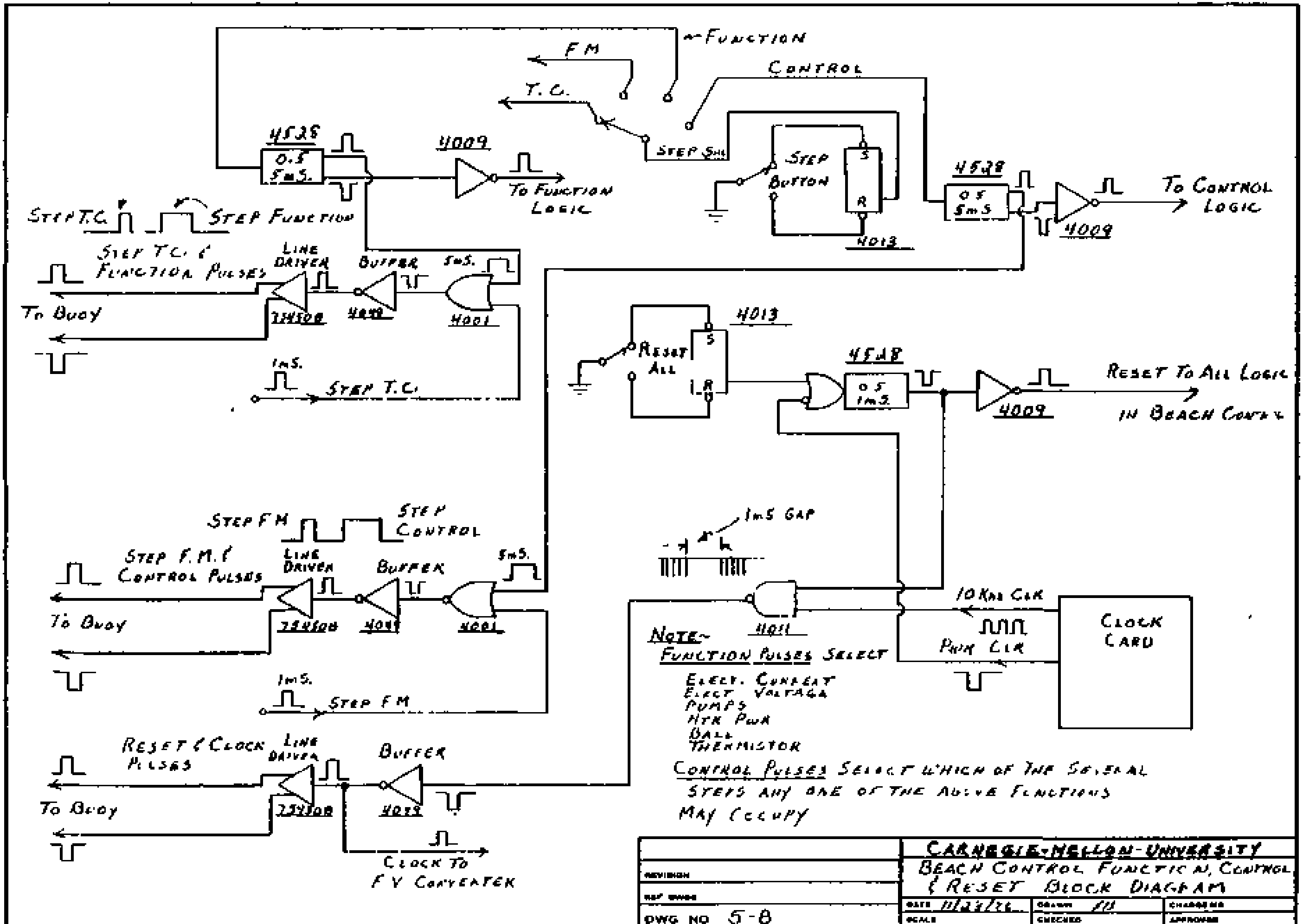


LINE RECEIVER
MISC DATA FROM BUOY
F-V CONV.
TO DVM SWITCH DWG. 5
LINE DRIVER
10 KHz CLK TO BUOY
XTAL CLOCK FROM DWG 5
LINE DRIVER
FUNCTION PULSES TO BUOY
0.5 1mS
"RESET"
LINE DRIVER
CONTROL PULSES TO BUOY
RESET
FUNCTION PULSES
ELECTROLYSIS CURRENT VOLTS
PUMP
HTR PWR
BAIL
THERMISTOR
BUOY THERMISTOR
FUNCTION LAMPS
SPARE
A B C D E F H J
7 BIT RING COUNTER
ELECTROLYSIS TAPS
6 BIT RING COUNTER
PUMPS
7 BIT RING COUNTER
BALL INDICATORS
6 BIT RING COUNTER
HI HTR PWR
LO HTR PWR
STEP T.C.
DWG 7 0.5 1mS
DWG 9 0.5 5mS
STEP T.C.
FM
FUNCTION
CONTROL
"STEP"
STEP SELECTOR SWITCH
DWG 9 0.5 5mS
CONTROL PULSES
DWG 7 0.5 1mS
STEP FM.
CARNEGIE-MELLON UNIVERSITY
BEACH CONTROL OF ELECTROLYSIS, PUMPS, THERMISTORS BLK. DIAGRAM
DATE 11/22/76
DWG. NO. 5-6


132

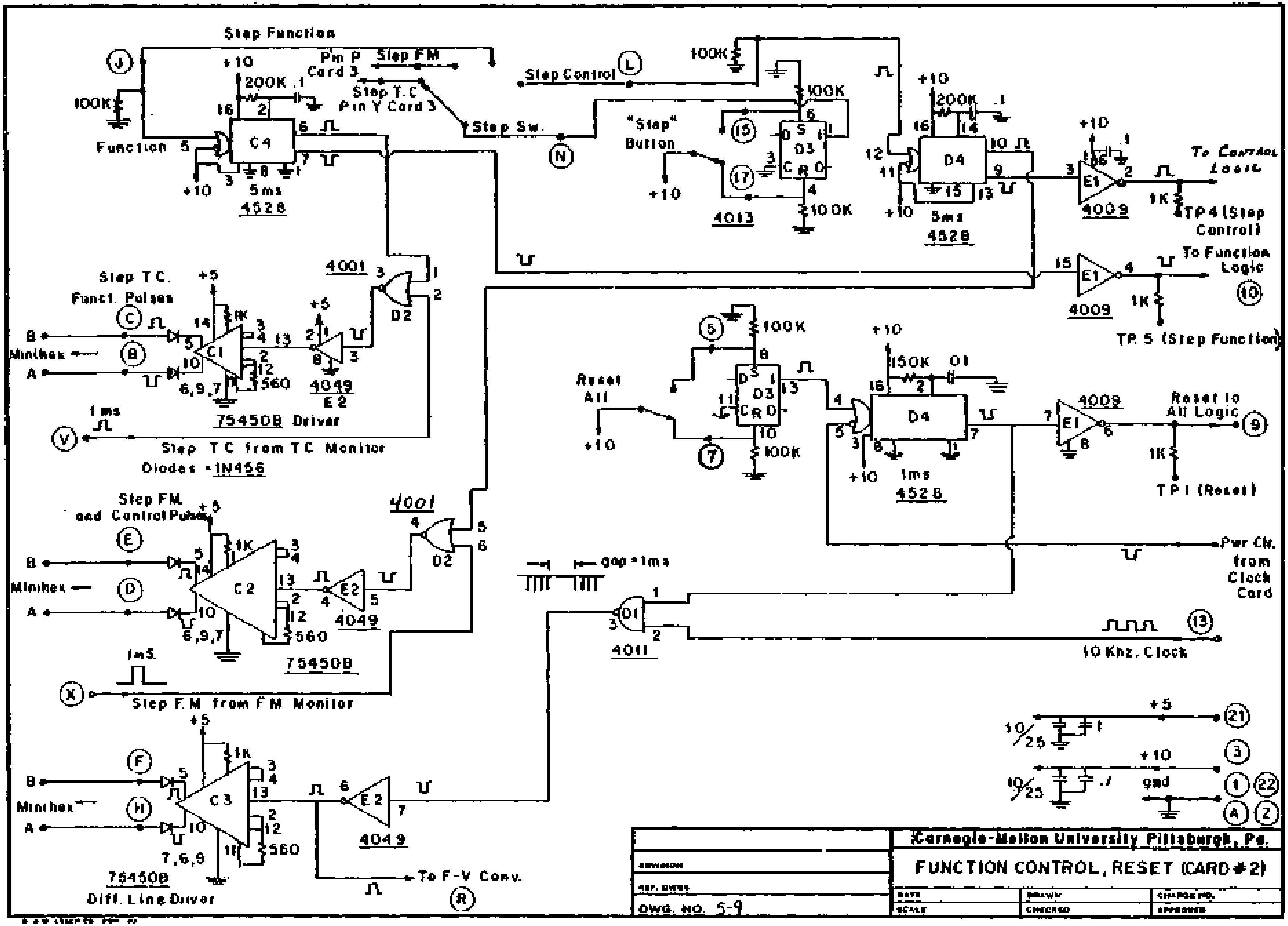

T.C Data
8T14
L.R
E1
2N3641
4049
B2
F-V. Conv
DV-611
E2
0,-10V
Analog T.C.
Readout to DVM
Clock
Square Wave 10Khz.
Clock from Funct Card
T.C Data to Micro Processor
50μs
4.7K
47K
10K
F.M Data
DV-611
S3
Analog F.M. Readout
(To Match Input to Output)
F.M Data to Micro Processor
T.P.-2
"Step T.C"
To Function Pulse L.D.
0.5 1ms C4
4528
D4
4009
To Lamp Drivers
Step T.C from SW
Step T.C. from Micro Processor
2N3641
D1
D2
D3
C1
4013
4015
T.C Register
Reset
Clk
Notes:
Gnd = Pin (1) only
gnd
Step F.M from Sw.
O.S. 1ms
Auto Pulser
Auto 10
Auto 1
Auto Manual SW
CIk
T.P 3
"Step FM"
Step F.M. To Control L.D.
Carnegie-Mellon University Pittsburgh, Pa
BEACH CONTROL-TC. AND FM MONITORS CARD # 3
DWG. NO. 5-7

Form 106



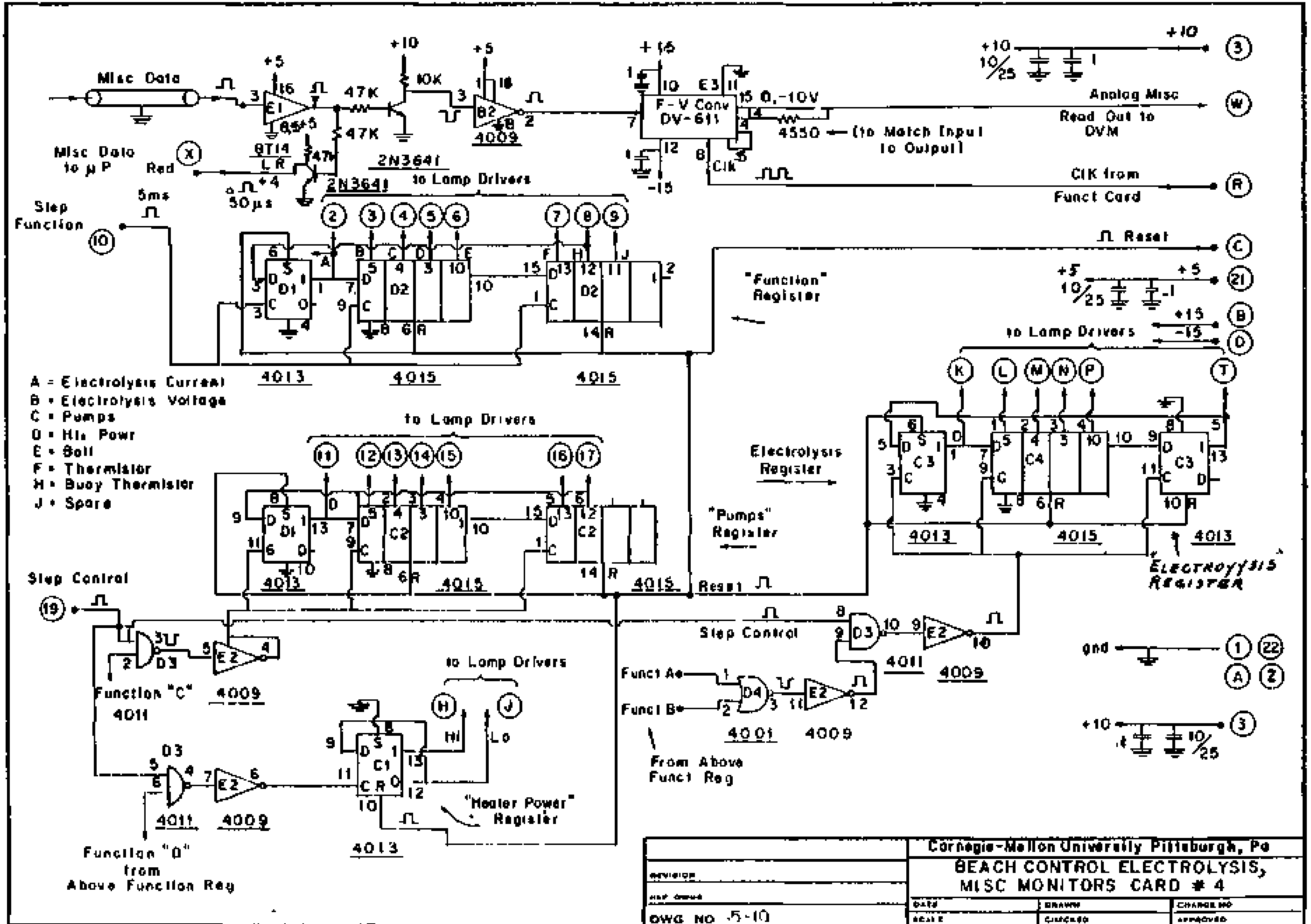
FUNCTION
FM
T.C.
CONTROL
4528
0.5
5mS.
4009
TO FUNCTION LOGIC
STEP SW.
STEP BUTTON
S
R
4013
4528
0.5
5mS
4009
TO CONTROL LOGIC
STEP T.C.
STEP FUNCTION
STEP T.C. & FUNCTION PULSES
LINE DRIVER
BUFFER
5mS.
TO BUOY
75450B
4049
4001
1mS.
STEP T.C.
4013
RESET ALL
S
R
4528
0.5
1mS.
4009
RESET TO ALL LOGIC IN BEACH CONTROL
1mS GAP
STEP FM
STEP CONTROL
STEP F.M. & CONTROL PULSES
LINE DRIVER
BUFFER
5mS.
TO BUOY
75450B
4049
4001
1mS.
STEP FM
4011
10 KHz CLK
PWR CLR
CLOCK CARD
NOTE–
FUNCTION PULSES SELECT
ELECT. CURRENT
ELECT VOLTAGE
PUMPS
HTR PWR
BALL
THERMISTOR
CONTROL PULSES SELECT WHICH OF THE SEVERAL STEPS ANY ONE OF THE ABOVE FUNCTIONS MAY OCCUPY
RESET & CLOCK PULSES
LINE DRIVER
BUFFER
TO BUOY
75450B
4049
CLOCK TO F V CONVERTER
CARNEGIE-MELLON-UNIVERSITY
BEACH CONTROL FUNCTION, CONTROL & RESET BLOCK DIAGRAM
REVISION
REF DWGS
DWG NO 5-8
DATE 11/23/76
DRAWN
CHECKED
SCALE
CHARGE NO
APPROVED

Form 104

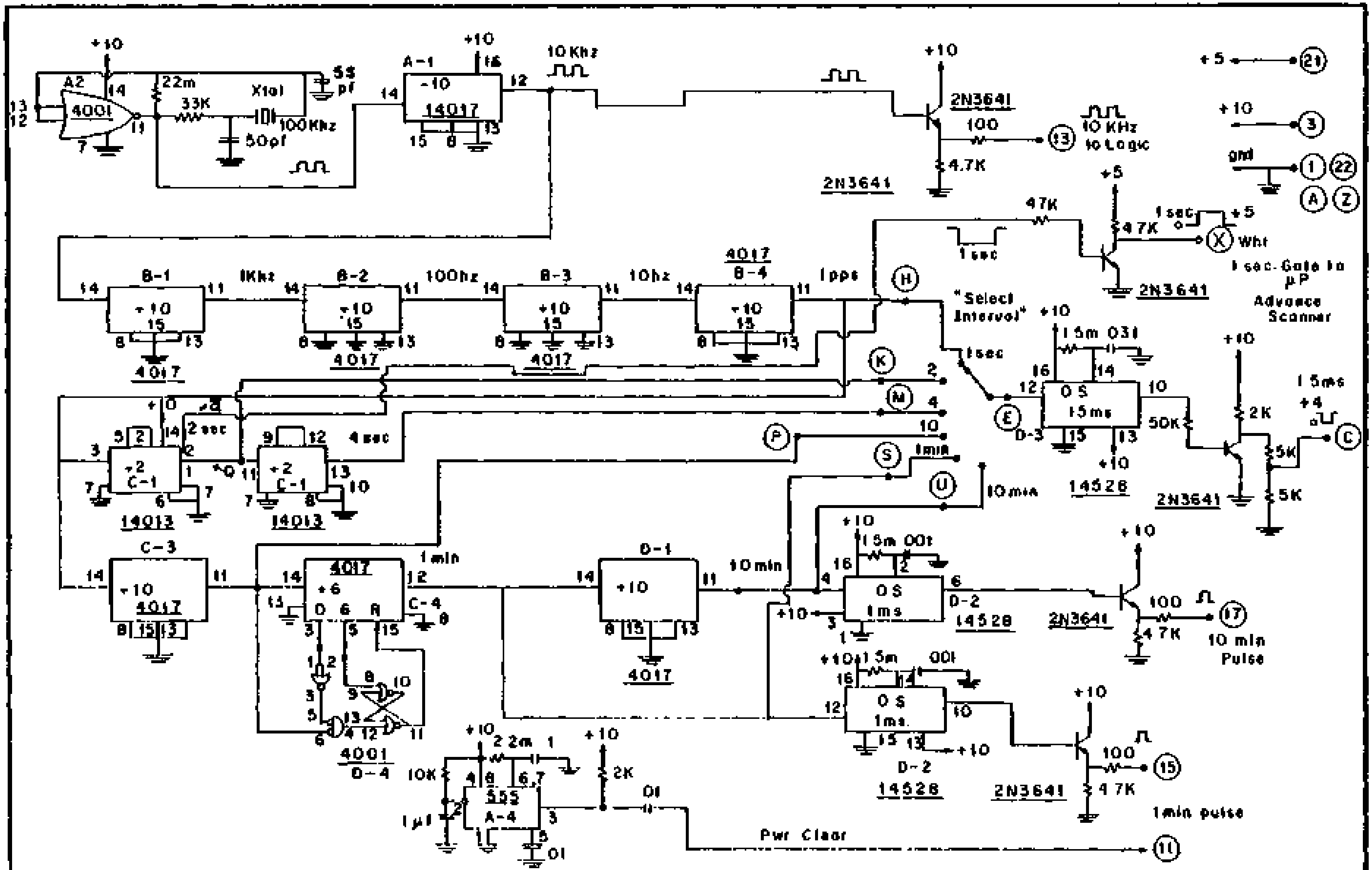


Step Function
Step Control
Pin P Card 3
Step FM
Step T.C Pin Y Card 3
Step Sw.
"Step" Button
Function
5ms
4528
4013
4009
To Control Logic
TP 4 (Step Control)
To Function Logic
TP. 5 (Step Function)
Step T.C. Funct. Pulses
Minihex
75450B Driver
4001
4049
Step T C from T C Monitor
Diodes = 1N456
Reset All
1ms
Reset to All Logic
TP 1 (Reset)
Pwr Clr. from Clock Card
Step FM and Control Pulse
75450B
gap = 1ms
4011
10 Khz. Clock
Step F M from F M Monitor
To F-V Conv.
Diff. Line Driver
Carnegie-Mellon University Pittsburgh, Pa.
FUNCTION CONTROL, RESET (CARD #2)
DWG. NO. 5-9

Form 100


Misc Data
Misc Data to µP
Red
Step Function
Step Control
to Lamp Drivers
F-V Conv DV-611
0, -10V
Analog Misc Read Out to DVM
4550 ← (to Match Input to Output)
Clk from Funct Card
Reset
"Function" Register
"Pumps" Register
Electrolysis Register
"Heater Power" Register
A = Electrolysis Current
B = Electrolysis Voltage
C = Pumps
D = Htr. Powr
E = Salt
F = Thermistor
H = Buoy Thermistor
J = Spare
2N3641
4013
4015
4011
4009
4001
Function "C"
Function "D" from Above Function Reg
Funct A
Funct B
From Above Funct Reg
gnd
Carnegie-Mellon University Pittsburgh, Pa
BEACH CONTROL ELECTROLYSIS, MISC MONITORS CARD # 4
DWG NO 5-10

Form 106



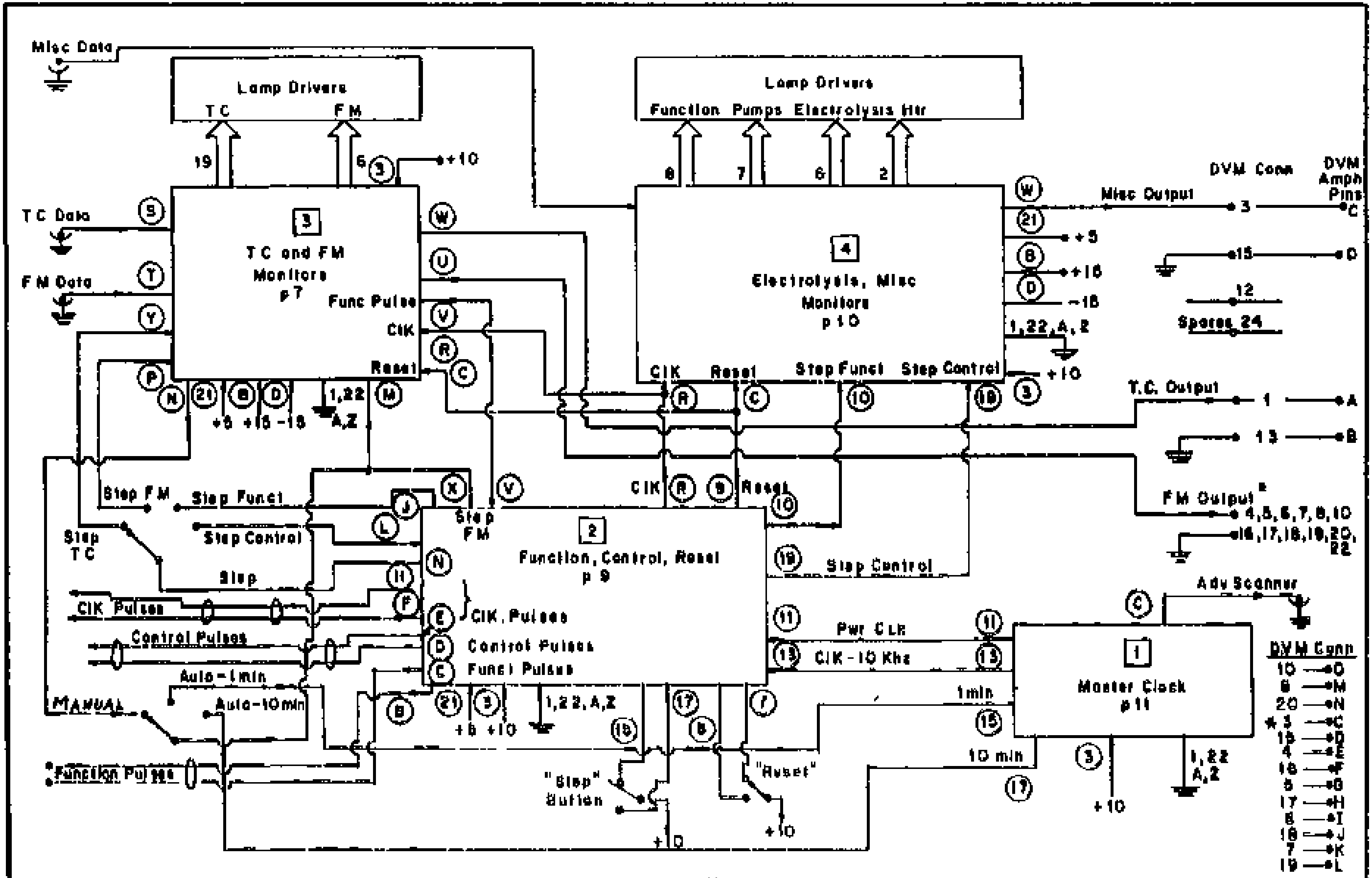

Carnegie-Mellon University Pittsburgh, Pa.

MASTER CLOCK #1

| REVISION | DATE | DRAWN | CHANGE NO |
| --- | --- | --- | --- |
| REF DWGS | SCALE | CHECKED | APPROVED |

DWG NO 5-11

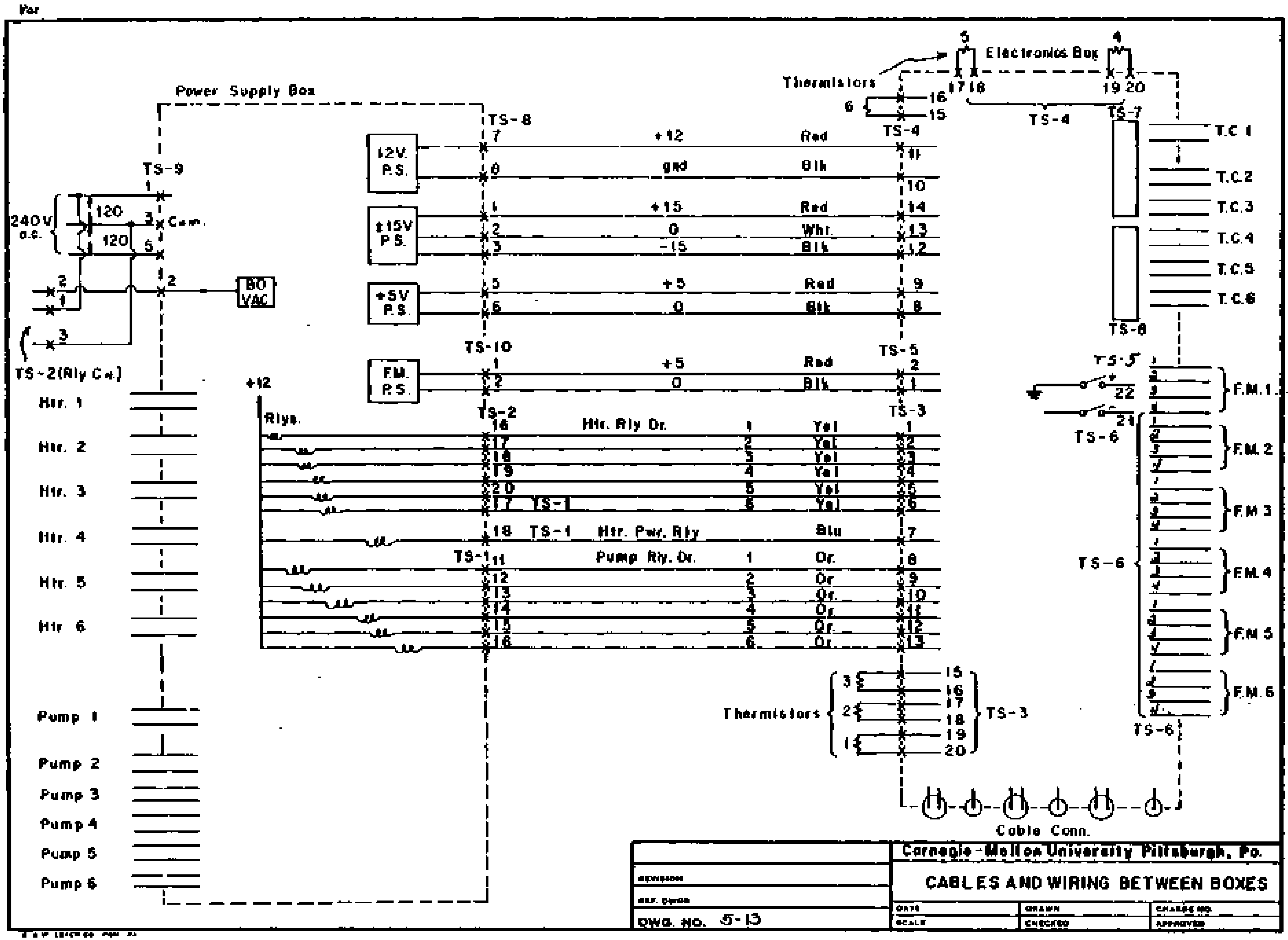
Form 106

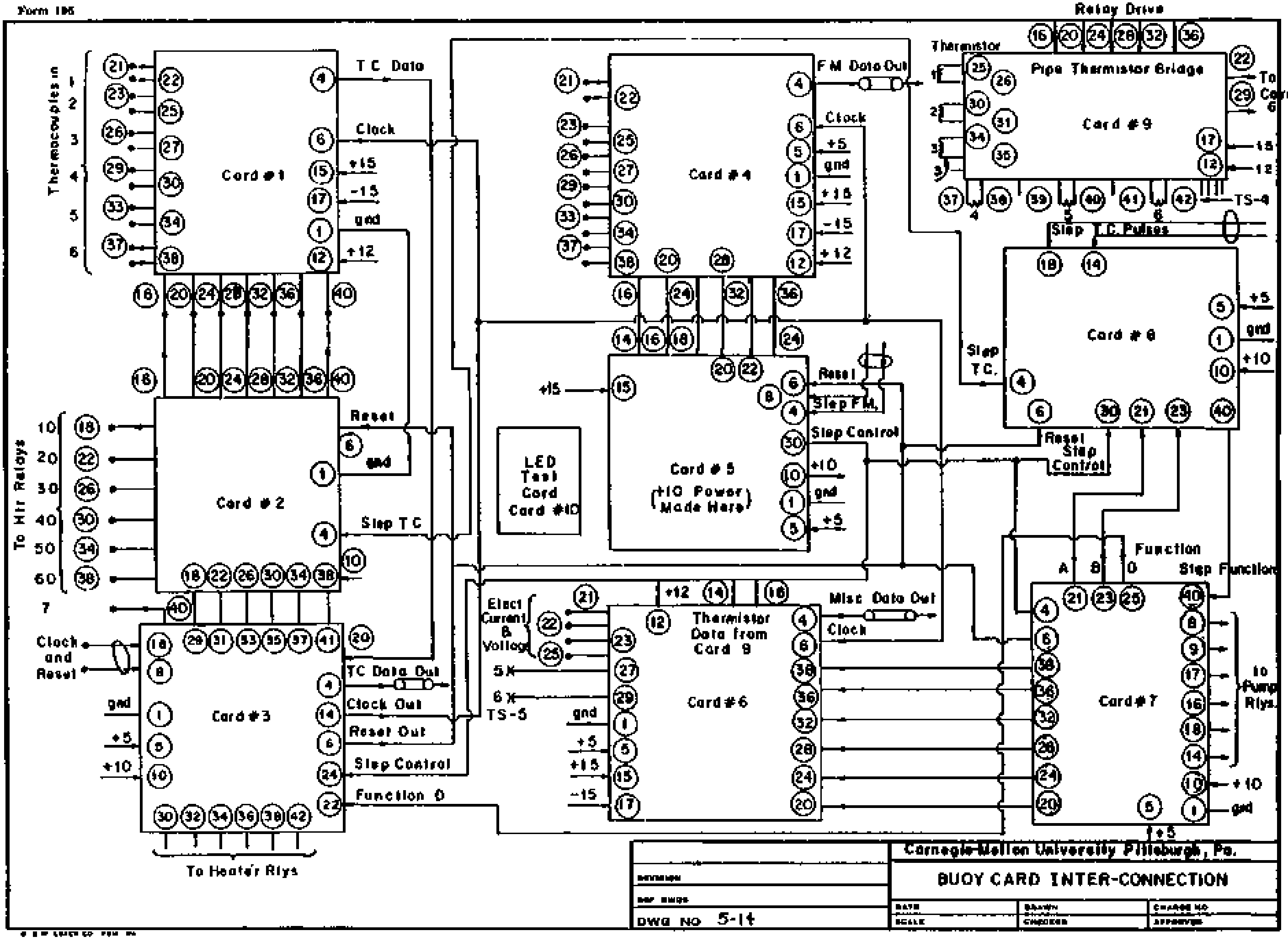


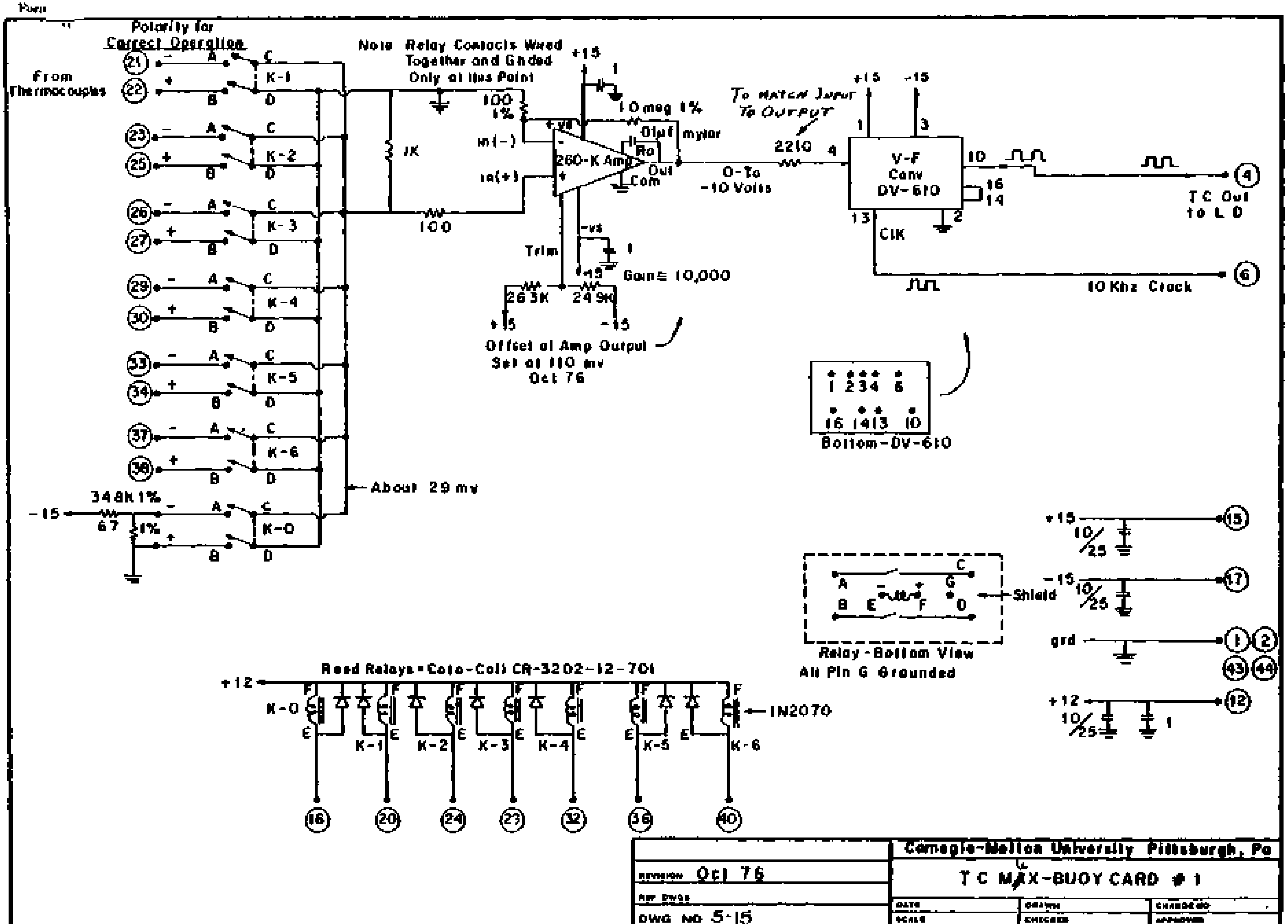

Carnegie-Mellon University Pittsburgh, PA

BEACH CONTROL-INTER-CONNECT WIRING

DWG NO 5 17

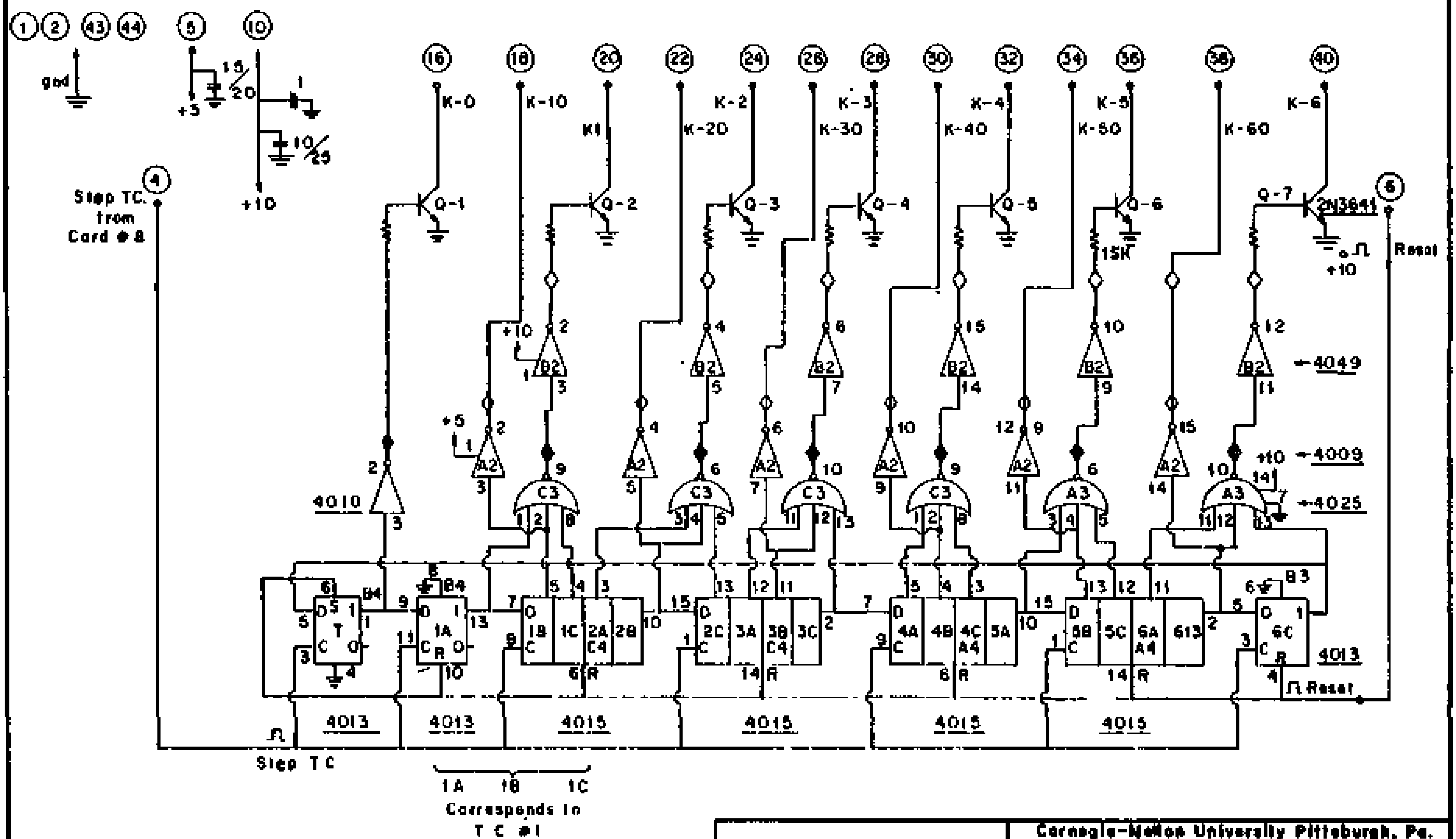

Power Supply Box
TS-9
240V a.c.
120
120
Com.
80 VAC
TS-2(Rly Cm.)
Htr. 1
Htr. 2
Htr. 3
Htr. 4
Htr. 5
Htr. 6
Pump 1
Pump 2
Pump 3
Pump 4
Pump 5
Pump 6
12V. P.S.
±15V P.S.
+5V P.S.
F.M. P.S.
TS-8
TS-10
TS-2
TS-1
+12
Rlys.
+12 Red
gnd Blk
+15 Red
0 Wht.
-15 Blk
+5 Red
0 Blk
+5 Red
0 Blk
Htr. Rly Dr.
Yel
Htr. Pwr. Rly
Blu
Pump Rly. Dr.
Or.
Thermistors
Electronics Box
TS-4
TS-5
TS-3
TS-7
TS-8
T.C 1
T.C 2
T.C 3
T.C 4
T.C 5
T.C 6
TS-5
TS-6
F.M. 1
F.M. 2
F.M. 3
F.M. 4
F.M. 5
F.M. 6
Cable Conn.
Carnegie-Mellon University Pittsburgh, Pa.
CABLES AND WIRING BETWEEN BOXES
REVISION
REF. DWGS
DWG. NO. 5-13
DATE
SCALE
DRAWN
CHECKED
CHARGE NO.
APPROVED


Form 106
Thermocouples in
Card #1
TC Data
Clock
+15
-15
gnd
+12
Card #4
FM Data Out
Relay Drive
Thermistor
Pipe Thermistor Bridge
Card #9
To Card 6
TS-4
Step T.C. Pulses
Card #8
Step T.C.
Reset
Step Control
To Htr Relays
Card #2
Step TC
LED Test Card Card #10
Card #5
(+10 Power Made Here)
Step F.M.
Function
Step Function
Card #3
Clock and Reset
TC Data Out
Clock Out
Reset Out
Step Control
Function 0
To Heater Rlys
Elect Current & Voltage
TS-5
Thermistor Data from Card 9
Card #6
Misc Data Out
Card #7
To Pump Rlys.
Carnegie-Mellon University Pittsburgh, Pa.
BUOY CARD INTER-CONNECTION
DWG NO 5-14



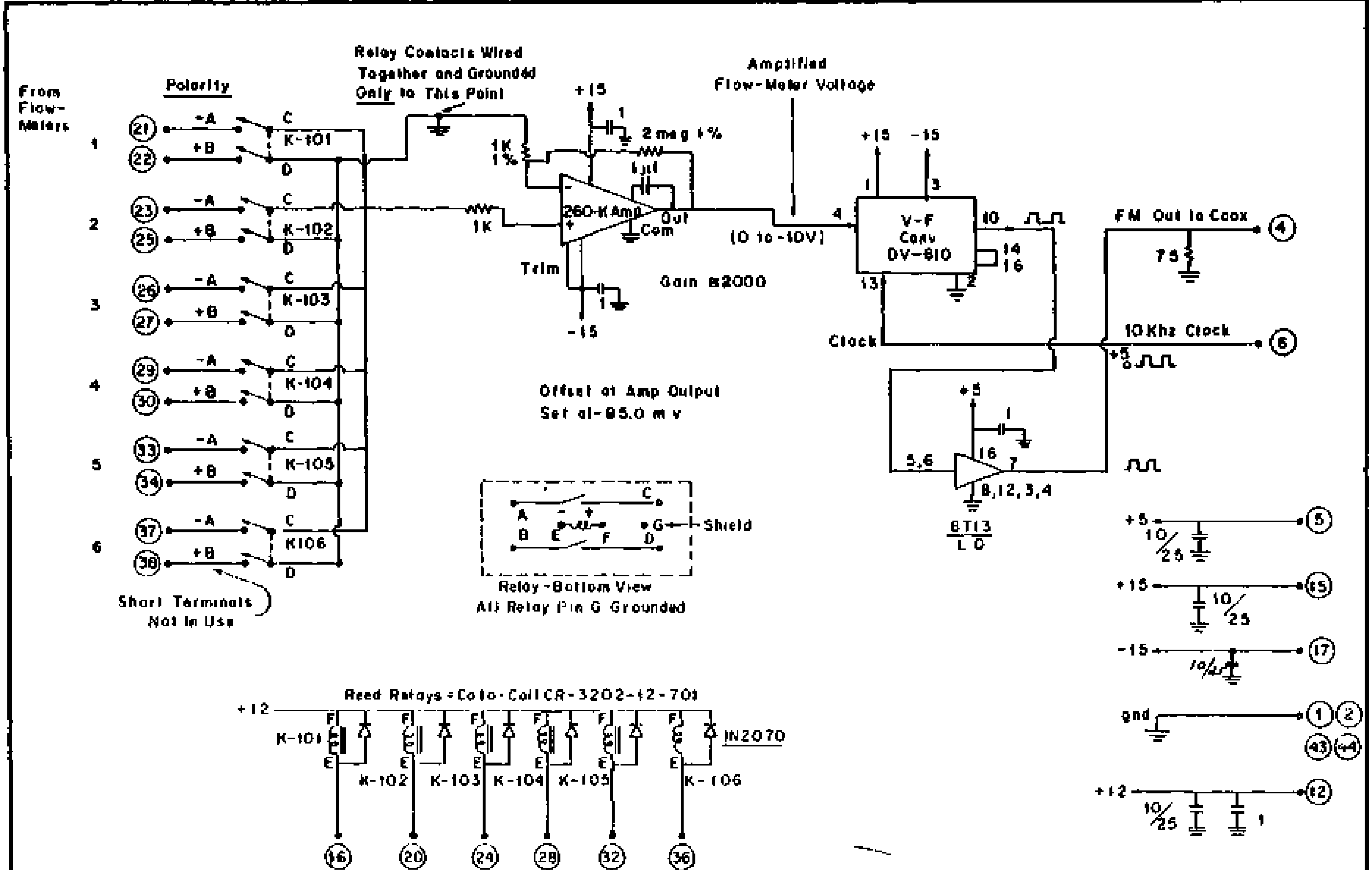
Polarity for Correct Operation
From Thermocouples
Note Relay Contacts Wired Together and Gnded Only at this Point
+15
1.0 meg 1%
.01uf mylar
To MATCH INPUT To OUTPUT
2210
+15
-15
100 1%
in(-)
in(+)
1K
100
260-K Amp
Out
Com
0-To -10 Volts
V-F Conv DV-610
TC Out to L D
CLK
10 Khz Clock
Trim
-vs
Gain ≅ 10,000
263K
24.9K
+15
-15
Offset at Amp Output Set at 110 mv Oct 76
Bottom-DV-610
About 29 mv
348K 1%
67 1%
-15
K-0
K-1
K-2
K-3
K-4
K-5
K-6
Relay - Bottom View
All Pin G Grounded
Shield
grd
Reed Relays = Coto-Coil CR-3202-12-701
+12
1N2070
Carnegie-Mellon University Pittsburgh, Pa
T C MAX-BUOY CARD # 1
REVISION Oct 76
DWG NO 5-15

Form 106




| | |
|---|---|
| | Carnegie-Mellon University Pittsburgh, Pa. |
| REVISION | T C MUX - BUOY CARD # 2 |
| REF DWGS | DATE / DRAWN / CHARGE NO |
| DWG NO 5-16 | SCALE / CHECKED / APPROVED |

Form 106

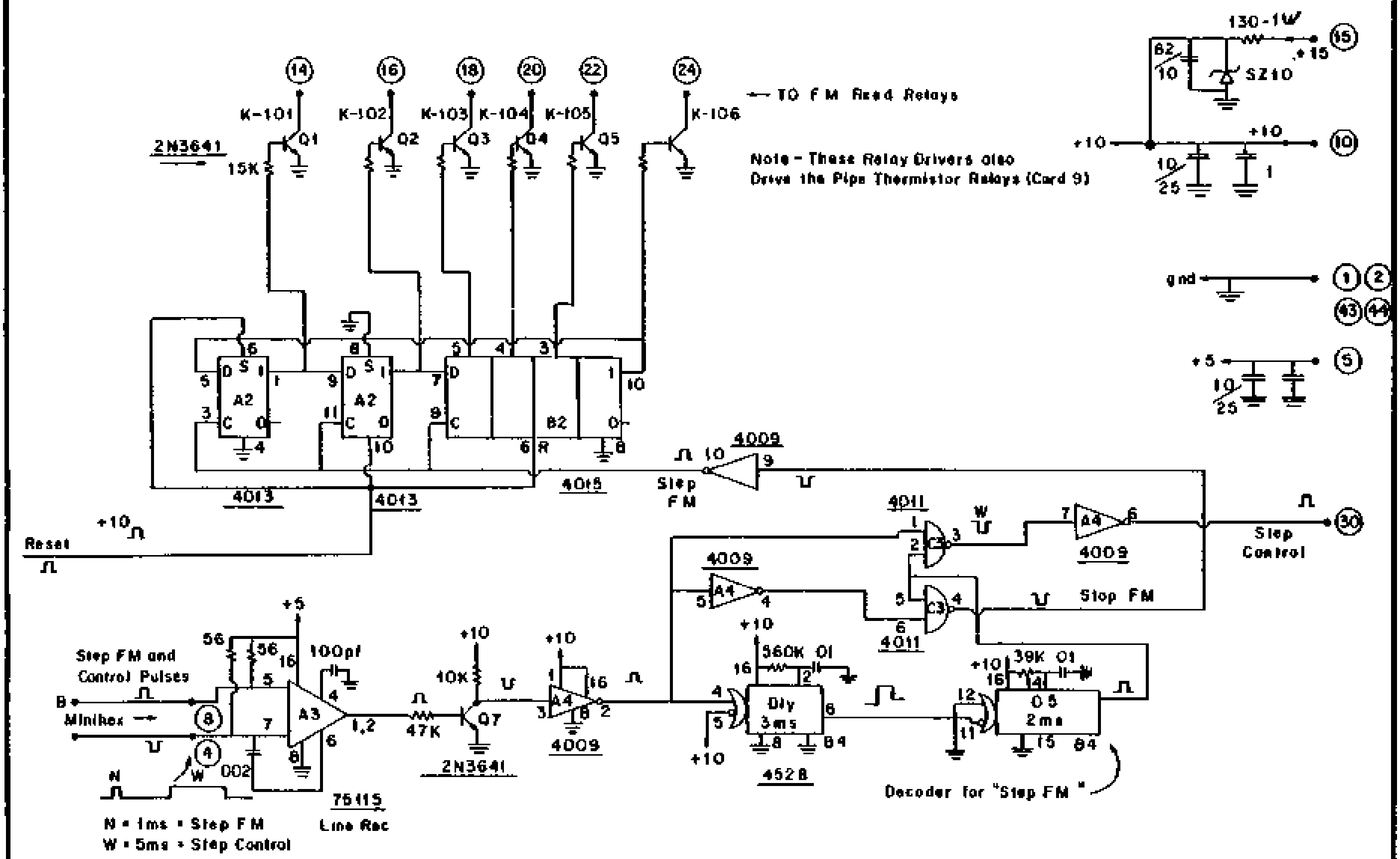



Carnegie-Mellon University Pittsburgh, Pa.

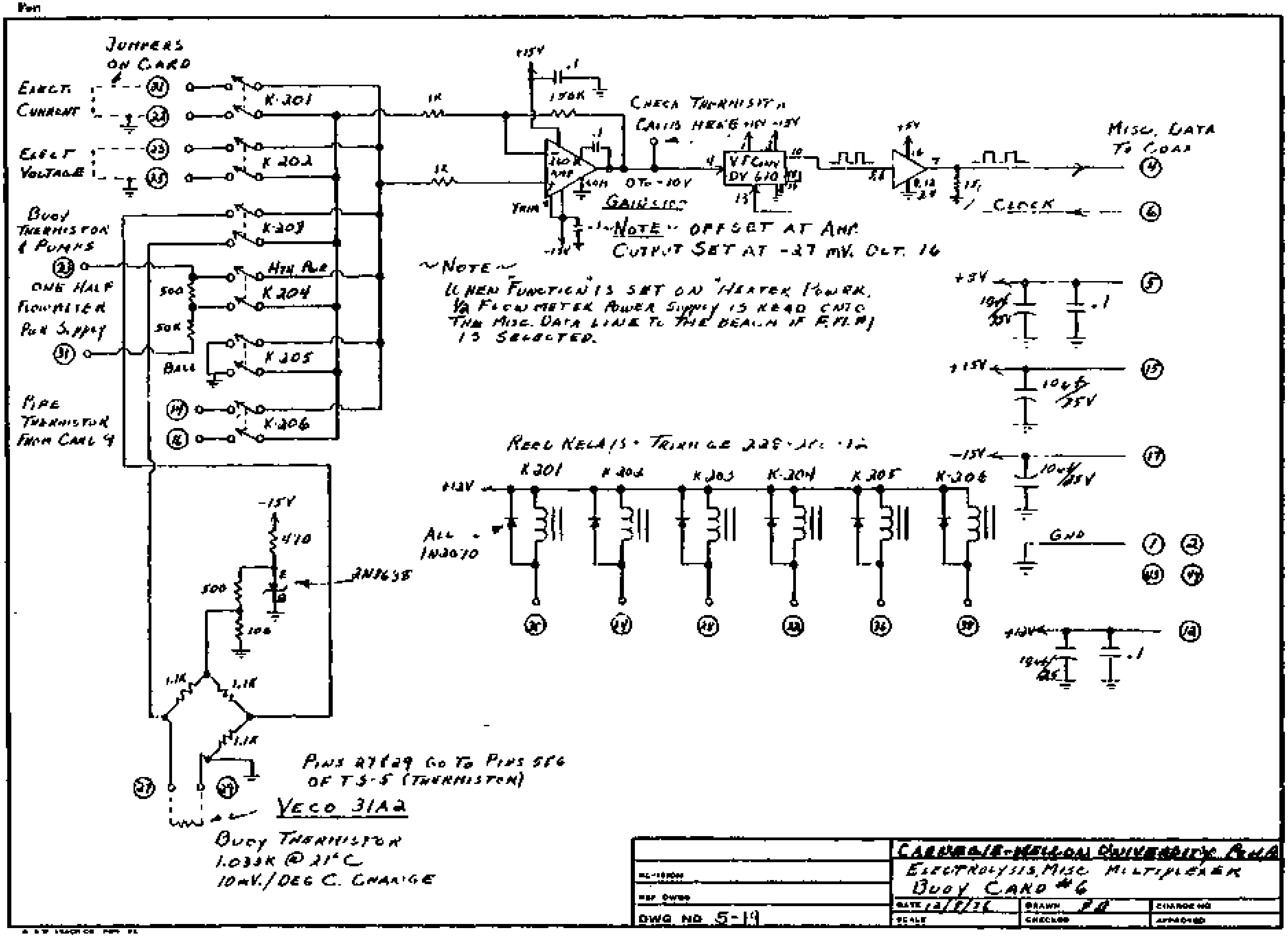
FLOW METER MUX (BUOY) CARD #4

REVISION
REF DWGS
DWG NO 5-17
DATE
SCALE
DRAWN
CHECKED
CHANGE NO
APPROVED

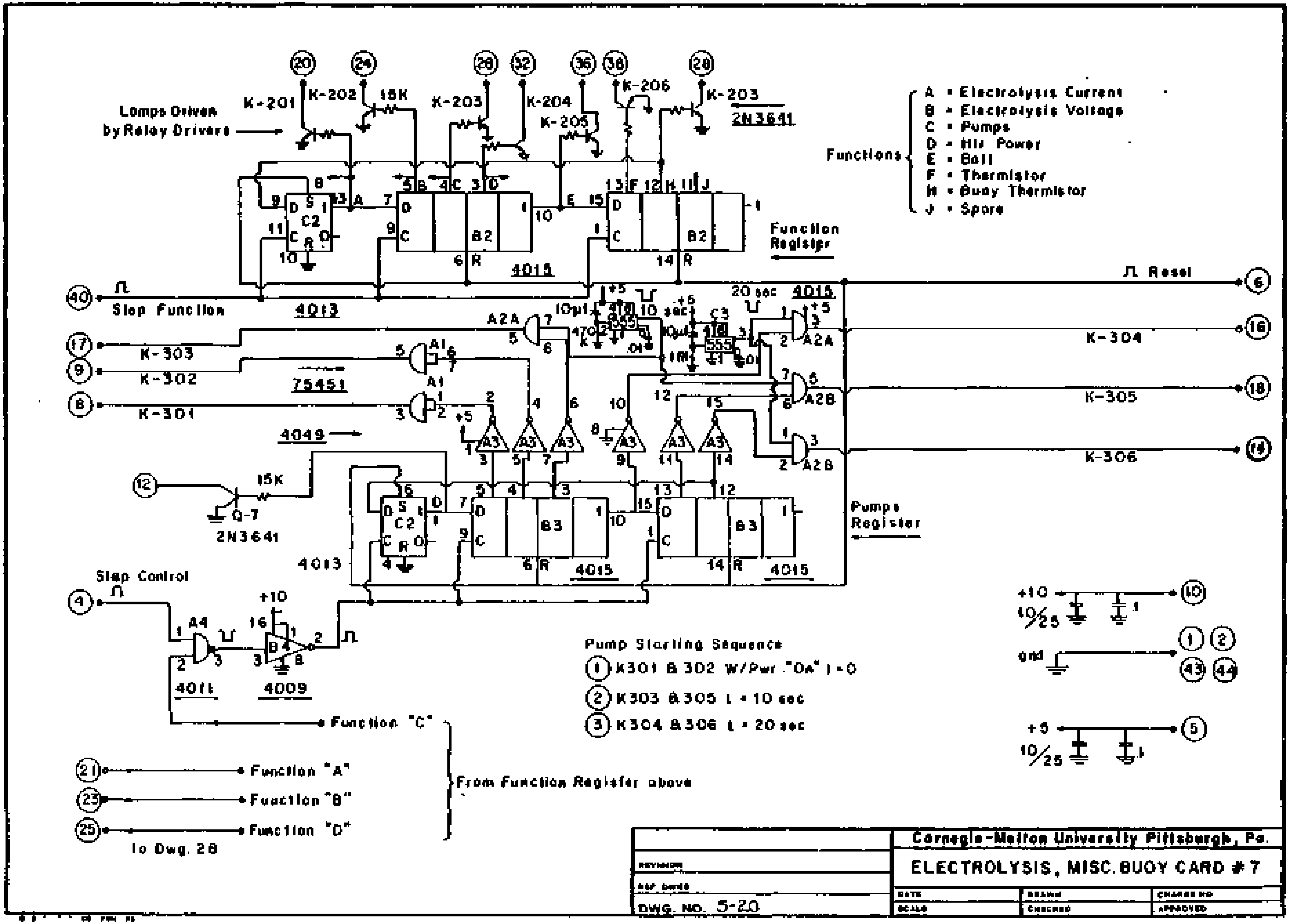
Form 106

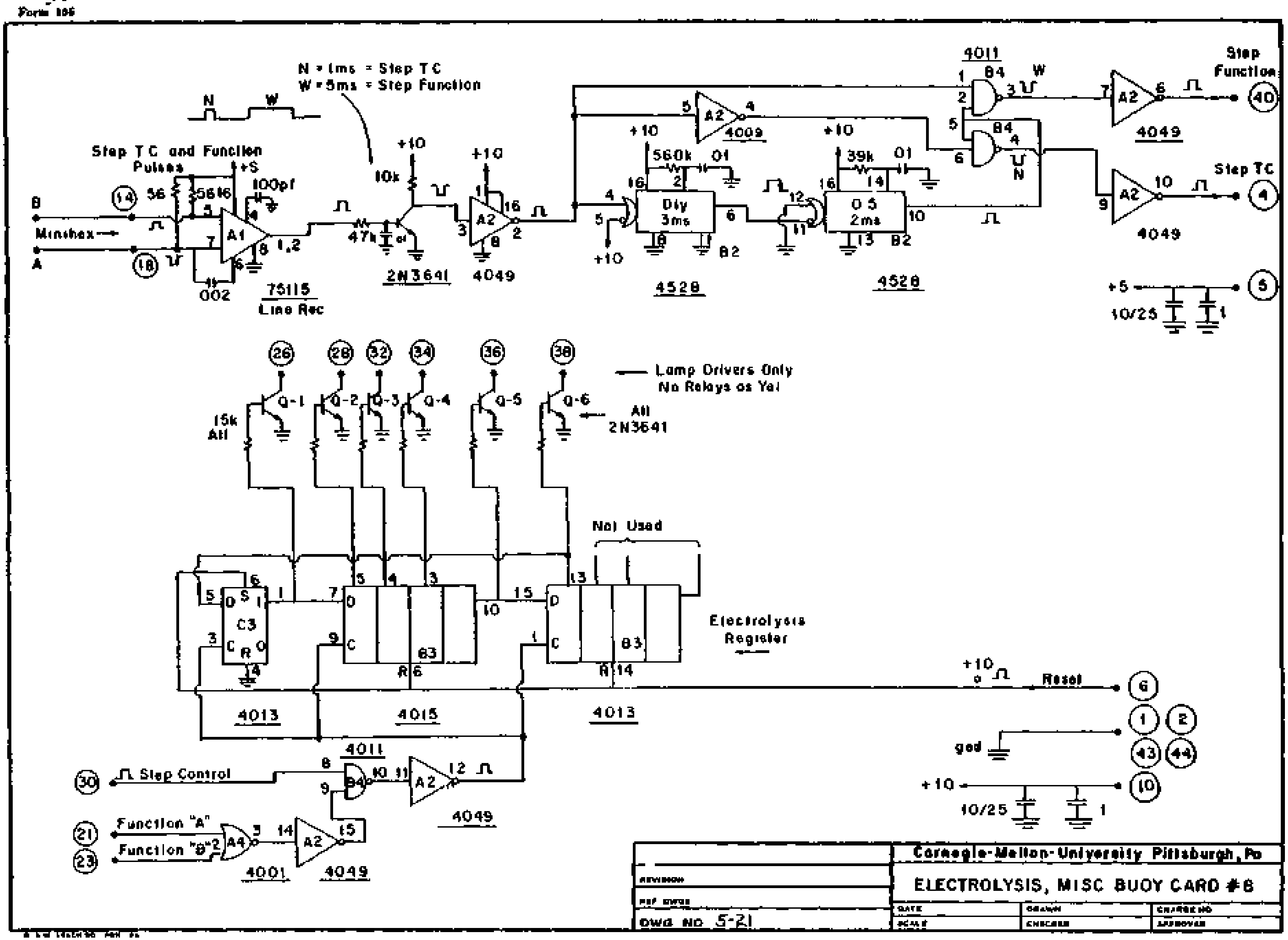



| | |
|---|---|
| | Carnegie-Mellon University Pittsburgh, Pa. |
| REVISION | FLOW-METER MUX-BUOY<br>CARD #5 |
| REF DWGS | DATE / DRAWN / CHANGE NO |
| DWG NO. 5-18 | SCALE / CHECKED / APPROVED |

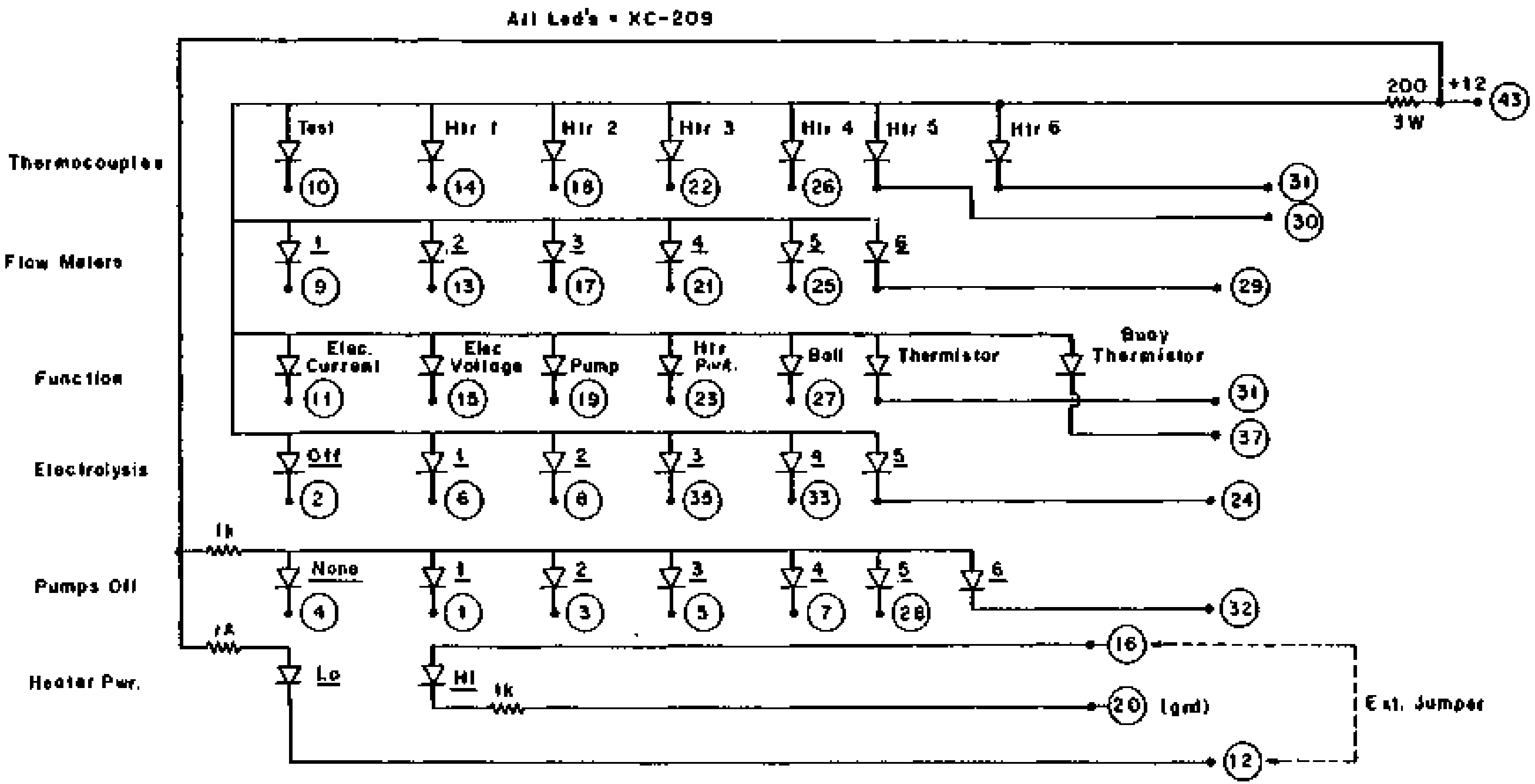


Jumpers on Card
Elect. Current
Elect. Voltage
Buoy Thermistor & Pumps
One Half Flowmeter Pwr Supply
Pipe Thermistor From Card 4
K 201
K 202
K 203
Htr Pwr
K 204
K 205
K 206
500
50K
Bal
1K
150K
Check Thermistor Calib Here
0 to -10 V
Gain Set
Trim
VF Conv DY 610
Misc. Data To Coax
Clock
Note: Offset at Amp Output Set at -27 mV. Oct. 16
~Note~
When "Function" is set on "Heater Power," ½ Flowmeter Power Supply is read onto the Misc. Data line to the beach if F.M. #1 is selected.
Reed Relays
K 201
K 202
K 203
K 204
K 205
K 206
All 1N3070
-15V
470
500
100
2N3638
1.1K
1.1K
1.1K
Pins 27 & 29 Go To Pins 5 & 6 of TS-5 (Thermistor)
Veco 31A2
Buoy Thermistor
1.033K @ 21°C
10 mV./Deg C. Change
+5V
+15V
-15V
GND
Carnegie-Mellon University Pgh
Electrolysis, Misc. Multiplexer
Buoy Card #6
DWG NO 5-19


Lamps Driven by Relay Drivers
K-201
K-202
15K
K-203
K-204
K-205
K-206
2N3641
Functions
A = Electrolysis Current
B = Electrolysis Voltage
C = Pumps
D = HIr Power
E = Ball
F = Thermistor
H = Buoy Thermistor
J = Spare
Function Register
4015
4013
Step Function
Reset
K-303
K-302
K-301
75451
4049
K-304
K-305
K-306
555
20 sec
10 sec
2N3641
Q-7
Pumps Register
Step Control
A4
4011
4009
Function "C"
Function "A"
Function "B"
Function "D"
From Function Register above
To Dwg. 28
Pump Starting Sequence
(1) K301 & 302 W/Pwr "On" t = 0
(2) K303 & 305 t = 10 sec
(3) K304 & 306 t = 20 sec
gnd
Carnegie-Mellon University Pittsburgh, Pa.
ELECTROLYSIS, MISC. BUOY CARD # 7
DWG. NO. 5-20


Form 106
N = 1ms = Step TC
W = 5ms = Step Function
Step TC and Function Pulses
Minshex
75115
Line Rec
2N3641
4049
4528
Dly 3ms
OS 2ms
4011
4009
Step Function
Step TC
Lamp Drivers Only
No Relays as Yet
15k All
All 2N3641
Not Used
Electrolysis Register
Reset
4013
4015
gnd
Step Control
Function "A"
Function "B"
4001
Carnegie-Mellon-University Pittsburgh, Pa
ELECTROLYSIS, MISC BUOY CARD #8
REVISION
REF DWGS
DWG NO 5-21
DATE
SCALE
DRAWN
CHECKED
CHARGE NO
APPROVED

Form 105

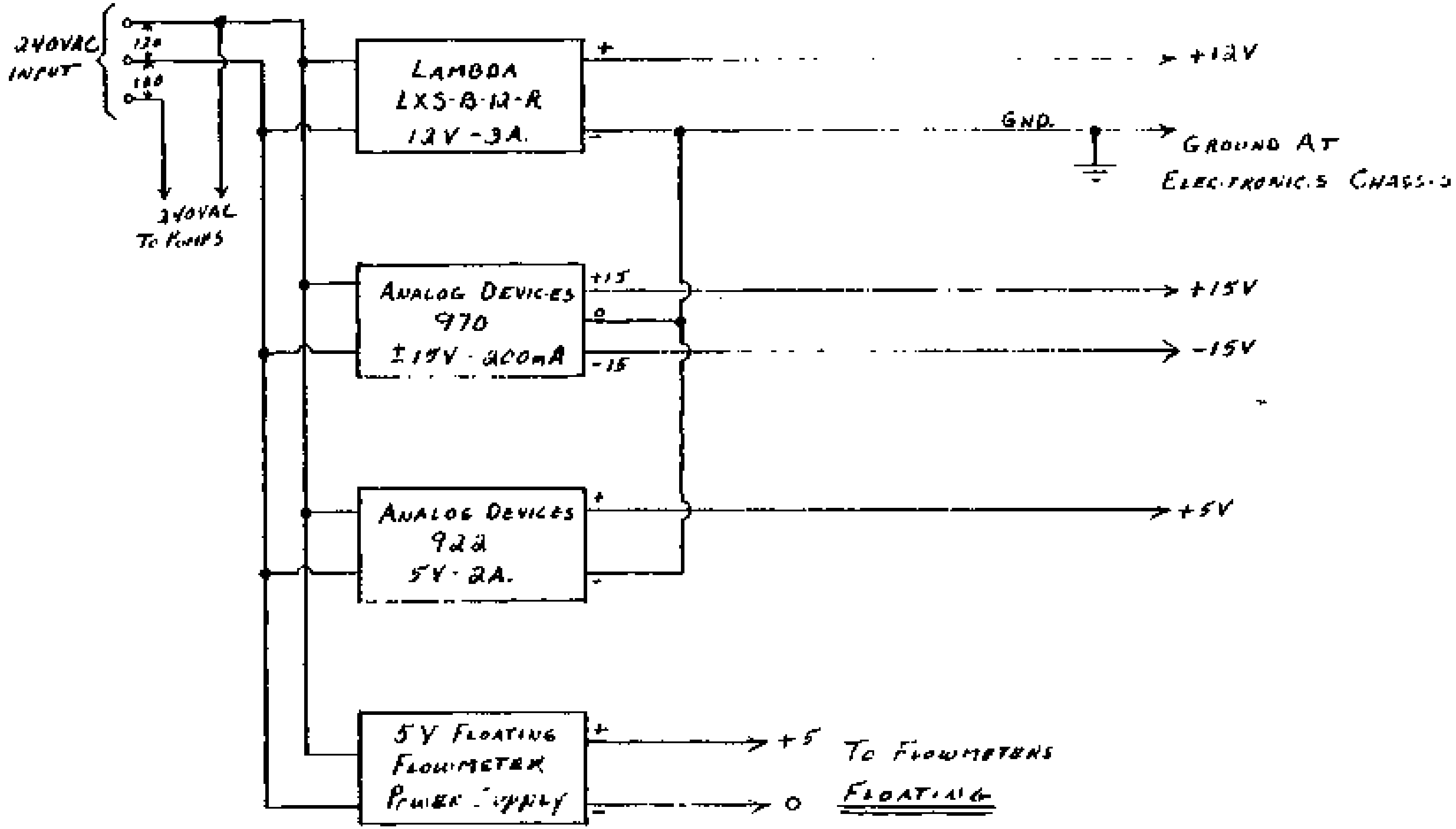



Left-Most Lamps in each Row Should Light on Power Turn-on

Sequence Should Advance in Step with Lamps on Beach Control Unit.

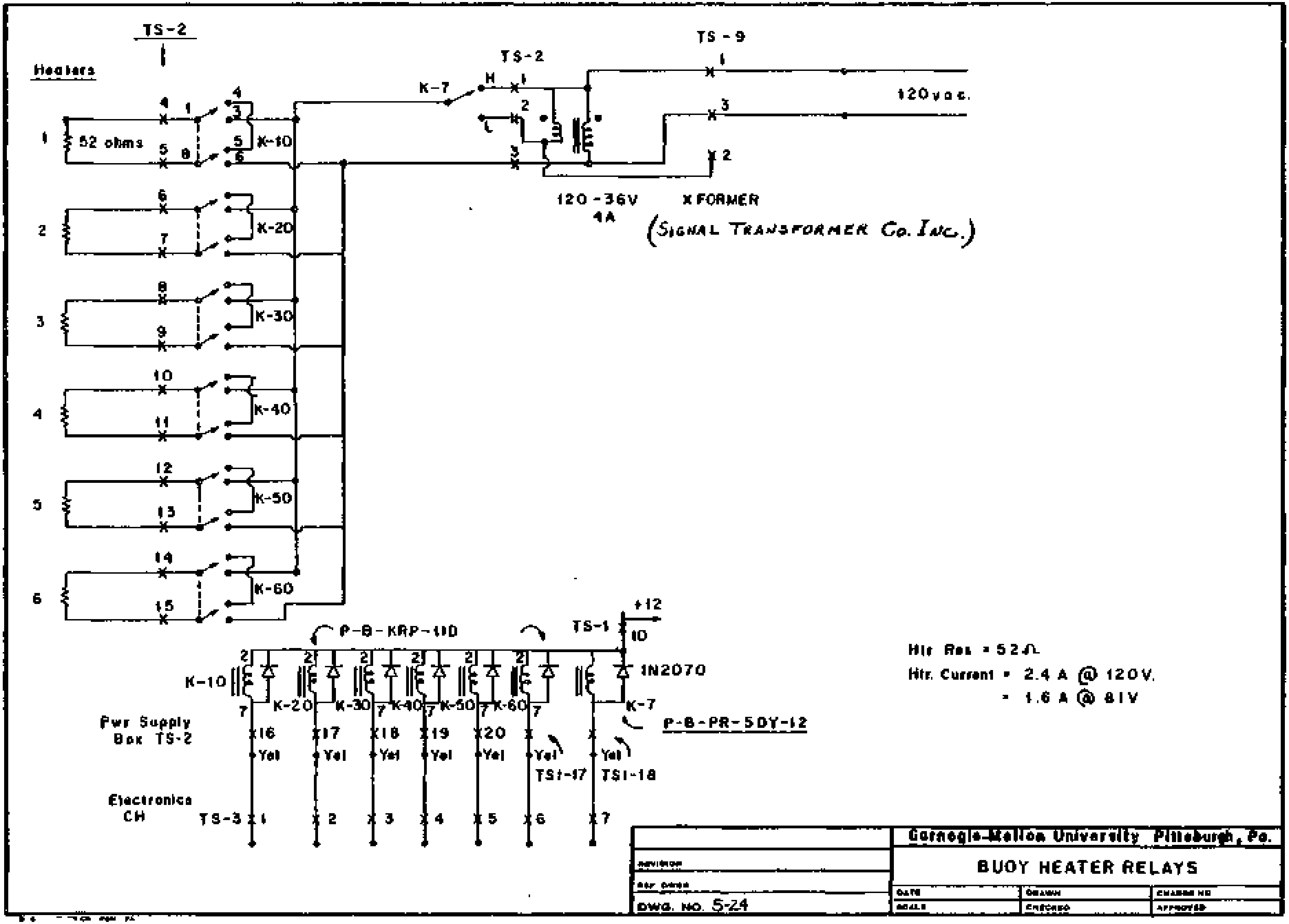
| | |
|---|---|
| REVISION | Carnegie-Mellon University Pittsburgh, Pa. |
| REF. DWGS | LED TEST CARD (BUOY) CARD #10 |
| DWG. NO. 5-22 | DATE / DRAWN / CHARGE NO. / SCALE / CHECKED / APPROVED |

Form 145

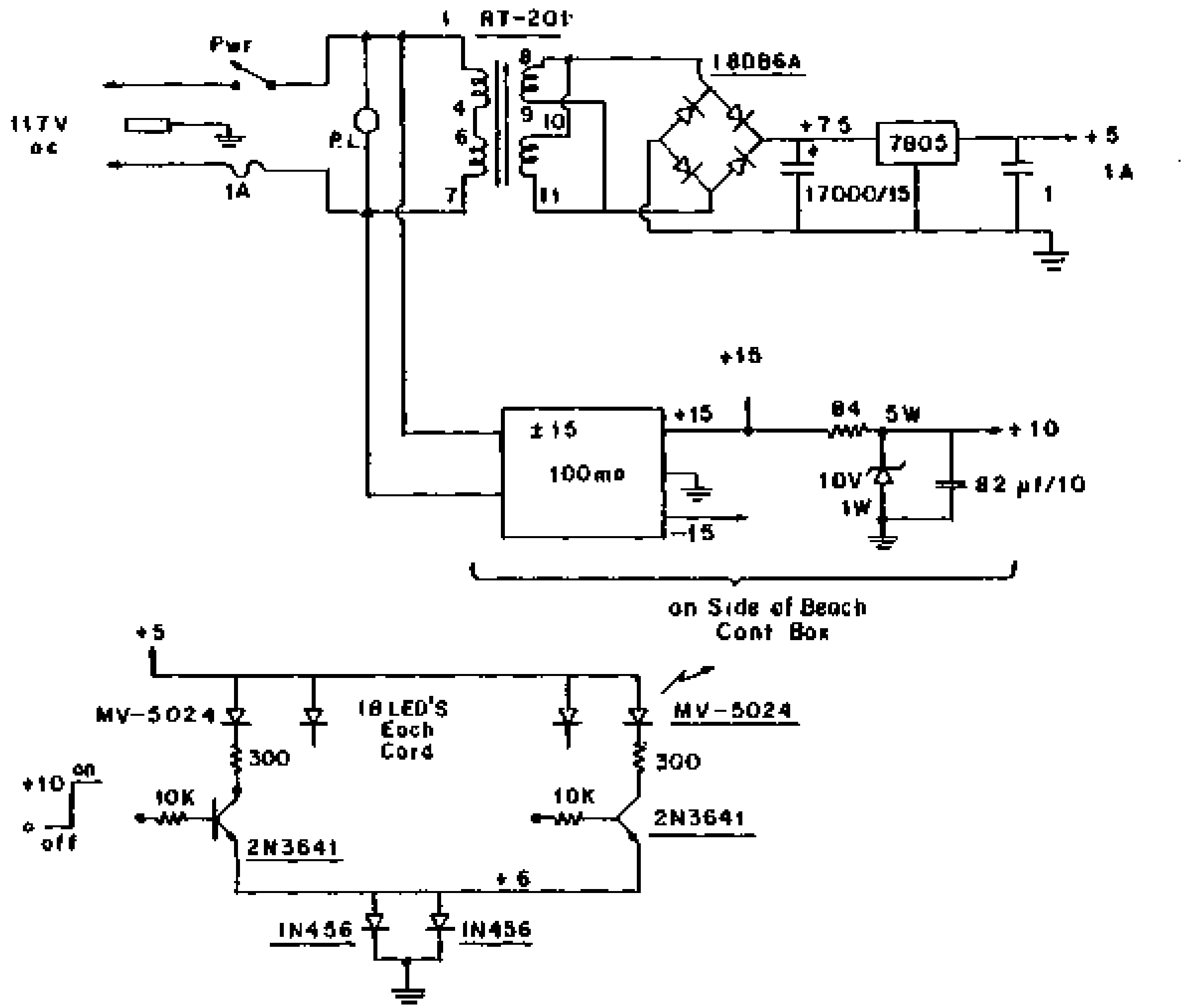



| | |
|---|---|
| | CARNEGIE-MELLON UNIVERSITY Pgh. Pa |
| REVISION | Buoy Power Supplies |
| REF DWGS. | DATE / DRAWN / CHARGE NO. |
| DWG. NO. 5-23 | SCALE / CHECKED / APPROVED |

Form 106


TS-2
Heaters
52 ohms
K-7
TS-2
TS-9
120 v.a.c.
K-10
K-20
K-30
K-40
K-50
K-60
120-36V 4A
X FORMER
(Signal Transformer Co. Inc.)
P-B-KRP-11D
TS-1
+12
1N2070
K-7
P-B-PR-5DY-12
Pwr Supply Box TS-2
Yel
TS1-17
TS1-18
Electronics CH
TS-3
Htr Res = 52 Ω
Htr. Current = 2.4 A @ 120V.
= 1.6 A @ 81V
Carnegie-Mellon University Pittsburgh, Pa.
BUOY HEATER RELAYS
DWG. NO. 5-24

Form 104



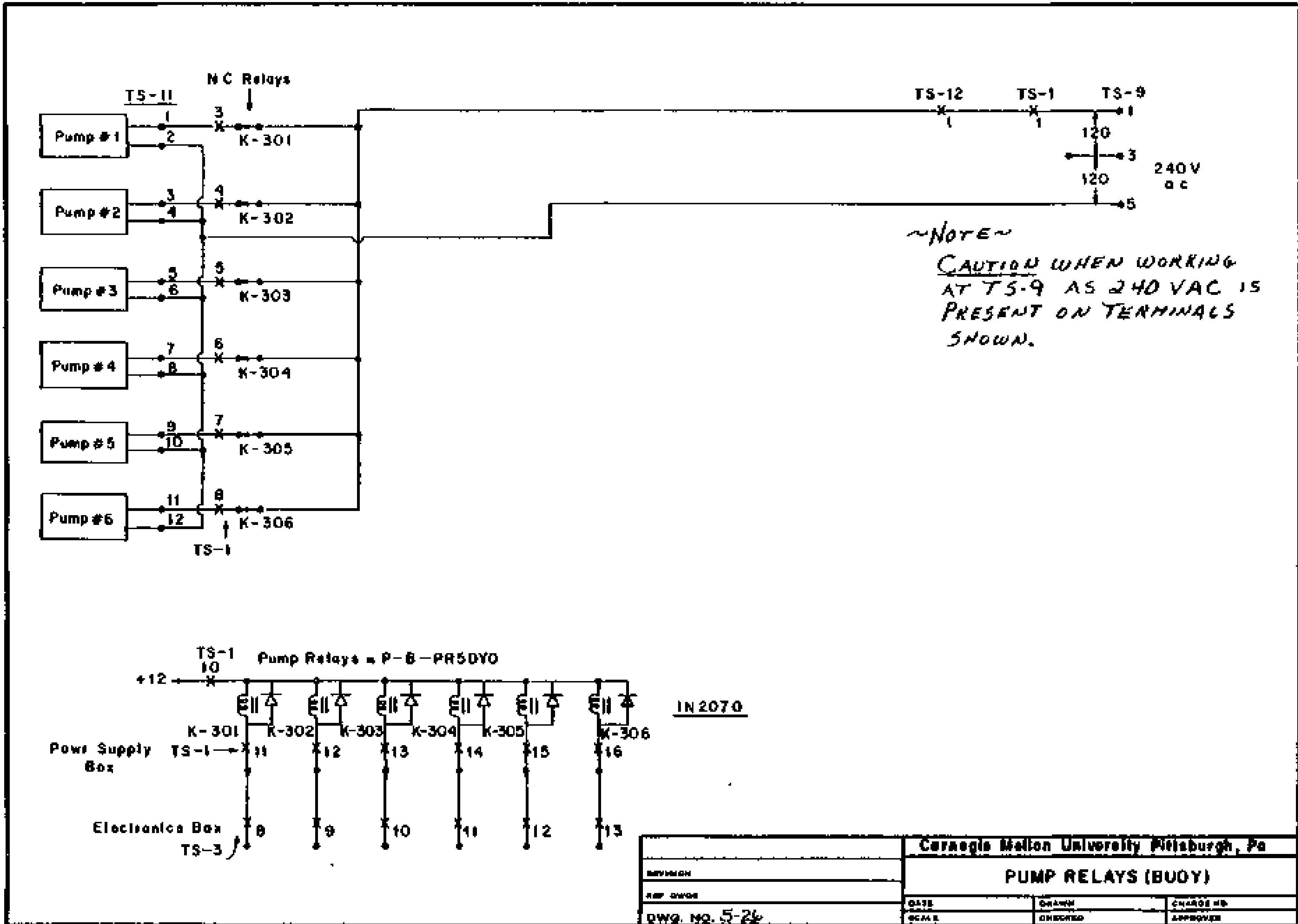

Carnegie-Mellon University Pittsburgh, Pa

BEACH CONTROL POWER SUPPLY, LAMP DRIVERS

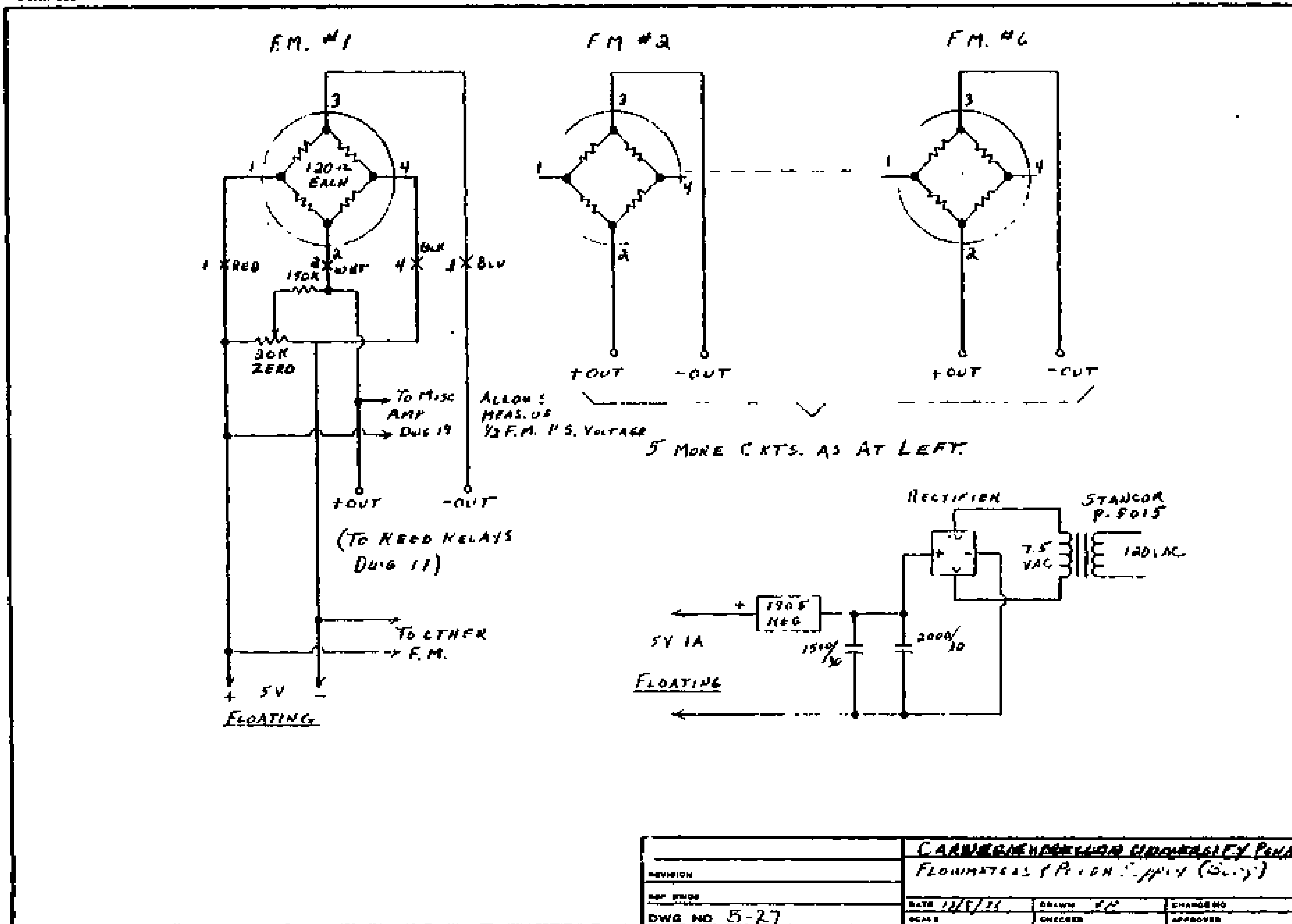
| REVISION | DATE | DRAWN | CATALOG NO |
|---|---|---|---|
| REF. DWG. | SCALE | CHECKED | APPROVED |

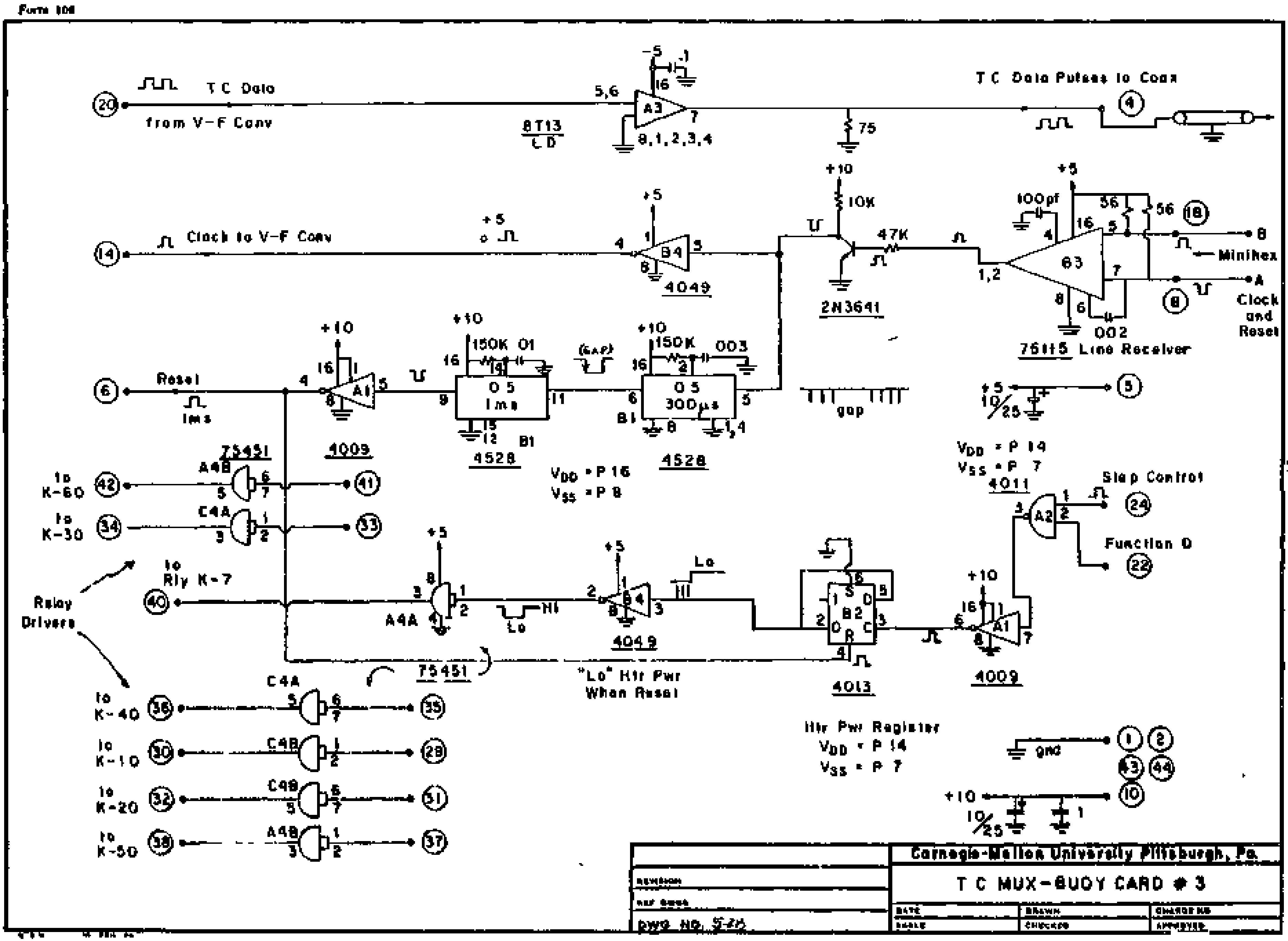
DWG. NO. 5-25

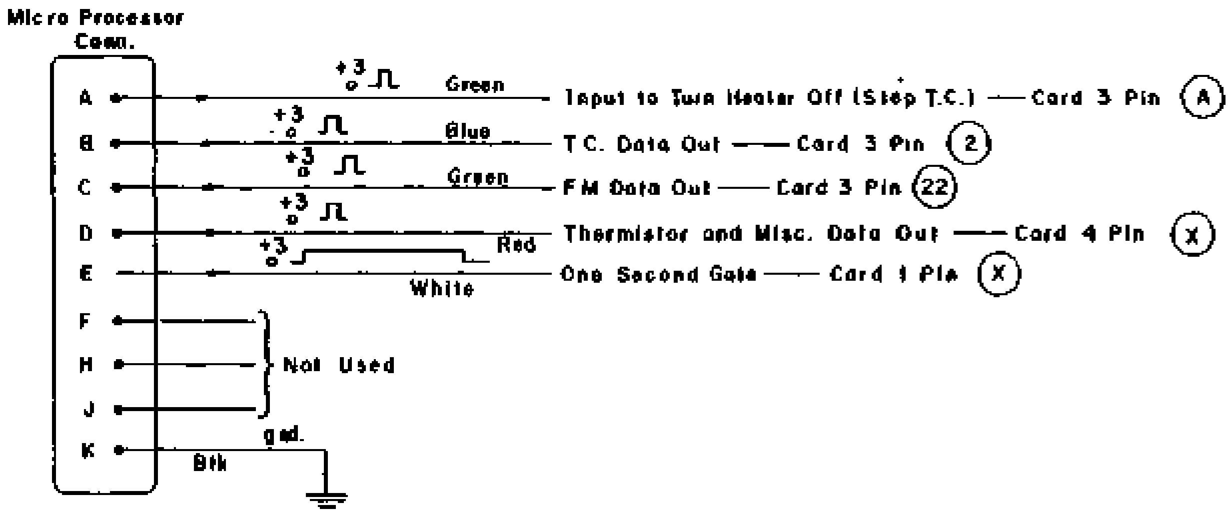
Form 166


N C Relays
TS-11
Pump # 1
Pump # 2
Pump # 3
Pump # 4
Pump # 5
Pump # 6
K-301
K-302
K-303
K-304
K-305
K-306
TS-1
TS-12
TS-1
TS-9
120
120
240 V
a c
~NOTE~
CAUTION WHEN WORKING AT TS-9 AS 240 VAC IS PRESENT ON TERMINALS SHOWN.
TS-1
10
Pump Relays = P-B-PR5DYO
+12
IN 2070
K-301
K-302
K-303
K-304
K-305
K-306
Powr Supply Box
TS-1
Electronics Box
TS-3
Carnegie Mellon University Pittsburgh, Pa
PUMP RELAYS (BUOY)
DWG. NO. 5-26

Form 106


F.M. #1
FM #2
F.M. #6
120Ω EACH
1 RED
2 WHT
4 BLK
3 BLU
150K
20K ZERO
To Misc Amp Dwg 19
Allows meas. of ½ F.M. P.S. Voltage
+OUT
-OUT
(To Reed Relays Dwg 11)
To other F.M.
+ 5V -
FLOATING
5 MORE CKTS. AS AT LEFT.
RECTIFIER
STANCOR P-8015
7.5 VAC
120 VAC
309 REG
1500/30
2000/30
5V 1A
FLOATING
DWG NO. 5-27


T C Data
from V-F Conv
8T13
LD
T C Data Pulses to Coax
Clock to V-F Conv
4049
2N3641
75115 Line Receiver
Minihex
Clock and Reset
Reset
1ms
4009
4528
O S 1ms
O S 300µs
gap
VDD = P 16
VSS = P 8
VDD = P 14
VSS = P 7
4011
Step Control
Function 0
75451
Relay Drivers
to Rly K-7
to K-60
to K-30
to K-40
to K-10
to K-20
to K-50
"Lo" Htr Pwr When Reset
4013
Htr Pwr Register
GND
Carnegie-Mellon University Pittsburgh, Pa.
T C MUX-BUOY CARD # 3




This Conn on Rear of Beach Control

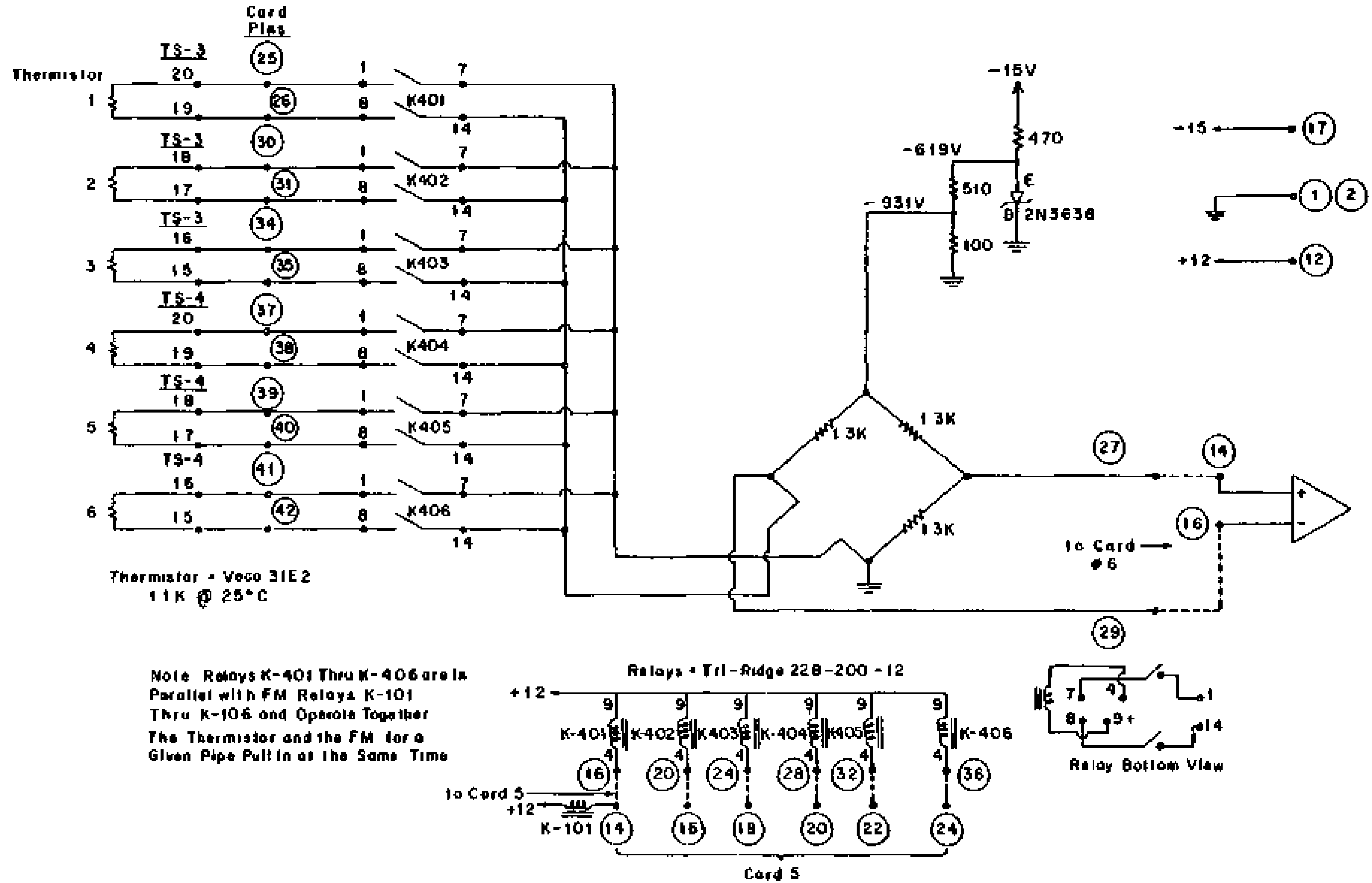
**Carnegie-Mellon University Pittsburgh, Pa.**

MICRO- PROCESSOR CONNECTIONS

| DATE | DRAWN | CHANGE NO. |
|---|---|---|
| SCALE | CHECKED | APPROVED |

DWG NO. 5-29

Form 108




Carnegie Mellon University Pittsburgh, Pa

PIPE THERMISTOR BRIDGE
CARD #9 (BUOY)

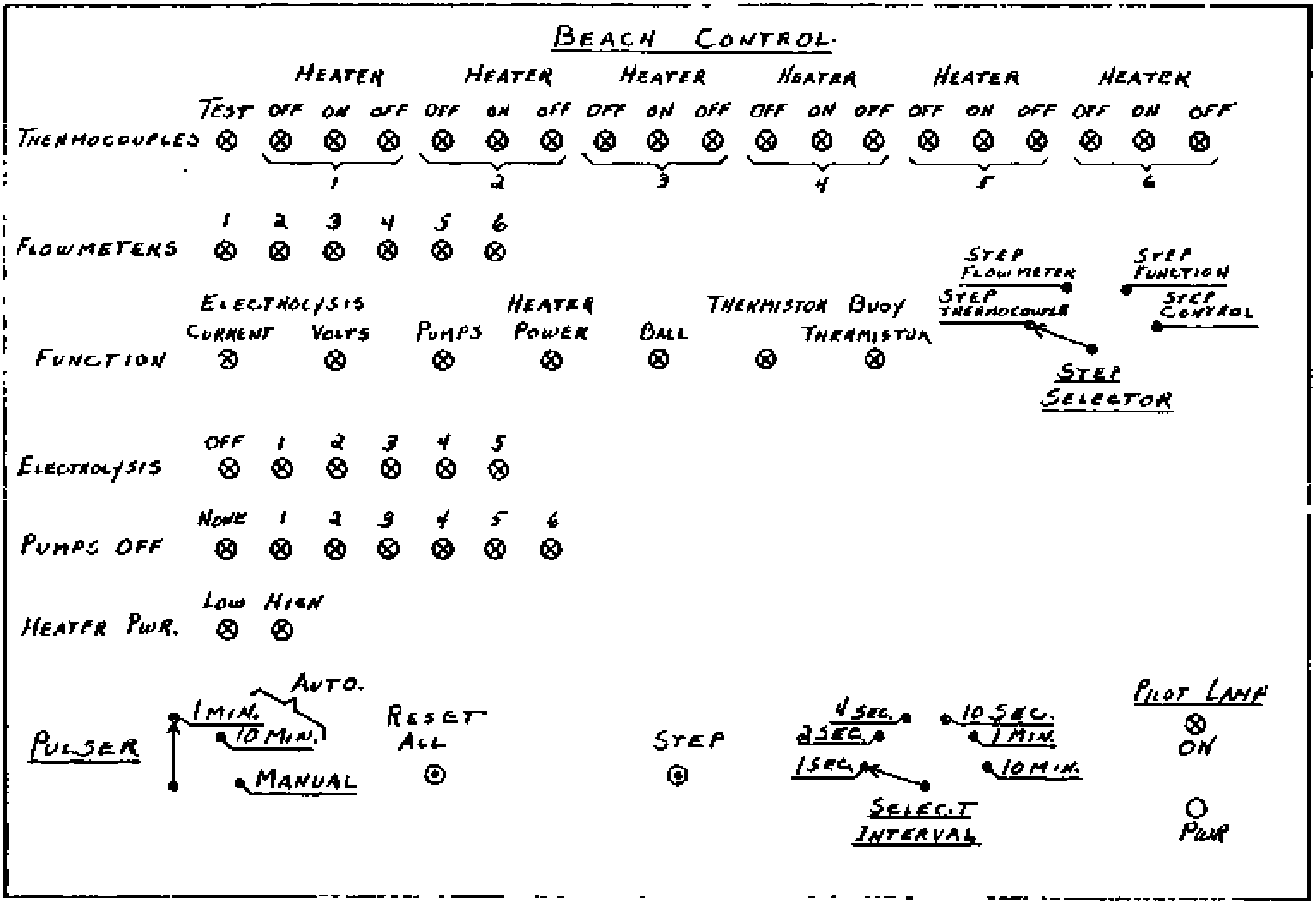
| | | |
|---|---|---|
| DATE | DRAWN | CHANGE NO |
| SCALE | CHECKED | APPROVED |

REVISION

REF DWGS

DWG NO 6-30

Form 106




| | |
|---|---|
| REVISION | CARNEGIE-MELLON UNIVERSITY PGH. PA. |
| REF SHEET | BEACH CONTROL FRONT PANEL |
| DWG. NO. 5-31 | DATE 12/9/72 · DRAWN KB · CHANGE NO. · SCALE · CHECKED · APPROVED |

## 6. OPERATING PROCEDURE

6.1. General. In operating the biofouling test apparatus described in this report, we have used two different electronics systems. It is very likely that different electronics systems will be employed in other circumstances in the future. For this reason, we describe here our operating procedures in sufficiently general terms so that they may be adapted to any electronics systems likely to be used. In addition, however, as one example of a specific operating procedure, we describe in complete detail the procedures used in the field aboard a moored boat during the summer of 1976. This is done in Appendix E. The electronics system in use at that time is that described in Sec. 5.

6.2. Preliminary Laboratory Checks and Calibrations. Each unit built according to the design of Sec. 4 was subjected to a series of tests in the laboratory before deployment in the field. First, each PVC instrument housing and pump housing was checked for vacuum leaks using a helium leak detector. Also, one instrument housing and one pump housing were pressure tested under over three atmospheres of external pressure (corresponding to a potential submergence depth of 100 feet), after which vacuum tests were again performed to confirm continued integrity against leaks.

In these tests, no evidence of a leak problem ever surfaced. This confirms our feeling that the seal designs are such that leaks are very unlikely when the apparatus is constructed according to the specifications of Sec. 4. Because of this we plan not to do such extensive testing on future units (however, occasional spot-testing will continue).

Naturally, if the units are not to be operated submerged, these leak and pressure tests are in any case not necessary. An instrument housing should still be used, however, both to protect the instruments from corrosive salt spray and to minimize sensitivity of the instrumentation to variable ambient conditions (temperature, wind, sunlight). In such a case, of course, the housing need not be as sturdy as that described in Sec. 4.

Several simple checks are made on the heat transfer instrumentation.

a) Check that no thermopile junctions are shorted electrically to the copper cylinders into which they are potted (resistance >10 megohm).

b) Check that the heater winding is not shorted to the copper cylinder (resistance >10 megohm).

c) Check for continuity of the heater winding (resistance ≅ 53 ohms).

d) Check that the thermopile responds to the application of heater power and yields approximately the correct output (0.57 mV/°C).

In the next step, the test unit is mounted on a stand (without the PVC housing, for convenience) and connected to a pump and a water reservoir so that water can be pumped through the unit, at controlled velocities, for calibration. This setup is described in detail in Sec. 3. Two calibrations are done.

The flow meter is calibrated. This may be done in several ways. One is to run the flow meter in series with another, previously calibrated one (we have used a rotameter type for this purpose). We have also calibrated just by running the pump effluent into a previously calibrated container (a plastic trash can is very good), and timing the fill.

Finally we test that the system as a whole is correctly measuring heat transfer rates. This is done by measuring the heat transfer coefficient (h) at five to eight velocities from 2 to 10 feet/sec. Then we plot these points ($1/h$ vs. $v^{-0.8}$). If the system is working properly, the data should fall on a straight line with a slope of $3.44 \times 10^{-3}$ (h in units of BTU/hr ft$^2$°F, and v in ft/sec.). Results of such tests are discussed in Sec. 3.4 (Figs. 3-3, 3-4, 3-5).

6.3. Data-Taking Procedures. A simplified block diagram of a complete data acquisition system is shown in Fig. 6-1 (for design details of two such systems, see Sec. 5 and Appendix D). Here, the thermistor signal (TM) measures the temperature of the water passing through the tube (this does not need to be accurately known). The flow meter signal (FM) measures the velocity of flow. The thermocouple signal (TC) measures the temperature of the (heated) copper cylinder relative to the flowing water temperature. These three signals are sequentially switched by the SCANNER to the digital voltmeter (DVM) for measurement (after amplification if necessary to match the input requirements of the DVM). The scan rate of the SCANNER is usually set to 2 sec. per channel because the teletype unit (TTY) cannot handle data more rapidly. The digital voltage reading output by the DVM is fed to the TTY by the interface circuit (IF). The TTY then prints the data and produces a punched paper tape record. The paper tape is subsequently read by a computer for analysis. (There are, of course, other ways for handling and storing the data. See Sec. 7 for examples.)

The normal procedure for taking a cooling curve (measuring a heat transfer coefficient) is as follows.

a) Initialize the system. Switch on all the electronics (Fig. 6-1). Read the TM, TC and FM to verify that the system is normal.

b) Switch on the heater power to heat the copper cylinder above the water temperature.

c) Set the scanner so that the TM, FM and TC signals are sequentially recorded by the TTY.

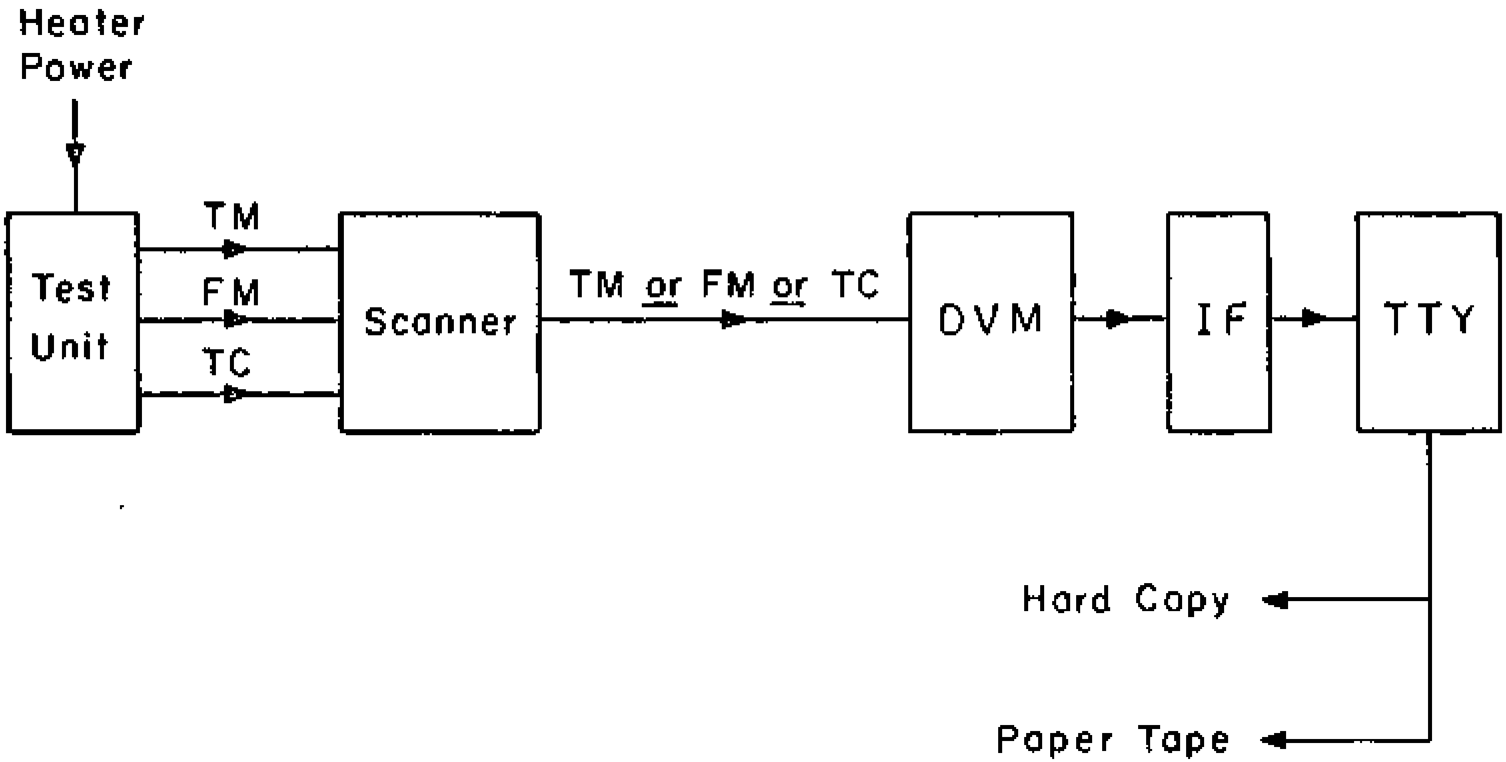



Figure 6-1. Block Diagram of a Data Acquisition System in the Lab.

d) When the copper cylinder is warm enough, switch off the heater power. The TTY is now recording the cooling curve (TC signal) as well as monitoring the flow velocity (FM) and the water temperature (TM). (The temperature at which the heater power is turned off is discretionary. It will be determined by the nature of the studies being done. In the work so far done with this system it has been in the range 1°F-2°F. In OTEC-related work it is presumably never necessary to go above ~10°F. If temperatures very much above this were used, one should be watchful of possible deterioration of the insulation materials used on the heater. At the other extreme, if temperatures less than ~0.1°F are used, the precision of determination of h might be be affected. (See Sec. 3 for more discussion.)

e) Allow the data recording to proceed for a time equal to 10 time-constants after switching off the heater power. Stop the recording system.

Normally, this procedure is repeated a number of times in order to check repeatability under identical conditions, and also to increase the precision of the result. When heat transfer rates in an ocean environment are being recorded, our practice has been to try to get at least 12 such cooling curves in one day.

6.4. Data Analysis. The data analysis, in the main, centers around the two computer programs HTAU and LABTTF. These are discussed in Sec. 2 (listings and other details in Appendix B and C). The program HTAU is used (before any data are taken) to determine the relationship between a measured time constant ($\tau$), and the corresponding heat transfer coefficient (h), for the test unit in question. The input to HTAU are the geometric and thermal characteristics of the system (dimensions, heat capacities, thermal conductivities). The output are the numerical values of the constants A, B, C and D in the relation $\ln(h) = A+B(\ln\tau)+C(\ln\tau)^2+D(\ln\tau)^3$.

The program LABTTF is used to fit an exponential function to the cooling curve taken with the apparatus. The fit yields a value of $\tau$ which, combined with the above equation, determines the heat transfer coefficient.

The normal procedure in the data analysis, then, is (assuming HTAU has already been run for the unit being used, and the values A, B, C, D input into LABTTF, along with other unit-dependent data) as follows.

a) Convert the TTY tape to cards for input to LABTTF.

b) Run LABTTF to get h.

c) Make standard checks on LABTTF output. (Among other things, LABTTF provides the average values of the water flow velocity and the water temperature, as well as the rms deviations of the readings from their averages, during the data-taking interval. As shown in Sec. 2 (Fig. 2-3 ), sudden variations in sea water temperature are sometimes seen. (If this occurs during the data analysis interval, the result for $\tau$ has larger-than-usual errors. To eliminate this source of error, we reject data sets if the TM rms deviation is greater than 0.01°C. We would similarly reject the data if we found very large variations in the water flow velocity. However, in spite of the fact that data were taken on a very "lively" rolling boat, velocity variations were never more than 1-2%. We have never had to reject for velocity variations. Reject data if TM rms deviation is greater than 0.01°C, or if $\chi^2$ per degree of freedom, for the exponential fit, is greater than 100.)

d) Correct the value of $1/h$ to the value corresponding to $v_o$ if $v \neq v_o$. (Here, v is the average water flow velocity during this measurement, and $v_o$ is the corresponding value at the time the unit was started pumping. The pump might have been started weeks or even months earlier. As the fouling in the system builds up, the velocity, v, slowly decreases. Since h depends upon v, we cannot compare the present h with its initial value, $h_o$, unless they correspond in velocity. We correct the value of $1/h$ to the initial velocity by using the previously determined slope of the $1/h$ vs. $v^{-0.8}$ function, as discussed in Sec. 6.2, last paragraph.)

e) Calculate the thermal resistance of the fouling layer (inverse of the heat transfer coefficient of the fouling layer)

$R_f = 1/h - 1/h_o$.

By following this procedure while sea water is continuously pumped through the tube under test, the growth of the fouling layer (and its effect on heat transfer) can be followed over any desired length of time.

# 7. MODIFICATIONS AND IMPROVEMENTS

7.1. Introduction. The experience gained during the design, construction, laboratory testing and, finally, field use of the apparatus discussed in this report has lead us to develop ideas for various modifications in the design which will improve its performance or simplify its use. We discuss these in 7.2, below.

Also, it is recognized that there are likely to be many applications for a system like this which do not require submerged or remote operation. In such circumstances, the apparatus can be simplified in several ways. These are discussed in Sec. 7.3.

Finally, this apparatus was designed to allow the determination of thermal resistances of fouling layers (i.e., to measure differences in 1/h) to high precision. There will be situations when only ordinary precision is required. In such cases further simplifications are possible. These are discussed in Sec. 7.4.

We have not tested the modifications discussed in this section, and so we cannot describe specific designs in detail. The ideas presented here, rather, are general and meant to be helpful to others who wish to build a similar system to be used in different circumstances. Our intent is to indicate broadly what sorts of modifications might be feasible and useful under various conditions, and to give some idea what their effects might be.

7.2. General Modifications and Improvements. There are three specific areas in which important improvements of the system suggest themselves. The first is to increase ease of assembly and disassembly. There are various design changes under consideration to this end. Since we have not yet completed these designs, we will not comment further here.

A second possible improvement is in the method of measuring the flow velocity. The flow meter being used in the present design was the best available (to our knowledge), when the system was being designed, from the points of view of precision, relative insensitivity to fouling and insensitivity to corrosion. Recently we have located a new (sonic) device which measures flow velocity without coming in contact with the flowing water. Apparently, then, it is immune both to fouling and corrosion. We have not yet fully determined whether its characteristics are such as to meet all our requirements for a flow meter, and therefore we do not now discuss it in detail.

Finally, there are obvious ways to increase the ease of operation of the system. In particular, we are now in the process of completing the development of a microprocessor system to add to the hardware. This will have two important results. First, the data taking can be (almost) completely automatic, requiring very little human intervention. This means that essentially one full-time man (the data taker) can be removed from the support crew. We expect also that the reduced level of human intervention will result in fewer mistakes. Second, the microprocessor is being coded to analyze the data as it comes in. This has several important consequences. The results of any given run will be immediately available for checking. Also, a great deal of manpower will be saved due to reduced data handling requirements (we eliminate the need to generate a paper tape, generate cards from the tape, and run the fitting program).

7.3. Non-Submerged, Non-Remote Operation. In applications not requiring submerged, remote operation the mechanical design can be much simplified. The instrument housing does not have to be leak-tight and resistant to high pressure. Thus it can be made much lighter and correspondingly simpler to build and assemble. The electronics could be much simpler in that complex multiplexing would not be required (see App. D). In general, access, maintenance and control can be much simplified.

7.4. Operation With Lower Precision. The discussion in Sec. 3 implies that the apparatus is capable of measuring differences in 1/h to better than 0.5% under appropriate conditions, and that this precision is probably limited by the measurement of flow velocity, not temperature. There may be many situations in which much less precision (say 5%-10%) is acceptable. In such cases certain design simplifications are possible.

For one, we could reduce the temperature measurement sensitivity by an order of magnitude. For ~5% precision, then, we could use a single pair of junctions instead of 11 pairs.

Another possibility is to reduce the axial length of the copper heater cylinder (and so simplify construction and assembly). Thus, for example, we could reduce the length from 12 inches to, say, 1-1/4 inches (an order of magnitude). This would have little effect on the time constant, or its precision of measurement. Rather, the primary effect would be on the accuracy of the correction for heat leak by conduction axially along the tube wall from the copper cylinder. In the present design, this correction is ~5% and is calculated to better than 10% of itself. That is, the error in measuring h due to error in the calculated correction is believed to be less than 0.5%. If the length of copper is reduced by a factor of 10, the correction rises to ~50%, and its contribution to the error in h rises to near 5%.

Instead of reducing the length of the copper heater cylinder, we might consider reducing its outer diameter. Suppose this was done so that the total mass of copper was reduced by a factor of 10. The principal effect of this would be to reduce the time constant of the cooling curve by a factor of 10, so that instead of typical clean-tube values of ~45 sec, it would be 4.5 sec. There are several effects of this change to consider. First, the precision of time measurement is relatively less. However, since timing is done with a quartz crystal which has very much more precision than needed anyway, this has no effect. Second (if we sample the data at the same rate), we measure the temperature one tenth as many times in a cooling curve. This would lead roughly to a loss of a factor of 3 (i.e. $\sqrt{10}$) in precision of the temperature decay rate. But, since the precision of temperature measurement is not now limiting (the flowmeter is), this will not have much effect on the precision of determination of h (it would probably still be good to 1-2%). Finally, cutting down the OD of the copper cylinder will further remove the geometry from the ideal of perfect cylindrical symmetry. The clamping bolts, the heater windings and insulation, the thermocouple holes, and the thermocouples themselves now become a much larger fraction of the total geometry. These effects are difficult to calculate, and we have not estimated the changes in precision of measurement.

A significant advantage, of course, to reducing the time constant in this way is that it correspondingly reduces the amount of data to be handled as well as the time required to take data.

Finally, one could reduce the heater power (and temperature rise) by a factor of 10 (to ~10 watts and ~0.1°F-0.2°F). This would increase the error in h, we estimate, to only ~2%.

Note that the numbers used here are chosen merely to illustrate the magnitudes involved, and do not represent recommendations. It should also be understood that any such changes will probably involve (possibly major) changes in other parts of the system design.

# APPENDIX A. DETAILED THEORY

## A.1. Introduction

In this appendix we develop in detail the mathematical analyses of a two-medium system having the geometry of Fig. 2-2. The heat flow equation is solved leading to the equations, necessary for determining h from a measured value of $\tau$, used in the program HTAU (App. B).

The analysis is done exactly for the situation in which heat flow is truly radial. A correction for axial conduction along the pipe wall is separately calculated.

## A.2. Two-Medium System

Consider the two-medium system depicted in Fig. 2-2. We assume that it is cylindrically symmetric and all heat flows radially. This permits us to assume that the temperature distributions in regions a and b are functions only of radius r, and time t (Subscripts a and b refer to pipe and copper block).

The system is designed so that $T_{air}=T_{water}$. The equations below are written using a temperature scale in which $T_{air}=T_{water}=0$.

Under the above assumptions, the heat flow equation may be written

$$\frac{1}{r}\frac{\partial}{\partial r}\left[r\frac{\partial}{\partial r}T(r,t)\right] = \frac{1}{\alpha}\frac{\partial}{\partial t}T(r,t) \qquad \text{(A-1)}$$

where $\alpha = \frac{k}{c\rho}$, k is the heat conductivity in the medium, c the specific heat, and $\rho$ the density.

Since this equation holds for both regions a and b, this means the general solution will take the form:

$$T(r,t) = \begin{cases} T_a(r,t) & \text{for} \quad r_1 \le r \le r_2 \\ T_b(r,t) & \text{for} \quad r_2 \le r \le r_3 \end{cases}$$

Separation of variables in Eq. A-1 leads to solutions in terms of Bessel functions:

$$T_a(r,t)=\left[A_aJ_o(\lambda_a r)+B_aY_o(\lambda_a r)\right]e^{-\alpha_a\lambda_a^2 t}$$

$$T_b(r,t)=\left[A_bJ_o(\lambda_b r)+B_bY_o(\lambda_b r)\right]e^{-\alpha_b\lambda_b^2 t}$$

$$\alpha_a=\frac{k_a}{\rho_a c_a} \quad \text{and} \quad \alpha_b=\frac{k_b}{\rho_b c_b}$$

where $A_a$, $B_a$, $A_b$, $B_b$ are constants of integration, while $\lambda_a$, $\lambda_b$ are separation constants.

In order to proceed further, we must now apply the following four boundary conditions:

1) The heat flux from the copper block to the air (at $r=r_3$), is determined by the convective heat transfer coefficient to air, $h_a$.
2) The heat flux across the boundary between the two media (at $r=r_2$) is continuous.
3) The temperature difference across the boundary between the two media ($T_a(r_2,t) - T_b(r_2,t)$) is determined by the heat transfer coefficient across the boundary ($h_i$) and the heat flux.
4) The heat flux from the copper block to the water (at $r=r_1$) is determined by the heat transfer coefficient to the water h.

In mathematical terms these are written:

$$(2\pi r_3 L)k_b\frac{\partial}{\partial r}T_b(r_3,t)=-(2\pi r_3 L)h_a T_b(r_3,t)$$

$$(2\pi r_2 L)k_b\frac{\partial}{\partial r}T_b(r_2,t)=(2\pi r_2 L)k_a\frac{\partial}{\partial r}T_a(r_2,t)$$

$$(2\pi r_2 L) k_a \frac{\partial}{\partial r} T_a(r_2,t) = (2\pi r_2 L) h_i [T_b(r_2,t) - T_a(r_2,t)]$$

$$(2\pi r_1 L) k_a \frac{\partial}{\partial r} T_a(r_1,t) = (2\pi r_1 L) h T_a(r_1,t)$$

Here $h_a$, $h_i$, h are the heat transfer coefficients between block and air, of the interface between the two media (Block and pipe), and between the pipe and water, respectively.

These boundary conditions lead to the relations:

1) $\alpha_a \lambda_a^2 = \alpha_b \lambda_b^2$, and

2) $F(x) = 0$, where

$$F(x) = \Lambda x \{ Z_1^T [x, (\gamma_2 x, \gamma_3 x)] + (\frac{h}{h_i}) \beta_2 \Lambda x \cdot Z_1^T [\gamma_2 x, \gamma_3 x] \cdot Z_1 [x, \omega_2 x] \} + \{ Z_0^T [x, (\gamma_2 x, \gamma_3 x)] + (\frac{h}{h_i}) \beta_2 \Lambda x \cdot Z_1^T [\gamma_2 x, \gamma_3 x] \cdot Z_0 [x, \omega_2 x] \}$$

Here

$$Z_{\{ {0 \atop 1} \}}^T [x, (\gamma_2 x, \gamma_3 x)] = J_{\{ {0 \atop 1} \}}(x) \mathcal{Y}_1^T [\omega_2 x, (\gamma_2 x, \gamma_3 x)] - Y_{\{ {0 \atop 1} \}}(x) \mathcal{J}_1^T [\omega_2 x, (\gamma_2 x, \gamma_3 x)]$$

$$\mathcal{J}_1^T [\omega_2 x, (\gamma_2 x, \gamma_3 x)] = J_1(\omega_2 x) Z_0^T [\gamma_2 x, \gamma_3 x] - \beta_2 J_0(\omega_2 x) Z_1^T [\gamma_2 x, \gamma_3 x]$$

$$\mathcal{Y}_1^T [\omega_2 x, (\gamma_2 x, \gamma_3 x)] = Y_1(\omega_2 x) Z_0^T [\gamma_2 x, \gamma_3 x] - \beta_2 Y_0(\omega_2 x) Z_1^T [\gamma_2 x, \gamma_3 x]$$

$$Z^{T}_{\left\{ 0 \atop 1 \right\}}[\gamma_2 x, \gamma_3 x] = Z_{\left\{ 0 \atop 1 \right\}}[\gamma_2 x, \gamma_3 x] - \left(\frac{h_a}{h}\right)\frac{1}{\beta_2 \Lambda x}\,\tilde{Z}_{\left\{ 0 \atop 1 \right\}}[\gamma_2 x, \gamma_3 x]$$

$$Z_{\left\{ 0 \atop 1 \right\}}[\gamma_2 x, \gamma_3 x] = J_{\left\{ 0 \atop 1 \right\}}(\gamma_2 x)Y_1(\gamma_3 x) - Y_{\left\{ 0 \atop 1 \right\}}(\gamma_2 x)J_1(\gamma_3 x)$$

$$\tilde{Z}_{\left\{ 0 \atop 1 \right\}}[\gamma_2 x, \gamma_3 x] = J_{\left\{ 0 \atop 1 \right\}}(\gamma_2 x)Y_0(\gamma_3 x) - Y_{\left\{ 0 \atop 1 \right\}}(\gamma_2 x)J_0(\gamma_3 x)$$

$$\Lambda = \frac{k_a}{h r_1}$$

$$x = \lambda_a r_1$$

$$\gamma_2 = \sqrt{\frac{\alpha_a}{\alpha_b}}\left(\frac{r_2}{r_1}\right) \quad , \quad \gamma_3 = \sqrt{\frac{\alpha_a}{\alpha_b}}\left(\frac{r_3}{r_1}\right)$$

$$\omega_2 = \frac{r_2}{r_1}$$

$$\beta_2 = \sqrt{\frac{k_b c_b \rho_b}{k_a c_a \rho_a}}$$

and J and Y are Bessel functions of the first and second kind, respectively.

Since F(x) is a sum of terms that are combinations of Bessel functions, F(x)=0 has an infinite number of roots which we shall label $X_1$, $X_2$, $X_3$, ... . But this implies an infinite number of $\lambda_a$'s (and $\lambda_b$'s). The values of $\lambda_a$ and $\lambda_b$ are determined from the roots according to the relations

$$\lambda_{a1} = \frac{X_1}{r_1} \quad , \quad \lambda_{b1} = \lambda_{a1}\sqrt{\frac{\alpha_a}{\alpha_b}}$$

$$\lambda_{a2} = \frac{X_2}{r_1} \quad , \quad \lambda_{b2} = \lambda_{a2}\sqrt{\frac{\alpha_a}{\alpha_b}}$$

... etc.

The general solution to the time-dependent heat flow equation subject to the boundary conditions is, finally:

$$T(r,t) = \sum_{n=1}^{\infty} R_n(r) e^{-\frac{t}{\tau_n}} \tag{A-2}$$

Where

$$\tau_n = \frac{r_1^2}{\alpha_a x_n^2}$$

$$R_n(r) = \begin{cases} R_{an}(r) & \text{for } r_1 \le r \le r_2 \\ R_{bn}(r) & \text{for } r_2 \le r \le r_3 \end{cases}$$

$$R_{an}(r) = C_{an}\Big\{Z_o^T\left[\lambda_n r_1 (\delta_2 \lambda_n r_2, \delta_2 \lambda_n r_3)\right] + \left(\frac{h}{h_i}\right)\beta_2 \Lambda x_n Z_1^T\left[\gamma_2 x_n, \gamma_3 x_n\right] \cdot Z_o\left[\lambda_n r, \lambda_n r_2\right]\Big\}$$

$$R_{bn}(r) = C_{bn} Z_o^T\left[\delta_2 \lambda_n r, \delta_2 \lambda_n r_3\right]$$

$$\delta_2 = \sqrt{\frac{\alpha_a}{\alpha_b}}$$

$C_{an}$ and $C_{bn}$ are constants that depend on the initial temperature distribution $T(r,0)$.

In some circumstances, the following point may be of interest.

If we set $k_a = k_b$, $c_a = c_b$, $\rho_a = \rho_b$, and $h_i = \infty$, these equations may be used to deal with a single-medium system. However, it should be noted that if the differential equation and boundary conditions appropriate to the single-medium case are used from the start, the resulting equations are of a much simplified form.

A.3. Heat Losses Along Thin-Walled Portions of Pipe

The correction to h due to heat losses along the thin-walled portions of the pipe will now be taken up. To this end consider Fig. A-1. Looking at the section of pipe between Z and Z+dZ, conservation of energy requires

$$\dot{Q}_{IN} - \left[\dot{Q}_{OUT} + \dot{Q}_{WATER}\right] = \frac{\partial Q}{\partial t}$$

or

$$\left[-\pi(r_2'^2 - r_1^2)k_1 \frac{\partial}{\partial Z} T_p(Z,t)\right] -$$

$$\left\{\left[-\pi(r_2'^2 - r_1^2)k_1 \frac{\partial}{\partial Z} T_p(Z+dZ,t)\right] + \left[(2\pi r_1 dZ)h T_p(Z,t)\right]\right\} =$$

$$c_1\rho_1\left[\pi(r_2'^2 - r_1^2)dZ\right] \frac{\partial}{\partial t} T_p(Z,t)$$

where $r_2' = (r_1 + t')$

and $T_p(Z,t)$ = temperature in pipe wall. This leads to the heat flow equation

$$\frac{\partial^2}{\partial Z^2} T_p - H^2 T_p = \frac{1}{\alpha_a} \frac{\partial}{\partial t} T_p$$

where

$$H^2 = \frac{h}{k_a t'}(1-\epsilon)$$

$$\epsilon = \frac{(t'/2r_1)}{1+(t'/2r_1)}$$

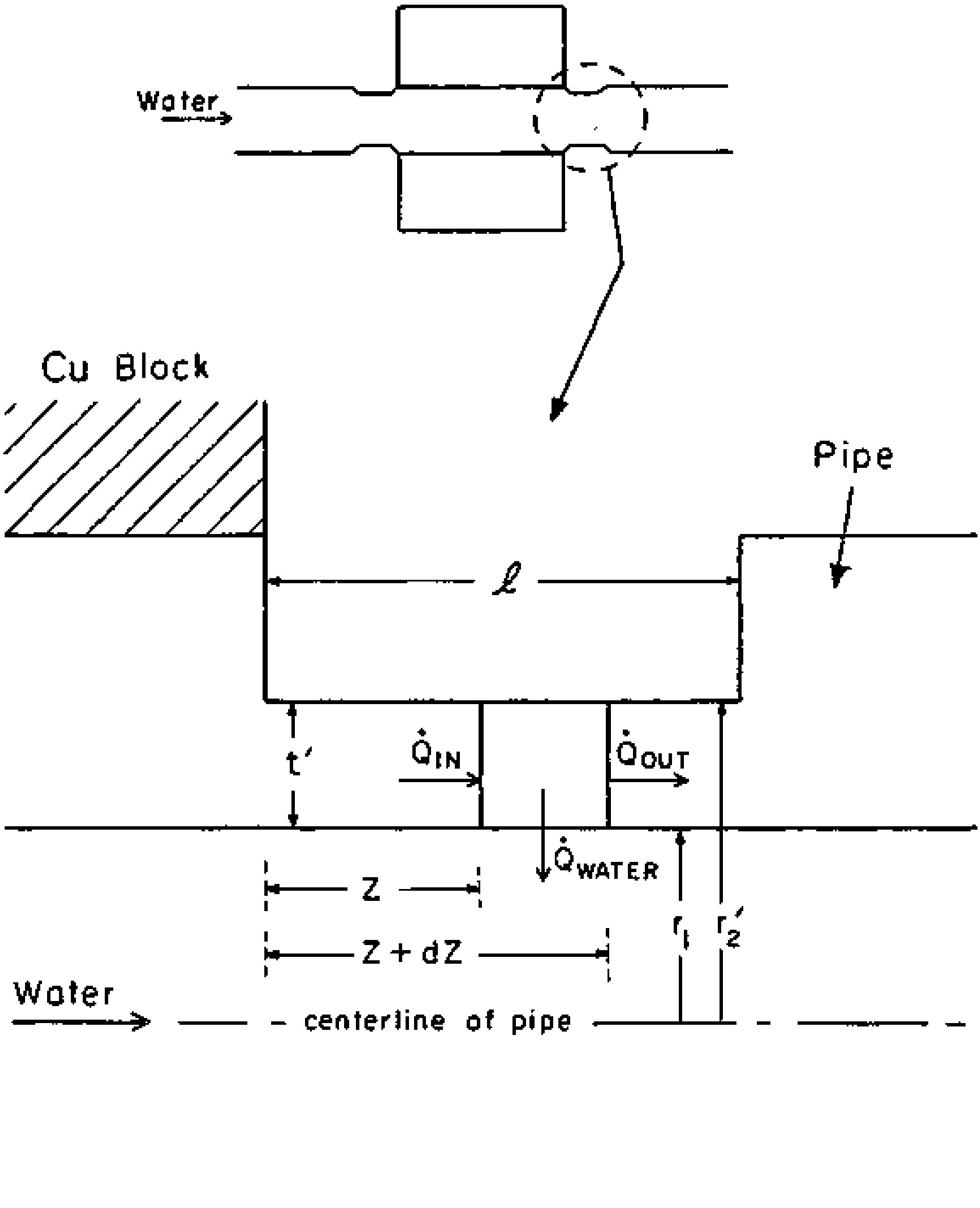



Figure A-1.- Thin-walled Portion of the Pipe

We now impose the boundary conditions:

1) The temperature, $T_p$, at $Z=\ell$ (where the wall thickens again) is equal to the temperature of the water:

i.e. $T_p(Z \geq \ell, t) = T_{WATER} = 0$

2) $T_p$ at $Z=0$ is given by Eq. A-2,

ie $T_p(0,t) = T_a(r_1,t) = \sum_{n=1}^{\infty} R_{an}(r_1) e^{-\frac{t}{\tau_n}}$

Under these conditions the general solution for $T_p(Z,t)$ is

$$T_p(Z,t) = T_p(0,0) \frac{2}{\ell} \sum_{n=1}^{\infty} \frac{(n\pi/\ell)}{H^2 + (n\pi/\ell)^2}$$

$$\sin\left(\frac{n\pi}{\ell} Z\right) e^{-\alpha_a\left[H^2 + \left(\frac{n\pi}{\ell}\right)^2\right]t} + \sum_{m=1}^{\infty} R_{am}(r_1) e^{\frac{-t}{\tau_m}} \cdot$$

$$\left\{\left(\frac{\ell - Z}{\ell} + \frac{2}{\pi} \sum_{n=1}^{\infty} \frac{(-1)^n}{n} \frac{\left(\frac{1}{\tau_m} - \alpha_a H^2\right)}{\left(\frac{1}{\tau_m} - \alpha_a H^2 - \frac{\alpha_a n^2 \pi^2}{\ell^2}\right)} \sin\left(\frac{n\pi(\ell - Z)}{\ell}\right)\right\} +$$

$$\frac{2}{\pi} \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} R_{am}(r_1) \left[1 - \frac{\left(\frac{1}{\tau_m} - \alpha_a H^2\right)}{\left(\frac{1}{\tau_m} - \alpha_a H^2 - \frac{\alpha_a n^2 \pi^2}{\ell^2}\right)}\right] \cdot$$

$$\frac{(-1)^n}{n} e^{-\alpha_a\left[H^2 + \left(\frac{n\pi}{\ell}\right)^2\right]t} \sin\left[\frac{n\pi(\ell - Z)}{\ell}\right]$$

The correction to h is due to the heat flow along the thin-walled portions of the pipe:

$$\dot{Q}_{PIPE} = 2[-\pi(r_2'^2 - r_1^2)]k_a \frac{\partial}{\partial Z} T_p(0,t)$$

Thus we see that

$$\dot{Q}_{total} = \dot{Q}_{Water} + \dot{Q}_{pipe}$$

or

$$\dot{Q}_{TOTAL} = 2\pi r_1 L h T_a(r_1,t) + 2\pi(r_2'^2 - r_1^2)k_a \frac{\partial}{\partial Z} T_p(0,t)$$

$$= 2\pi r_1 L h_{unc} T_a(r_1,t)$$

If we assume this correction is small and use the asymptotic form for $T_a(r_1,t)$:

$$T_a(r_1,t) \simeq R_{11}(r_1)e^{-\frac{t}{\tau_1}}$$

Then it can be shown, with a little work, that

$$\frac{\partial}{\partial Z} T_p(0,t) = -H' T(r_1,t)$$

where

$$H' = \sqrt{1 - \frac{1}{\alpha_a H^2 \tau_1}}\ H$$

This leads to the result

$$h_{unc,wall} = \left[1 + \left(1 + \frac{t'}{4r_1} - \frac{1}{2\alpha_a H^2 \tau_1}\right) \cdot \frac{2}{L}\sqrt{\frac{k_a t'}{h}}\right] h$$

Because of the smallness of the last two terms for materials of interest, to first order we have

$$h_{unc,wall} \simeq \left[1 + \frac{2}{L}\sqrt{\frac{k_a t'}{h}}\right] h$$

This is the result used in Sec. 2.2.2. (Eqn. 2-6).

A.4. Air Correction

If we have determined a heat transfer coefficient $h_{unc}$ ignoring the small heat flow from the copper block to the surrounding air, we need to correct for this neglect. The heat transfer coefficient corrected for heat loss to the air is designated $h'_{unc}$. As stated in Sec. 2, we define a correction term, $R_{air}$, so that

$$h'_{unc} = (1-R_{air})\ h_{unc} \tag{A-3}$$

Clearly,

$$R_{air} = \dot{Q}_a/\dot{Q}\ , \tag{A-4}$$

where $\dot{Q}_a$ and $\dot{Q}$ are respectively the heat fluxes to the air and to the water during the cooling process. (it is easy to show that although $\dot{Q}_a$ and $\dot{Q}$ vary, their ratio is a constant, after the initial transient of a few seconds duration, during the cooling).

The exact calculation of $R_{air}$ is somewhat involved. We simplify the problem by calculating it at the initial instant of the cooling period, when the temperature distribution in the block corresponds to a steady-state heat flow radially inward from the heater to the water. We let (referring to Fig. 2-2) $T_1$, $T_{2a}$, $T_{2b}$, and $T_3$ be the temperatures, respectively, of the pipe at $r=r_1$, the pipe at $r=r_2$, the block at $r=r_2$, and the block at $r=r_3$. The thermal conductivities of the pipe and block are $k_a$ and $k_b$, respectively. The heat flow through the block is $\dot{Q}$. The heat transfer coefficients to the water and air are h and $h_a$, respectively.

Then,

$$\dot{Q} = hT_1(2\pi r_1 L)\quad , \tag{A-5}$$

and

$$\dot{Q}_a = h_a T_3(2\pi r_3 L)\quad , \tag{A-6}$$

so that

$$R_{air} = \frac{\dot{Q}_a}{\dot{Q}} = \frac{h_a}{h}\frac{T_3 r_3}{T_1 r_1}\quad . \tag{A-7}$$

We need now to relate $T_3$ to $T_1$. This is done using the well-known equations for steady state radial heat flow in a cylinder. If $r_i$ is the inner radius of the cylinder, the temperature at any radius r is given by,

$$T(r) - T(r_i) = \frac{\dot{Q}}{2\pi L k_b} \ln\left(\frac{r}{r_i}\right) \quad . \tag{A-8}$$

Applying this to the outer and inner radii of the block yields

$$T_3 = T_{2b} + \frac{\dot{Q}}{2\pi L k_b} \ln(r_3/r_2) \quad . \tag{A-9}$$

If $h_i$ is the heat transfer coefficient across the interface at $r_2$, then

$$T_{2b} = T_{2a} + \frac{\dot{Q}}{2\pi L r_2 h_i} \tag{A-10}$$

Consideration of the temperatures in the pipe gives,

$$T_{2a} = T_1 + \frac{\dot{Q}}{2\pi L k_a} \ln(r_2/r_1) \quad . \tag{A-11}$$

When we combine equations A-9, A-10 and A-11 while eliminating $\dot{Q}$ in favor of $T_1$ using Eqn. A-5, we find

$$T_3 = h r_1 T_1 \left[ \frac{\ln(r_3/r_2)}{k_b} + \frac{\ln(r_2/r_1)}{k_a} + \frac{1}{r_2 h_i} + \frac{1}{r_1 h} \right] \tag{A-12}$$

Equation A-12 and A-7 then yield

$$R_{air} = h_a \frac{r_3}{r_1} \left[ \frac{1}{h_{block}} - \frac{1}{h_{pipe}} + \frac{r_1}{r_2} \frac{1}{h_i} + \frac{1}{h} \right] \quad ,$$

where we have defined

$$h_{block} = \frac{k_b}{r_1 \ln(r_3/r_2)}$$

and

$$h_{pipe} = \frac{k_a}{r_1 \ln(r_2/r_1)} \quad .$$

The interested reader is referred to Section 2.2.2. for a description of how $R_{air}$ is determined in practice and how it is incorporated into the computer program for data analysis.

# APPENDIX B. COMPUTER PROGRAM HTAU

Input data required is described by comment cards at the beginning of the program listing. A sample of processed data is included at the end of the program listing.

```
@ RUN HTAU,P1740H20,5.0,100,,,PRI
@ PWD DAN
@ MOG       RUN OF HTAU FOR ERDA REPORT (NOV 77)
@I FOR HTAU
C
C      ORDER OF DATA CARDS
C
C   1. LABEL (20A4)
C   2. THERMAL CONDUCTIVITY (BTU/HR.FT.F), HEAT CAPACITY (BTU/LB.F),
C      AND DENSITY (LB/IN**3) OF CYLINDER 1 (TUBE)  (3F10.0)
C   3. THERMAL CONDUCTIVITY (BTU/HR.FT.F), HEAT CAPACITY (BTU/LB.F),
C      AND DENSITY (LB/IN**3) OF CYLINDER 2 (HEATER CYLINDER)  (3F10.0)
C   4. INNER RADIUS OF CYLINDER 1 (IN), INNER RADIUS OF CYLINDER 2 (IN),
C      OUTER RADIUS OF CYLINDER 2 (IN), AND RADIUS OF TEST POINT, I.E.,
C      THERMOMETER LOCATION  (4F10.0)
C
      COMMON /SHAKIT/ ELAMBD,GAMMA,DELTA,OMEGA,R,XTP
      DIMENSION LABEL(20)
      DIMENSION HA(20,3),RADTPA(20,3),TAUA(20,3),TZA(20,3)
      DOUBLE PRECISION HREL(100),TAUREL(100)
      DATA TOLER/1.0E-04/
      DATA XINT/0.020/,XFIN/1.0/,DELX/0.01/
      DATA IEND/20/
C
      READ(5,500) LABEL
  500 FORMAT(20A4)
      READ(5,505) THCON1,HTCAP1,DENST1
      READ(5,505) THCON2,HTCAP2,DENST2
  505 FORMAT(3F10.0)
      READ(5,510) RAD1,RAD2,RAD3,RADTP
  510 FORMAT(4F10.0)
C
C  CALCULATE CONSTANTS
C
      ALPHA1=THCON1/(HTCAP1*DENST1)
      ALPHA2=THCON2/(HTCAP2*DENST2)
      ALPHA=SQRT(ALPHA1/ALPHA2)
      GAMMA=ALPHA*RAD3/RAD1
      DELTA=ALPHA*RAD2/RAD1
      OMEGA=RAD2/RAD1
      R=ALPHA*THCON2/THCON1
C
      DO 999 I=1,IEND
      DO 999 J=1,3
      HA(I,J)=100.*I+50.
      ELAMBD=(THCON1*12.0)/(HA(I,J)*RAD1)
      GO TO(210,220,230),J
  210 RADTPA(I,J)=RAD1
```

```
      GO TO 240
  220 RADTPA(I,J)=RADTP
      GO TO 240
  230 RADTPA(I,J)=RAD3
  240 CONTINUE
      XTP=RADTPA(I,J)/RAD1
      X = XINT - DELX
      INO = 0
C010  CONTINUE
      DELXX = DELX
      X = X + DELX
      IF(X.GT.XFIN) WRITE(6,699) INO,HA(I,J)
  699 FORMAT(10X,'NO SOLUTION FOUND (X.GT.XFIN).',/,10X,'INO =',
     1I5,10X,'HA(I,J) =',F10.3,//)
      IF(X.GT.XFIN) GO TO 999
      FF = F(X)
      ISIGN = SIGN(1.0,FF)
      XW = X + DELX
      FF = F(XW)
      JSIGN = SIGN(1.0,FF)
      W = X
      IF(ISIGN + JSIGN) 90,60,90
C060  CONTINUE
      DELXX = DELXX/10.0
      IF(DELXX.LT.DELX/10000.0) GO TO 10
C070  CONTINUE
      FF = F(W)
      ISIGN = SIGN(1.0,FF)
      W = W + DELXX
      IF(W.GT.XW) GO TO 10
      FW = F(W)
      JSIGN = SIGN(1.0,FW)
      IF(ISIGN + JSIGN) 70,80,70
C080  CONTINUE
      WW = W - DELXX
      XW = W
      FF = F(XW)
      FW = F(WW)
      ANS = FF
      IF(ABS(FF).GT.ABS(FW)) ANS = FW
      Z = XW
      IF(ABS(FF).GT.ABS(FW)) Z = WW
      IF(ABS(ANS).LT.TOLER) GO TO 95
      W = WW
      GO TO 60
C090  CONTINUE
      GO TO 10
C095  CONTINUE
      INO = INO + 1
C     RA(X) AND RB(X) ARE ENTERED HERE
C
C
C     XTP IS THE RATIO OF THE TEST PT. TO INNER RADIUS
C
```

```
C
      IF(XTP-OMEGA) 333,333,334
0333  RR=RA(Z)
      TZA(I,J)=RR
      GO TO 335
0334  RR=RB(Z)
      TZA(I,J)=RR
0335  CONTINUE
C
C
C     TAU IS ENTERED HERE
C
C     TAU = (RAD1**2)/(ALPHA1*Z**2)  WHERE Z IS A ZERO OF FUNCTION F(X) ABOVE
C
      TAU=(RAD1**2*3600.*12.)/(ALPHA1*Z**2)
      TAUA(I,J)=TAU
C
C     WRITE(6,602)
C     WRITE(6,604) XINT,XFIN,CELX,ELAMBD,GAMMA,DELTA,OMEGA,Z,XTP
C     WRITE(6,603)
C     WRITE(6,601) IND,Z,ANS,RR,TAU
C602  FORMAT(///)
C604  FORMAT(1X,9F12.5)
C603  FORMAT(1X,'SOL          X            F(X)            RR              TAU',/)
C601  FORMAT(1X,I3,2X,4F12.5)
C
      IF(IND.EQ.1) GO TO 999
      X = X + CELX
      GO TO 10
  999 CONTINUE
      WRITE(6,600)
  600 FORMAT(1H1)
      WRITE(6,610) LABEL
  610 FORMAT(10X,20A4,//)
      WRITE(6,620)
  620 FORMAT(31X,'THERMAL CONDUCTIVITY (BTU/HR.FT.F)      HEAT CAPACITY (
     1BTU/LB.F)      DENSITY (LB/IN**3)',/)
      WRITE(6,630) THCON1,HTCAP1,DENST1,THCON2,HTCAP2,DENST2
  630 FORMAT(10X,'CYLINDER 1 (TUBE)    ',F21.2,F32.4,F27.4,/,
     1         10X,'CYLINDER 2 (HEATER) ',F21.2,F32.4,F27.4,//)
      WRITE(6,640)
  640 FORMAT(31X,'RADIAL DIMENSIONS (INCHES)',/)
      WRITE(6,650) RAD1,RAD2,RAD3,RADTP
  650 FORMAT(10X,'RADIUS 1 (ID OF TUBE/2)              =',F6.3,/,
     1         10X,'RADIUS 2 (MACHINED OD OF TUBE/2)    =',F6.3,/,
     2         10X,'RADIUS 3 (OD OF HEATER CYLINDER/2) =',F6.3,/,
     3         10X,'RADIUS OF TEST POINT (TC LOCATION) =',F6.3,///)
      WRITE(6,660)
  660 FORMAT(10X,'H (BTU/HR.FT**2.F)  TEST POINT RADIUS (IN)      TAU (SE
     1C)      TOLZ1(R=TEST POINT RADIUS)',/)
      WRITE(6,670) (HA(I,1),RADTPA(I,1),TAUA(I,1),TZA(I,1),
     1              HA(I,2),RADTPA(I,2),TAUA(I,2),TZA(I,2),
     2              HA(I,3),RADTPA(I,3),TAUA(I,3),TZA(I,3),I=1,IEND)
  670 FORMAT(3(F19.0,F24.3,F21.3,F23.4,/))
```

```
C
      DO 360 I=1,IEND
      PREL(I)=PA(I,2)
      TAUREL(I)=TAUA(I,2)
  360 CONTINUE
      CALL RELATN(PREL,TAUREL,IEND)
C
      CALL EXIT
      END
@1 FOR HICKEY,HICKEY
      FUNCTION F(X)
      DIMENSION YY(1000),ZZ(1000)
      COMMON /SMAKIT/ ELAMBO,GAMMA,DELTA,OMEGA,R,XTP
C
C
C     JO,J1,YO,Y1'BESSEL FCNS FOR X
C
C
      XX = X
      AJ=BSSL(XX,1)
      XX = X
      A1J = BSSL(XX,3)
      XX = X
      CALL BESY(XX,0.0,1,YY,ZZ)
      YO  = ZZ(1)
      Y1A = ZZ(2)
C
C
C     JO,J1,YO,Y1'BESSEL FCNS FOR OMEGA ' X
C
C
      T=X*OMEGA
      XX=T
      CJ=BSSL(XX,1)
      XX=T
      CJA=BSSL(XX,3)
      XX=T
      CALL BESY(XX,0.0,1,YY,ZZ)
      CY=ZZ(1)
      CYA=ZZ(2)
C
C
C     JO,J1,YO,Y1'BESSEL FCNS FOR DELTA'X
C
C
      U=X*DELTA
      XX=U
      DJ=BSSL(XX,1)
      XX=U
      DJA=BSSL(XX,3)
      XX=U
      CALL BESY(XX,0.0,1,YY,ZZ)
      DY=ZZ(1)
      DYA=ZZ(2)
```

```
C
C
C      J0,J1,Y0,Y1*BESSEL FCNS FOR GAMMA*X
C
C
       Y = X*GAMMA
       XX = Y
       BCJ=BSSL(XX,1)
       XX=Y
       B1J = BSSL(XX,3)
       XX=Y
       CALL BESY(XX,0.0,1,YY,ZZ)
       Y0B=ZZ(1)
       Y1B = ZZ(2)
C
C
C      FUNCTIONS THAT FORM F(X)
C
C
       Z0=Y1B*DJ-B1J*DY
       Z1=Y1B*DJA-B1J*DYA
       V1=Z0*DYA-R*Z1*DY
       V2=Z0*DJA-R*Z1*DJ
       F2=AJ*V1-Y0*V2
       F1=ELAMBD*X*(A1J*V1-Y1A*V2)
       F=F1+F2
       RETURN
       END
*  FOR RA,RA
       FUNCTION RA(X)
       REAL K0,K1,K2,K3,K4
       DIMENSION YY(1000),ZZ(1000)
       COMMON /SHAKIT/ ELAMBD,GAMMA,DELTA,OMEGA,R,XTP
C
C
C      J0,J1,Y0,Y1*BESSEL FCNS FOR X
C
C
       XX = X
       AJ=BSSL(XX,1)
       XX = X
       A1J = BSSL(XX,3)
       XX = X
       CALL BESY(XX,0.0,1,YY,ZZ)
       Y0  = ZZ(1)
       Y1A = ZZ(2)
C
C
C      J0,J1,Y0,Y1*BESSEL FCNS FOR OMEGA * X
C
C
       T=X*OMEGA
       XX=T
       CJ=BSSL(XX,1)
```

```
      XX=T
      CJA=BSSL(XX,3)
      XX=T
      CALL BESY(XX,0.0,1,YY,ZZ)
      CY=ZZ(1)
      GYA=ZZ(2)
C
C
C     J0,J1,Y0,Y1'BESSEL FCNS FOR DELTA'X
C
C
      U=X*DELTA
      XX=U
      DJ=BSSL(XX,1)
      XX=U
      DJA=BSSL(XX,3)
      XX=U
      CALL BESY(XX,0.0,1,YY,ZZ)
      DY=ZZ(1)
      DYA=ZZ(2)
C
C
C     J0,J1,Y0,Y1'BESSEL FCNS FOR GAMMA'X
C
C
      Y = X*GAMMA
      XX=Y
      B0J=BSSL(XX,1)
      XX = Y
      B1J = BSSL(XX,3)
      XX=Y
      CALL BESY(XX,0.0,1,YY,ZZ)
      Y0B=ZZ(1)
      Y1B = ZZ(2)
C
C
C     J0,J1,Y0,Y1'BESSEL FCNS FOR TEST PT
C
C
      TP=XTP*X
      XX=TP
      OJT=BSSL(XX,1)
      XX=TP
      OJU=BSSL(XX,3)
      XX=TP
      CALL BESY(XX,0.0,1,YY,ZZ)
      CYT=ZZ(1)
      DYU=ZZ(2)
C
C
C     J0,J1,Y0,Y1'BESSEL FCNS FOR TEST PT MOD
C
C
      TP=XTP*X
```

```
      TPM=(DELTA*TP)/OMEGA
      XX=TPM
      CJR=BSSL(XX,1)
      XX=TPM
      OJS=BSSL(XX,3)
      XX=TPM
      CALL BESY(XX,0.0,1,YY,ZZ)
      OYR=ZZ(1)
      OYS=ZZ(2)
C
C
C     FUNCTIONS THAT FORM RA(X)
C
C
      ZCO=CJ*CYA-OY*OJA
      ZO=Y1B*CJ-B1J*OY
      Z1=Y1B*OJA-B1J*OYA
      VJ=OJA*ZO-R*CJ*Z1
      VY=OYA*ZC-R*OY*Z1
      ZR1=CJT*VY-OYT*VJ
      ZRZ=OJR*Y1B-OYR*B1J
      ZZO=AJ*VY-YO*VJ
C
C
C     CONSTANT COEFFICIENTS
C
C
      KO=-0.1168
      K1=(0.4053*OMEGA)/DELTA
      K2=(1/R)-(DELTA/OMEGA)
      K3=R-(DELTA/OMEGA)
      K4=2.467/R
C
C
C     RADIAL TERMS FOR POWER SERIES
C
C
      PS1=K1+((OMEGA*X)**2)*K2*(ZO**2)+K3*(OMEGA*X*Z1)**2
      PS2=K4*(1+1/((ELAMBD*X)**2))*((OMEGA*(X**2)*ZZO)**2)
      PS=PS1-PS2
      PSC=KO/(X*PS)
      RA=(PSC*ZR1)/ZCO
      RETURN
      END
& FOR RB,RB
      FUNCTION RB(X)
      DIMENSION YY(1000),ZZ(1000)
      COMMON /SHAKIT/ ELAMBC,GAMMA,DELTA,OMEGA,R,XTP
      REAL KC,K1,K2,K3,K4
C
C
C     JC,J1,YC,Y1'BESSEL FCNS FOR X
C
C
```

```
      XX = X
      AJ=BSSL(XX,1)
      XX = X
      A1J = BSSL(XX,3)
      XX = X
      CALL BESY(XX,0.0,1,YY,ZZ)
      YC  = ZZ(1)
      Y1A = ZZ(2)
C
C
C     J0,J1,Y0,Y1*BESSEL FCNS FOR OMEGA * X
C
C
      T=X*OMEGA
      XX=T
      OJ=BSSL(XX,1)
      XX=T
      OJA=BSSL(XX,3)
      XX=T
      CALL BESY(XX,0.0,1,YY,ZZ)
      CY=ZZ(1)
      CYA=ZZ(2)
C
C
C     J0,J1,Y0,Y1*BESSEL FCNS FOR DELTA*X
C
C
      U=X*DELTA
      XX=U
      DJ=BSSL(XX,1)
      XX=U
      CJA=BSSL(XX,3)
      XX=U
      CALL BESY(XX,0.0,1,YY,ZZ)
      DY=ZZ(1)
      DYA=ZZ(2)
C
C
C     J0,J1,Y0,Y1*BESSEL FCNS FOR GAMMA*X
C
C
      Y = X*GAMMA
      XX=Y
      BCJ=BSSL(XX,1)
      XX = Y
      B1J = BSSL(XX,3)
      XX=Y
      CALL BESY(XX,0.0,1,YY,ZZ)
      Y0B=ZZ(1)
      Y1B = ZZ(2)
C
C
C     J0,J1,YC,Y1*BESSEL FCNS FOR TEST PT
C
```

```
C
      TP=XTP*X
      XX=TP
      OJT=BSSL(XX,1)
      XX=TP
      CJU=BSSL(XX,3)
      XX=TP
      CALL BESY(XX,0.0,1,YY,ZZ)
      CYT=ZZ(1)
      CYU=ZZ(2)
C
C
C     JO,J1,YO,YI'BESSEL FCNS FOR TEST PT MOD
C
C
      TP=XTP*X
      TPM=(DELTA*TP)/OMEGA
      XX=TPM
      CJR=BSSL(XX,1)
      XX=TPM
      OJS=BSSL(XX,3)
      XX=TPM
      CALL BESY(XX,0.0,1,YY,ZZ)
      OYR=ZZ(1)
      CYS=ZZ(2)
C
C
C     FUNCTICNS THAT FORM RB(X)
C
C
      ZCO=CJ*CYA-CY*OJA
      ZC=Y1B*OJ-B1J*OY
      Z1=Y1B*CJA-B1J*DYA
      VJ=OJA*ZC-R*OJ*Z1
      VY=OYA*ZC-R*CY*Z1
      ZR1=OJT*VY-OYT*VJ
      ZR2=CJR*Y1B-CYR*B1J
C
C
C     ZZO CNLY APPEARS IN REGION 2'3
C
C
      ZZO=AJ*VY-YO*VJ
C
C
C     CONSTANT COEFFICIENTS
C
C
      XO=-0.1166
      K1=(0.4053*OMEGA)/DELTA
      K2=(1/R)-(DELTA/OMEGA)
      K3=R-(DELTA/OMEGA)
      K4=2.467/R
C
```

```
C
C     RADIAL TERMS FOR POWER SERIES
C
C
      PS1=K1+((OMEGA*X)**2)*K2*(ZO**2)+K3*(OMEGA*X*Z1)**2
      PS2=K4*(1+1/((ELAMBO*X)**2))*((OMEGA*(X**2)*ZZO)**2)
      PS=PS1-PS2
      PSC=KO/(X*PS)
      R@=(PSC*ZR2)
      RETURN
      END
```

```
@I FOR RELATN
      SUBROUTINE RELATN(H,TAU,N)
C     THIS PROGRAM FITS HEAT TRANSFER COEFFICIENT VS. TAU DATA TO A CURVE
C      SUCH THAT LN(H)=A+B*LN(TAU)+C*(LN(TAU))**2+D*(LN(TAU))**3.
      INTEGER N,M
      REAL*8 STD,TAU(100),H(100),TTRANS(100),HTRANS(100),HCALC(100)
      REAL*8 A(4),C(10),ALPHA(10),BETA(10),T1(100),T2(100),T3(100)
      REAL*8 DELTA(100),PRCENT(100),W(100)
C
      DO 10 I=1,N
      TTRANS(I)=DLOG(TAU(I))
      HTRANS(I)=DLOG(H(I))
   10 CONTINUE
      CALL ORTHLS(TTRANS,HTRANS,W,N,0,0,C,ALPHA,BETA,3,T1,T2,T3,IND1)
      CALL COEFS(0,C,ALPHA,BETA,3,A,T1,T2,T3,IND2)
C
      STD=0.0
      DO 30 M=1,N
         HCALC(M)=A(1)+A(2)*TTRANS(M)+A(3)*TTRANS(M)**2+A(4)*TTRANS(M)
     1    **3
         HCALC(M)=DEXP(HCALC(M))
         DELTA(M)=H(M)-HCALC(M)
         PRCENT(M)=DELTA(M)/H(M)*100.0
         STD=STD+DELTA(M)**2
 30   CONTINUE
      STD=DSQRT(STD/(N-4))
      WRITE(6,200)
      WRITE(6,300)
      WRITE(6,400)A(1),A(2),A(3),A(4)
      WRITE(6,500)STD
      WRITE(6,600)
      WRITE(6,700)(M,TAU(M),H(M),TTRANS(M),HTRANS(M),HCALC(M),DELTA(M),
     1 PRCENT(M),M=1,N)
 200  FORMAT('1',/,/,/,5X,'HEAT TRANSFER COEFFICIENT VS. TAU')
 300  FORMAT(' ',/,/,/,5X,'COEFFICIENTS FOR LN(H)=A+B*LN(TAU)+C*(LN(TAU)
     1)**2+D*(LN(TAU))**3 ARE')
 400  FORMAT(' ',10X,'A=',F12.6,/,11X,'B=',F12.6,/,11X,'C=',F12.6,
     1/,11X,'D=',F12.6,/,/,/,/,/)
 500  FORMAT('-',5X,'RMS DEVIATION OF OBSERVED H FROM THE CALCULATED H I
     1S',F8.4,' BTU/(HR-FT**2-DEG. F)',/,/,/)
 600  FORMAT('-',7X,'POINT',10X,'TAU',6X,'HEAT TRANS. COEF.     LN(TAU)
     1         LN(H)        CALCULATED H    H DIFFERENCE     PERCENT DIFFEREN
     2CE',/)
 700  FORMAT(' ',I10,2F16.4,5F16.6)
      RETURN
      END
@I FOR ORTHLS
      SUBROUTINE ORTHLS (X,Y,W,N,L,J,C,ALPHA,BETA,K,T1,T2,T3,IND1)
```

```
C      THIS SUBROUTINE COMPUTES THE COEFFICIENTS OF THE POLYNOMIAL
C      EQUATION OF DEGREE K AND THE ALPHA AND BETA PARAMETERS.
       IMPLICIT DOUBLE PRECISION (A-H,O-Z)
       DIMENSION X(N),Y(N),W(N),C(K),ALPHA(K),BETA(K),T1(N),T2(N),T3(N)
C      PROGRAM INITIALIZATION.
       KJ1=K-J+1
       IF (KJ1.LE.0) GO TO 16
       SUM=0.0
       IF (L.EQ.1) GO TO 3
       DO 2 I=1,N
       T3(I)=X(I)
       IF (J.GT.0) GO TO 1
       SUM=SUM+1.0
       GO TO 2
     1 SUM=SUM+X(I)**(2*J)
     2 W(I)=1.0
       GO TO 7
     3 DO 6 I=1,N
       T3(I)=X(I)
       IF (J.GT.0) GO TO 4
       SUM=SUM+W(I)
       GO TO 5
     4 SUM=SUM+W(I)*X(I)**(2*J)
     5 X(I)=W(I)*X(I)
     6 Y(I)=W(I)*Y(I)
     7 B=0.0
       RO=SUM
       DO 9 I=1,N
       IF (J.GT.0) GO TO 8
       T2(I)=1.0
       GO TO 9
     8 T2(I)=T3(I)**J
     9 T1(I)=0.0
C      BEGIN COMPUTATION.
       II=1
    10 S=0.0
       DO 11 I=1,N
    11 S=S+Y(I)*T2(I)
C      COMPUTATION OF A COEFFICIENT IN THE POLYNOMIAL EQUATION.
       C(II)=S/RO
       IF (II.GE.KJ1) GO TO 15
C       COMPUTATION OF AN ALPHA FOR THE POLYNOMIAL EQUATION.
       SUMXPS=0.0
       DO 12 I=1,N
    12 SUMXPS=SUMXPS+X(I)*T2(I)*T2(I)
       ALPHA(II)=SUMXPS/RO
C      COMPUTATION OF A NEW POLYNOMIAL.
       DO 13 I=1,N
       TEMP=T2(I)
       T2(I)=(T3(I)-ALPHA(II))*T2(I)-B*T1(I)
    13 T1(I)=TEMP
C      COMPUTATION OF A BETA FOR THE POLYNOMIAL EQUATION.
       R=0.0
       DO 14 I=1,N
```

```
   14 R=R+W(I)*T2(I)*T2(I)
      BETA(II)=R/RO
      RO=R
      B=BETA(II)
      II=II+1
      GO TO 10
C     SUCCESSFUL RETURN.
   15 IND1=+1
      RETURN
C     ERROR RETURN.  SET ALL C COEFFICIENTS, ALPHA AND BETA TO ZERO.
   16 DO 17 II=1,K
      C(II)=0.0
      ALPHA (II)=0.0
   17 BETA(II)=0.0
      C(K+1)=0.0
      IND1=-1
      RETURN
      END
$IBFTC COEFS
      SUBROUTINE COEFS (J,C,ALPHA,BETA,KC,A,T1,T2,T3,IND2)
C     THIS SUBROUTINE COMPUTES THE A COEFFICIENTS FOR A POLYNOMIAL
C     OF DEGREE KC WHERE KC IS LESS THAN OR EQUAL TO K.
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      DIMENSION C(KC),ALPHA(KC),BETA(KC),A(KC),T1(KC),T2(KC),T3(KC)
C     PROGRAM INITIALIZATION.
      KCJ1=KC-J+1
      IF(KCJ1.LE.0) GO TO 9
      B=0.0
      DO 1 NN=1,KCJ1
      A(NN)=C(NN)
      T1(NN)=0.0
      T2(NN)=0.0
    1 T3(NN)=0.0
      IF (KC.LE.J) GO TO 5
      II=2
C     BEGIN COMPUTATION.
    2 T2(II)=1.0
      DO 3 NN=2,II
      T3(NN)=T2(NN-1)-T2(NN)*ALPHA(II-1)-B*T1(NN)
C     COMPUTATION OF AN A COEFFICIENT.
    3 A(NN-1)=A(NN-1)+C(II)*T3(NN)
      IF (II.GE.KCJ1) GO TO 5
C     RESETTING THE VECTORS FOR THE NEXT COEFFICIENT.
      DO 4 NN=1,II
      T1(NN)=T2(NN)
    4 T2(NN)=T3(NN)
      B=BETA(II-1)
      II=II+1
      GO TO 2
    5 IF (J.LE.0) GO TO 8
C      ARRANGE COEFFICIENTS PROPERLY IF J IS NON ZERO.
      DO 6 NN=1,KCJ1
      N1=KCJ1-NN+1
      N2=N1+J
```

```
    6 A(N2)=A(N1)
      DO 7 NN=1,J
    7 A(NN)=0.0
C     SUCCESSFUL RETURN.
    8 INO2=+2
      RETURN
C      ERROR RETURN.  SET ALL THE A COEFFICIENTS EQUAL TO ZERO.
    9 DO 10 NN=1,KC
   10 A(NN)=0.0
      A(KC+1)=0.0
      INO2=-2
      RETURN
      END
$I FOR BSSL
      FUNCTION BSSL(X,M)
      DIMENSION T(2),XB(2),BESSL(2)
      EQUIVALENCE (FN2P,FNPZ)
      DATA TWOP26,TWOM30/0147400000000,0143400000000/
      DATA TWOPI,PI3FRS,PIHALF,PIFRTH/6.2831853,2.3561945,1.5707963,
     10.785398163/
      X=ABS(X)
      IF(X.GT.6.)GO TO 10
      SIGN=1.
      IF((M.EQ.1).OR.(M.EQ.3)) SIGN=-1.
      Z=.5*X
      ZZ=Z*Z
      GO TO (1,6,7,9),M
    1 ERR=TWOM30
    2 F2=1.
    3 F1=1.
      C=1.
      BSSL=D
      BS=BSSL
      DO 4 I=1,100
      C=D*ZZ*SIGN/(F1*F2)
      BSSL=BSSL+D
      IF((ABS(C).LT.ERR).OR.(ABS(BSSL-BS).LT.1.E-35)) GO TO 5
      BS=BSSL
      F1=F1+1.
    4 F2=F2+1.
    5 IF((M.EQ.3) .OR.(M.EQ.4)) BSSL=BSSL*Z
      RETURN
    6 ERR=TWOM26
      GO TO 2
    7 ERR=TWOM30
    8 F2=2.
      GO TO 3
    9 ERR=TWOM26
      GO TO 8
   10 XB(1)=.125/X
      I1=1
      I2=2
      GO TO (11,17,18,20),M
   11 XB(2)=-XB(1)
```

```
      TEST=TWOM30
   12 T(1)=4.5*X8(1)*X8(2)
      T(2)=-X8(1)
      C=-5.333333333
      FNP1=3.0
      F2NP=5.0
      FM2N=-5.0
   13 BESSL(1)=1.0
      BESSL(2)=0.0
   14 DO 15 I=1,100
      BESSL(I2)=BESSL(I2)+T(I2)
      T(I2)=C*X8(I1)*T(I1)
      IF(ABS(T(I1)).LT.ABS(T(I2))) GO TO 16
      I1=I2
      I2=3-I1
      IF(ABS(T(I1)).LT.TEST) GO TO 16
      FNP1=FNP1+1.0
      F2NP=F2NP+2.0
      FM2N=FM2N-2.0
   15 C=F2NP*FM2N/FNP1
   16 BESSL(I1)=BESSL(I1)+0.5*T(I1)
      GO TO (22,24,25,24),M
   17 X8(2)=X8(1)
      TEST=TWOM26
      IF(X.LT.88.) GO TO 12
      RETURN
   18 X8(2)=-X8(1)
      TEST=TWOM30
   19 T(1)=-7.5*X8(1)*X8(2)
      T(2)=3.0*X8(1)
      C=-7.0
      FNP1=3.0
      F2NP=3.0
      FM2N=-7.0
      GO TO 13
   20 X8(2)=X8(1)
      TEST=TWOM26
      IF(X.LT.88.) GO TO 19
      RETURN
   22 XMP=X-PIFRTH
   23 BSSL  =(1.0/SQRT(PIHALF*X))*(BESSL(1)*COS(XMP)-BESSL(2)*SIN(XMP))
      RETURN
   24 BSSL  =(EXP(X)/SQRT(TWOPI*X))*(BESSL(1)-BESSL(2))
      RETURN
   25 XMP=X-PI3FRS
      GO TO 23
      END
$I FOR BESY
      SUBROUTINE BESY (X,FNU,N,BJ,BY)
      DIMENSION BJ(1),BY(1)
C-------------------------------------------------------------------------
C     IRREGULAR BESSEL FUNCTIONS OF REAL ARGUMENT.
C-------------------------------------------------------------------------
C     ARGUMENT DEFINITION
```

```
C         X     IS THE ARGUMENT OF THE BESSEL FUNCTION.
C         FNU   IS THE FRACTIONAL PART OF TH+ ORDER.
C         N     IS THE INTEGRAL PART OF THE HIGHEST ORDER TO BE
C               COMPUTED.
C         BJ    IS THE ARRAY OF REGULAR  BESSEL FUNCTIONS
C-----------------------------------------------------------------------
      DATAPI/3.14159265/
      M=N
      BY(1)=X
      BY(2)=FNU+2.
      CALL BESJ(BY(1),BY(2),M,BJ)
      CX=2./X
      CXNU=CX*FNU
      MP1=M+1
      K=M+MP1
      NN=IABS(N)
      N1=NN-1
      P1=PI*FNU
      IF(X .GT.10.) GO TO 18
      CALL GAMMA(1.+FNU,GG,$50,$50)
      CG= (CX**FNU*GG)**2/PI
      IF( ABS(FNU).LT.1.E-35)GO TO 2
      GO=COS(P1)/SIN(P1)-GG
      T1=1.-FNU
      BY(1)=FNU*2.*(FNU+2.)*GG/T1
      TT=1.
      T2=-T1-1.
      T3=FNU-T1
      DO 1 I=2,MP1
      TT=TT+1.
    1 BY(I)=BY(I-1)*(FNU+TT+TT)*(T3+TT)*(T1-TT)/(TT*(TT-FNU)*(T2+TT+TT)
      GO TO 4
    2 GO=.6366198*(.577215665-ALOG(CX))
      DO 3 I=2,MP1
      BY(1)=4.0/PI
    3 BY(I)=BY(I-1)*(1./(I-1.)
    4 YNU=GO*BJ(1)
      DO 5 I=1,M
    5 YNU=YNU+BY(I)*BJ(2*I+1)
      IF(ABS(BJ(1)).GT.0.000005) GO TO 7
      YNUP1= -GG*CXNU   *BJ(1)+(GO-.5*BY(1))*BJ(2)
      TT=1.5*CXNU
      MM1 =M-1
      DO 6 I=1,MM1
    6 YNUP1=YNUP1+TT*BY(I)*BJ(2*I+I)+.5*(BY(I)-BY(I+1))*BJ(2*I+1)
      BY(2)=YNUP1+TT*BY(M)+BJ(K)
      GO TO 8
    7 BY(2)=(YNU*BJ(2)+CX/PI)/BJ(1)
    8 BY(1)=YNU
   18 IF ( N .LT. 0) GO TO 10
      IF(NN.LE.1)RETURN
      TT=FNU
      DO 9 I=1,N1
      TT=TT+1.
```

```
    9 BY(I+2)=CX*TT*BY(I+1)-BY(I)
   50 RETURN
   10 IF(ABS(FNU-.5).GT.1.E-35) GO TO 15
      BY(2)=BJ(1)
      IF(NN-1)50,14,11
   11 BY(3)=-BJ(2)
      BJ(2)=CX  NU*BJ(1)-BJ(2)
      BJ(3)=(CXNU-CX)*BJ(2)-BJ(1)
      IF(NN.LE.2)RETURN
   12 ARG=1.
      TT=FNU-1.
      DO 13 I=2,N1
      BY(I+2)=ARG*BJ(I+1)
      TT=TT-1.
      BJ(I+2)=(CX*TT*BY(I+2)-BY(I+1))*ARG
   13 ARG=-ARG
      RETURN
   14 BJ(2)=CX  NU*BJ(1)-BJ(2)
      RETURN
   15 BY(2)=CX  NU*BY(1)-BY(2)
      BJ(2)=CX  NU*BJ(1)-BJ(2)
      IF(NN.LE.1)RETURN
      TT=FNU
      DO 16 I=1,N1
      TT=TT-1.
      BJ(I+2)=TT*CX*BJ(I+1)-BJ(I)
   16 BY(I+2)=TT*CX*BY(I+1)-BY(I)
      RETURN
      END
*I FOR BESJ
      SUBROUTINE BESJ(X,FNU,N,F)
C-----------------------------------------------------------------------
C     REGULAR BESSEL FUNCTIONS OF REAL ARGUMENT.
C-----------------------------------------------------------------------
C     ARGUMENT DEFINITION
C        X     IS THE ARGUMENT OF THE BESSEL FUNCTION.
C        FNU   IS THE FRACTIONAL PART OF THE ORDER.
C        N     IS THE INTEGRAL PART OF THE HIGHEST ORDER TO BE
C              COMPUTED.
C        F     IS THE OUTPUT ARRAY OF BESSEL FUNCTIONS.
C-----------------------------------------------------------------------
C     REFERENCES
C        M. GOLDSTEIN AND R.M. THALER, RECURRENCE TECHNIQUES FOR THE
C              CALCULATION OF BESSEL FUNCTIONS, MTAC, 1959.
C        M. GOLDSTEIN AND R. M. THALER, BESSEL FUNCTIONS FOR LARGE
C              ARGUMENTS, MTAC, 1958.
C        G.N. WATSON, A TREATISE ON THE THEORY OF BESSEL FUNCTIONS,
C              CAMBRIDGE UNIVERSITY PRESS, 1948.
C-----------------------------------------------------------------------
      DIMENSION F(1),C(5)
      DATA PI2/1.57079632/
      NN=IABS(N)
      CX=2./X
      IF(FNU.GT.1.5)GO TO 1
```

```
      IY=1
      GO TO 2
    1  FNU=FNU-2.
      IY=2
    2 CXNU=CX*FNU
      IF(X.GT.50.)GO TO 12
      KK=X+20.
      M=MAX0(KK,NN+10)
      IF(X.LT.1.)GO TO 3
      KK=39.*X**.333333333
      GO TO 4
    3 KK=172.69388/(3.6828795-ALOG(X))
    4 M=MIN0(M,KK)/2
      K=M+M+1
      F(K+1)=1.E-37
      F(K+2)=0.
      KK=K+1
      TT=FNU+KK
      DO 5 I=1,K
      J=KK-I
      TT=TT-1.
    5 F(J)=CX*TT*F(J+1)-F(J+2)
      IF(X.GT.10.)GO TO 12
      PHI=FNU+2.
      ALFA=F(1)+F(3)*PHI
      T1=FNU-1.
      T2=T1-1.
      TT=1.
      DO 6 I=2,M
      TT=TT+1.
      PHI=PHI*(FNU+TT+TT)*(T1+TT)/(TT*(T2+TT+TT))
    6 ALFA=PHI*F(2*I+1)+ALFA
      CALL GAMMA(1.+FNU,TT,$50,$50)
      ALFA=CX**FNU*ALFA*TT
      I1=1
    7 DO 8 I=I1,K
    8 F(I)=F(I)/ALFA
      IF(N.GE.0)GO TO 11
    9 IF (IY.EQ.2) GO TO 49
      F(2)=CXNU*F(1)-F(2)
      IF(NN.LE.1)RETURN
      TT=FNU
      DO 10 I=2,NN
      TT=TT-1.
   10 F(I+1)=CX*TT*F(I)-F(I-1)
   11 IF(IY.EQ.1)RETURN
   49 N=M
      X=Y1
      FNU=Y2
   50 RETURN
C.....ASYMPTOTIC EXPANSION......
   12 KK=1
      FU=FNU
      XXX=1./X
```

```
      XX=XXX*XXX
      TT=1./SQRT(PI2*X)
   13 A=FU**2-.25
      C(5)=.25
      C(4)=.15625*A-.375
      C(3)=(.1171875*A-1.15625)*A+1.875
      C(2)=((.09521484375*A-2.38671875)*A+14.2265625)*A-19.6875
      C(1)=(((.08093261719*A-4.100585937)*A+58.224609375)*A-277.875)*A+
     1354.375
      P=C(1)
      DO 14 I=2,5
   14 P=P*XX+C(I)
      BT=(P*A*XX+1.)*TT
      C(5)=.5
      C(4)=.04166666*A-.25
      C(3)=(.0125*A-.35)*A+.75
      C(2)=((.0005580357143*A-.4241071428)*A+3.602678571)*A-5.625
      C(1)=(((.0030381944*A-.4861111)*A+10.29645833)*A-58.)*A+78.75
      P=C(1)
      DO 15 I=2,5
   15 P=P*XX+C(I)
      PHI=X+XXX*P*A-(FU+.5)*PI2
      IF(KK.EQ.2)GO TO 16
      F1=BT*COS(PHI)
      Y1=BT*SIN(PHI)
      FU=FAU+1.
      KX=2
      GO TO 13
   16 F2=BT*COS(PHI)
      Y2=BT*SIN(PHI)
      IF(X.GT.50.)GO TO 17
      IF(ABS (F1).LT.ABS(F2))GO TO 20
      ALFA=F(1)/F1
      GO TO 22
   17 F(1)=F1
      F(2)=F2
      IF(N)9,11,18
   18 IF(N.LE.1)GO TO 11
      TT=FNU
      DO 19 I=2,NN
      TT=TT+1.
   19 F(I+1)=CX*TT*F(I)-F(I-1)
      GO TO 11
   20 ALFA=F(2)/F2
   22 F(1)=F1
      F(2)=F2
      I1=3
      GO TO 7
      END
&I FOR GAMMA
      SUBROUTINE GAMMA(X,GAMMAX,$,$)
C-----------------------------------------------------------------------
C     CALCULATION OF THE GAMMA FUNCTION OF X.
C-----------------------------------------------------------------------
```

```
      DIMENSION A(8)
      DATA  (A(I),I=1,8)  /-.577191652,.988205891,-.897056937,
     1.918206857,-.756704078,.482199394,-.193527818,.035868343/
      DATA CV/.434294482/
      IF(ABS(X).LT.33.) GO TO 1
C-----------------------------------------------------------------------
C      THE MAGNITUDE OF X IS GREATER THAN 33.
C      THE BRIGGSIAN LOGARITHM OF THE GAMMA FUNCTION OF X  IS CALCULATED.
C-----------------------------------------------------------------------
      GAMMAX=(X-.5)*CV*ALOG(ABS(X))-CV*X+.39908995+CV*ALOG(1.+1./(12.*X)
     1+1./(288.*X*X)-139./(51840.*X*X*X))
      RETURN 3
C-----------------------------------------------------------------------
C      INITIALIZATION OF FACTOR (FACTORIAL X) AND XFACT (X-1).
C-----------------------------------------------------------------------
    1 FACTOR=1.
      XFACT=X-1.
      IF(XFACT.LT.0.) GO TO 3
C-----------------------------------------------------------------------
C      POSITIVE X
C-----------------------------------------------------------------------
    2 IF(XFACT.LT.1.) GO TO 5
      FACTOR=FACTOR*XFACT
      XFACT=XFACT-1.
      GO TO 2
C-----------------------------------------------------------------------
C      NEGATIVE X
C-----------------------------------------------------------------------
    3 XFACT=XFACT+1.
      FACTOR=FACTOR*XFACT
      IF(XFACT) 3,7,4
    4 FACTOR=1./FACTOR
C-----------------------------------------------------------------------
C      CALCULATION OF THE GAMMA FUNCTION OF X
C      THIS IS EQUAL TO THE GAMMA FUNCTION OF XFACT+1.
C-----------------------------------------------------------------------
    5 GAMMAX=0.
      DO 6 I=8,1,-1
    6 GAMMAX=(GAMMAX+A(I))*XFACT
      GAMMAX=(1.+GAMMAX)*FACTOR
      RETURN
C-----------------------------------------------------------------------
C      ERROR RETURN FOR X NEGATIVE INTEGER.
C-----------------------------------------------------------------------
    7 RETURN 4
      END
AN XCT HTAU
```

HT 0003-1A PIPE

| | THERMAL CONDUCTIVITY (BTU/HR.FT.F) | HEAT CAPACITY (BTU/LB.F) | DENSITY (LB/IN**3) |
|---|---|---|---|
| CYLINDER 1 (TUBE) | 89.50 | .2500 | .276 |
| CYLINDER 2 (HEATER) | 220.00 | .0950 | .3240 |

RADIAL DIMENSIONS (INCHES)

RADIUS 1 (ID OF TUBE/2) = .522
RADIUS 2 (MACHINED OD OF TUBE/2) = .649
RADIUS 3 (OD OF HEATER CYLINDER/2) = 1.500
RADIUS OF TEST POINT (TC LOCATION) = 1.094

| H (BTU/HR.FT**2.F) | TEST POINT RADIUS (IN) | TAU (SEC) | T0/T (AT TEST POINT RADIUS) |
|---|---|---|---|
| 150. | .522 | 194.365 | 4.4218 |
| 150. | 1.094 | 194.365 | 4.4485 |
| 150. | 1.500 | 194.365 | 4.4672 |
| 200. | .522 | 115.761 | 2.[illegible]10 |
| 200. | 1.094 | 115.761 | 3.[illegible]03 |
| 200. | 1.500 | 115.761 | 3.[illegible]51 |
| 300. | .522 | 86.931 | 2.[illegible]76 |
| 300. | 1.094 | 86.931 | 2.2073 |
| 300. | 1.500 | 86.931 | 2.2323 |
| 400. | .522 | 66.675 | 1.7200 |
| 400. | 1.094 | 66.675 | 1.7401 |
| 400. | 1.500 | 66.675 | 1.7672 |
| 500. | .522 | 57.090 | 1.4257 |
| 500. | 1.094 | 57.090 | 1.4572 |
| 500. | 1.500 | 57.090 | 1.4743 |
| [illegible] | .522 | [illegible] | 1.1209 |
| [illegible] | 1.094 | [illegible] | 1.1520 |
| [illegible] | 1.500 | [illegible] | 1.[illegible] |
| [illegible] | .522 | 4[illegible] | .[illegible] |
| [illegible] | 1.094 | 4[illegible] | 1.[illegible] |
| [illegible] | 1.500 | 4[illegible] | 1.1254 |
| [illegible] | .522 | 30.605 | .[illegible] |
| [illegible] | 1.094 | 30.605 | .[illegible] |
| [illegible] | 1.500 | 30.605 | 1.[illegible] |
| [illegible] | .522 | 30.111 | .7701 |
| [illegible] | 1.094 | 30.111 | .[illegible] |
| [illegible] | 1.500 | 30.111 | .[illegible] |
| [illegible] | [illegible] | [illegible] | .[illegible] |

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| | | | |
|---|---|---|---|
| 1050. | 1.044 | 34.233 | .6339 |
| 1050. | 1.500 | 35.233 | .6514 |
| 1150. | .522 | 20.857 | .6637 |
| 1150. | 1.044 | 20.857 | .7245 |
| 1150. | 1.500 | 20.857 | .7916 |
| 1250. | .522 | 27.861 | .6733 |
| 1250. | 1.044 | 27.861 | .7242 |
| 1250. | 1.500 | 27.861 | .7418 |
| 1350. | .522 | 26.163 | .6094 |
| 1350. | 1.044 | 26.163 | .6810 |
| 1350. | 1.500 | 26.163 | .6975 |
| 1450. | .522 | 26.698 | .6133 |
| 1450. | 1.044 | 26.698 | .6148 |
| 1450. | 1.500 | 26.698 | .6076 |
| 1550. | .522 | 23.422 | .6010 |
| 1550. | 1.044 | 23.422 | .7146 |
| 1550. | 1.500 | 23.422 | .6390 |
| 1650. | .522 | 25.302 | .6576 |
| 1650. | 1.044 | 25.302 | .6847 |
| 1650. | 1.500 | 25.302 | .7046 |
| 1750. | .522 | 21.309 | .6274 |
| 1750. | 1.044 | 21.309 | .6598 |
| 1750. | 1.500 | 21.309 | .6777 |
| 1850. | .522 | 2[illegible].425 | .6149 |
| 1850. | 1.044 | 2[illegible].425 | .6376 |
| 1850. | 1.500 | 2[illegible].425 | .6556 |
| 1950. | .522 | 11.634 | .7847 |
| 1950. | 1.044 | 11.634 | .6176 |
| 1950. | 1.50 | 11.634 | .6357 |
| 2050. | .522 | 10.913 | .6604 |
| 2050. | 1.044 | 10.913 | .7976 |
| 2050. | 1.500 | 10.913 | .6177 |

HEAT TRANSFER COEFFICIENT VS. TAU

COEFFICIENTS FOR LN(H)=A+B*LN(TAU)+C*(LN(TAU))**2+D*(LN(TAU))**3

A= 13.302429
B= -2.612504
C= .303179
D= -.029704

RMS DEVIATION OF OBSERVED H FROM THE CALCULATED H IS 1.6805 BTU/HR-FT**2-DEG F

| POINT | TAU | HEAT TRANS. COEF. | LN(TAU) | LN(H) | CALCULATED H | H DIFFERENCE | PERCENT DIFFERENCE |
|---|---|---|---|---|---|---|---|
| 1 | 196.3009 | 150.0000 | 5.279975 | 5.010635 | 149.819047 | .180953 | .120635 |
| 2 | 119.7686 | 250.0000 | 4.785404 | 5.521461 | 250.733703 | -.733703 | -.293481 |
| 3 | 86.9913 | 350.0000 | 4.465818 | 5.857933 | 350.320976 | -.320976 | -.091707 |
| 4 | 68.6945 | 450.0000 | 4.229670 | 6.109248 | 449.645298 | .354702 | .078823 |
| 5 | 57.0703 | 550.0000 | 4.044030 | 6.309918 | 549.123778 | .876222 | .159313 |
| 6 | 49.0984 | 650.0000 | 3.893012 | 6.476972 | 648.872780 | 1.127220 | .173418 |
| 7 | 43.1088 | 750.0000 | 3.765117 | 6.620073 | 748.932689 | 1.067311 | .142549 |
| 8 | 38.6045 | 850.0000 | 3.653947 | 6.745236 | 849.234679 | .765321 | .087645 |
| 9 | 35.1119 | 950.0000 | 3.558516 | 6.856462 | 949.750643 | .249357 | .026205 |
| 10 | 32.2920 | 1050.0000 | 3.472985 | 6.956545 | 1050.419541 | -.419541 | -.039956 |
| 11 | 29.8372 | 1150.0000 | 3.396075 | 7.047517 | 1151.033729 | -1.033729 | -.089889 |
| 12 | 27.6010 | 1250.0000 | 3.327230 | 7.130899 | 1251.630620 | -1.630620 | -.130450 |
| 13 | 26.1027 | 1350.0000 | 3.264333 | 7.207860 | 1351.970427 | -1.970427 | -.145982 |
| 14 | 24.6776 | 1450.0000 | 3.206707 | 7.279319 | 1452.174601 | -2.174601 | -.149972 |
| 15 | 23.4426 | 1550.0000 | 3.153678 | 7.346010 | 1552.062564 | -2.062564 | -.133069 |
| 16 | 22.3415 | 1650.0000 | 3.106695 | 7.408531 | 1651.567164 | -1.567164 | -.094980 |
| 17 | 21.3387 | 1750.0000 | 3.059115 | 7.467371 | 1750.700880 | -.700880 | -.040048 |
| 18 | 20.4647 | 1850.0000 | 3.016744 | 7.522941 | 1849.222051 | .777949 | .042051 |
| 19 | 19.6249 | 1950.0000 | 2.977056 | 7.575585 | 1947.390699 | 2.609301 | .133400 |
| 20 | 18.9432 | 2050.0000 | 2.939861 | 7.625595 | 2044.965316 | 5.034684 | .245599 |

[illegible]   16102141.489

# APPENDIX C. COMPUTER PROGRAM LABTTF

Input data required is described by comment cards at the beginning of the program listing. A sample of processed data is included at the end of the program listing.

```
@ RUN LABTTF,PL7SDH20,0,9,099,,,PR1
@ PWC CAN
@ HDG       RUN OF LABTTF FOR ERDA REPORT (NOV 77)
@I FOR LABTTF
C
C  ORDER OF DATA CARDS FOR EACH SET OF DATA
C
C  LABEL   IDENTIFICATION OF HEAT EXCHANGER TUBE (20A4)
C  NPRELN  NUMBER OF THERMOCOUPLE POINTS TAKEN BEFORE HEAT IS CUT   (I3)
C  ICHAN(I),IDATA(I)  CHANNEL NUMBER AND THERMOCOUPLE, THERMISTOR, OR FLOW
C                     METER DATA   (I1,1X,I6,7(1X,I1,1X,I6)
C                     END OF DATA SET IS RECCRDED AS AN ICHAN VALUE OF 9 AND
C                     AN IDATA VALUE OF 99999.
C
      DIMENSION LABEL(20)
      DIMENSION ICHAN(2000),IDATA(2000),TTC(2000),VTC(2000),VTCSHF(1000)
      DIMENSION TTH(2000),VTH(2000),TTHSHF(1000),VTHSHF(1000)
      DIMENSION TFM(2000),VFM(2000),TFMSHF(1000),VFMSHF(1000)
      DIMENSION X(1000),Y(1000),SIGMAY(1000),CHISQR(1000),WT(1000),
     D DIFF(1000),YFIT(1000)
      DIMENSION TWATER(1000),FLOVEL(1000)
C
C      EXPLANATION OF INPUTS MADE THROUGN DATA STATEMENTS
C
C  TIMIVL  TIME INTERVAL BETWEEN SUCCESSIVE PIECES OF DATA.  FOR EXAMPLE, IF
C          THERMOPILE DATA ARE TAKEN AT T=0 SEC. THERMISTOR DATA AT T=2 SEC.
C          AND FLOW METER DATA AT T=4 SEC. THEN TIMIVL=2.0 SEC.
C  NZERO   NUMBER OF THERMOPILS DATA POINTS AT THE END OF THE DECAY WHICH WILL BE
C          USED IN CALCULATING THE ZERO POINT FOR THE THERMOPILE AS WELL AS IN
C          ESTIMATING A CONSTANT IN THE WEIGHTING OF THE DECAY DATA FOR THE FIT
C          OF TAU.
C  THMIN   TIME (MEASURED AFTER HEAT HAS BEEN CUT) WHICH MARKS THE BEGINNING
C          OF THE ANALYSIS WINCOW FOR FITTING TAU.
C  WINDOW  NUMBER OF TIME CONSTANTS AFTER THMIN DURING WHICH THE THERMOPILE
C          DECAY IS TO BE ANALYZED TO EXTRACT A TAU.
C  NPCARD  NUMBER OF DATA POINTS PER CARD.
C  THINT   INTERCEPT IN CENTIGRADE DEGREES OF THE THERMISTOR CALIBRATION CURVE
C          (TWATER(I)=THINT+THSLP*VTH(I))
C  THSLP   SLOPE OF THERMISTOR CALIBRATION CURVE ABOVE.
C  AVOLFM  CALIBRATION CONSTANT OF RAMAPO FLOW METER FOR USE IN CALIBRATION
C          EQUATION  FLOW(GAL/MIN)=AVOLFM*SQRT((VFM-VFMZRO)/VEXCIT)
C  VEXCIT  EXCITATION VOLTAGE IN VOLTS OF RAMAPO FLOW METER STRAIN GAUGE BRIDGE.
C  TUBEID  ID OF HEAT EXCHANGER TUBE (IN).
C  VFMZRO  FLOW METER VOLTAGE READING WITH NO FLOW (MV).
C  HINTR   INTERCEPT ON ORDINATE AXIS IN 1/H VERSUS 1/V**0.8 PLOT.
C  ACCN, BCCN, CCCN, DCCN  COEFFICIENTS IN THE RELATION WHICH CONVERTS TAU TO
C          H ACCORDING TO A TWO-CYLINDER MODEL WITH NO AIR, WALL, OR INTERFACE
C          CORRECTIONS.  WITH TAU IN SECONDS AND H IN BTU/HR FT**2 F, THE
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C          RELATION IS
C          LN(H)=ACCN+BCCN*(LN(TAU))+CCCN*(LN(TAU))**2+DCCN*(LN(TAU))**3.
C   RAD1  1/2 ID OF TUBE (IN).
C   RAD2  1/2 OD OF TUBE (IN).
C   RAD3  1/2 OD OF HEATER CYLINDERS (IN).
C   AKTUBE  THERMAL CONDUCTIVITY OF TUBE (BTU/HR FT F).
C   AKCYL  THERMAL CONDUCTIVITY OF HEATER CYLINDERS (BTU/HR FT F).
C   ALNGTH  LENGTH OF HEATER CYLINDER SET (IN).
C   TTHWLL  WALL THICKNESS OF THIN-WALLED SECTION OF THE TUBE (IN).
C
      DATA TIMIVL/2.0/,NZERO/10/,TMININ/20.0/,WINDOW/3.5/,NPCARD/8/
      DATA THINT/25.331/,THSLP/0.2715/
      DATA AVOLFM/35.16/,VEXCIT/5.00/,TUBEID/1.055/,VFMZRO/000./
      DATA HINTR/0.000023/,ACCN/36.0840/,BCCN/-16.2760/,CCCN/3.0628/,
     1 DCCN/-0.20682/,AKTUBE/12.7/,AKCYL/225./,RAD1/0.5275/,RAD2/0.6495/
     2,RAD3/1.500/,HAIR/1.57/,ALNGTH/12.00/,TTHWLL/0.122/
C
      ISET=0
    1 CONTINUE
      ISET=ISET+1
      READ(5,505,END=999) LABEL
  505 FORMAT(20A4)
      READ(5,525) NPRELM
  525 FORMAT(I3)
C
C   READ AND COUNT DATA POINTS FOR THIS SET (ASSUMES NPCARD DATA POINTS/CARD)
C
      ICARD=0
  100 CONTINUE
      ICARD=ICARD+1
      IBEGIN=(ICARD-1)*NPCARD+1
      IEND=IBEGIN+NPCARD-1
      READ(5,530) (ICHAN(I),IDATA(I),I=IBEGIN,IEND)
  530 FORMAT(I1,1X,I6,7(1X,I1,1X,I6))
      DO 105 I=IBEGIN,IEND
      IF(ICHAN(I).EQ.9.AND.IDATA(I).EQ.99999) GO TO 110
      NPOINT=I
  105 CONTINUE
      GO TO 100
  110 CONTINUE
      WRITE(6,600) ISET
  600 FORMAT(1H1,19X,'DATA SET',I3,/,20X,'**** *** **',/)
      WRITE(6,605) LABEL
  605 FORMAT(20X,20A4)
      WRITE(6,625) TIMIVL
  625 FORMAT(25X,'TIME BETWEEN SUCCESSIVE VOLTAGE READINGS =',F7.2,
     1' SECONDS')
      WRITE(6,630) NPRELM
  630 FORMAT(25X,'NUMBER OF V(TC) POINTS TAKEN BEFORE HEAT IS CUT =',I3)
      WRITE(6,635) NPOINT
  635 FORMAT(//,9X,'TOTAL NUMBER OF POINTS IN THIS DATA SET =',I4)
      WRITE(6,640)
  640 FORMAT(/,1X,9(3X,'ICHAN IDATA'),/)
      WRITE(6,645) (ICHAN(I),IDATA(I),I=1,NPOINT)
```

```
  645 FORMAT(9(I8,I6))
C
C  BEGIN ANALYSIS WITH THE FIRST OCCURRENCE OF CHANNEL 0.  (BLANKS CAN APPEAR
C  ON LEFT OF FIRST DATA CARD).
C
      I=0
  112 I=I+1
      IF(ICHAN(I).NE.0) GO TO 112
      IBEGIN=I
C
C  FILL THE (REAL) VTC, VTH, AND VFM ARRAYS BEGINNING WITH THE ZERO TIME POINT
C  (SKIP INITIAL STEADY STATE POINTS).  THE FOLLOWING CODE ASSUMES THE DATA
C  POINTS ARE NOW IN PROPER SEQUENCE (0,1,2)
C
      JBEGIN=IBEGIN+3*INPRELM-1)
      ITC=0
      ITH=0
      IFM=0
      DO 119 J=JBEGIN,NPOINT
      IDIRCT=ICHAN(J)+1
      GO TO (115,116,117),IDIRCT
  115 ITC=ITC+1
      VTC(ITC)=+IDATA(J)
      TTC(ITC)=(J-JBEGIN)*TIMIVL
      GO TO 118
  116 ITH=ITH+1
      VTH(ITH)=+IDATA(J)
      TTH(ITH)=(J-JBEGIN)*TIMIVL
      GO TO 118
  117 IFM=IFM+1
      VFM(IFM)=+IDATA(J)
      TFM(IFM)=(J-JBEGIN)*TIMIVL
  118 CONTINUE
      ITCEND=ITC
      ITHEND=ITH
      IFMEND=IFM
C
C  PRINTOUT OF DATA WHICH HAS BEEN SHIFTED TO BEGIN AT THE TIME WHEN THE HEAT
C  IS CUT
C
      WRITE(6,610) NPRELM,TIMIVL
  610 FORMAT(//,4X,'PRINTOUT OF SHIFTED DATA WITH NPRELM =',I3,
     1 ' AND TIMIVL =',F5.1,' SECONDS.')
      WRITE(6,612) ITCEND
  612 FORMAT(//,4X,'CHANNEL 0 - THERMOPILE (',I4,' POINTS)',/,
     17(5X,'TTC',5X,'VTC',1X))
      WRITE(6,614) (TTC(I),VTC(I),I=1,ITCEND)
  614 FORMAT(7(F9.0,F8.0))
      WRITE(6,616) ITHEND
  616 FORMAT(//,4X,'CHANNEL 1 - THERMISTOR (',I4,' POINTS)',/,
     1 7(5X,'TTH',5X,'VTH',1X),/)
      WRITE(6,614) (TTH(I),VTH(I),I=1,ITHEND)
      WRITE(6,618) IFMEND
  618 FORMAT(//,4X,'CHANNEL 2 - FLOW METER (',I4,' POINTS)',/,
```

```
     1 7(5X,'TFM',5X,'VFM',1X),/)
      WRITE(6,614) (TFM(I),VFM(I),I=1,IFMEND)
C
C  DETERMINE THERMOCOUPLE ZERO-POINT AND ITS RMS DEVIATION TO BE USED
C  IN WEIGHTING FACTOR
C
      IZEROB=ITCEND-NZERO+1
      IZEROE=ITCEND
      SUMZRO=0.0
      DO 120 I=IZEROB,IZEROE
      SUMZRO=SUMZRO+VTC(I)
  120 CONTINUE
      VTCZRO=SUMZRO/NZERO
      SUMVAR=0.0
      DO 125 I=IZEROB,IZEROE
      SUMVAR=SUMVAR+(VTC(I)-VTCZRO)**2
  125 CONTINUE
      VARZRO=SUMVAR/(NZERO-1)
      STDZRO=SQRT(VARZRO)
C
C  ADJUSTING RAW DATA FOR ZERO POINT
C
      DO 127 I=1,ITCEND
      VTC(I)=VTC(I)-VTCZRO
  127 CONTINUE
      WRITE(6,650) NZERO,VTCZRO
  650 FORMAT(//,20X,'ZERO POINT FOR THIS MEASUREMENT DETERMINED FROM THE
     1 LAST',I4,' THERMOPILE DATA POINTS =',F9.2)
      WRITE(6,655) STDZRO,VARZRO
  655 FORMAT(20X,'RMS DEVIATION FROM ZERO POINT =',F8.2,/,20X,
     1 'VARIANCE (USED IN WEIGHTING OF DATA FOR FIT) =',F9.2)
C
C  FITTING THE DATA OVER SPECIFIED TIME 'WINDOWS'
C
      DO 888 IFIT=1,2
      GO TO (122,123),IFIT
  122 TMIN=-1.0
      TMAX=-1.0
      GO TO 128
  123 TMIN=TMININ
      TMAX=TMIN+WINDOW*TAU
C
      IF(TMAX.GT.TMIN) GO TO 128
      TMXSAV=TMAX
      TMAX=TMIN
      TMIN=TMXSAV
  128 CONTINUE
      MAXTIM=TTC(ITCEND)
      IF(TMIN.GE.MAXTIM) TMIN=-1.0
      IF(TMIN.GT.0.0) GO TO 130
      TMIN=0.0
      LBEGIN=1
      GO TO 140
  130 CONTINUE
```

```
      DO 135 I=1,ITCEND
      IF(TMIN.GT.TTC(I)) GO TO 135
      LBEGIN=I
      GO TO 140
  135 CONTINUE
  140 CONTINUE
      IF(TMAX.GE.MAXTIM)  TMAX=-1.0
      IF(TMAX.GT.0.0) GO TO 145
      TMAX=MAXTIM
      LEND=ITCEND
      NPTFIT=LEND-LBEGIN+1
      GO TO 150
  145 CONTINUE
      DO 147 I=LBEGIN,ITCEND
      IF(TTC(I).LT.TMAX) GO TO 147
      LEND=I-1
      NPTFIT=LEND-LBEGIN+1
      GO TO 150
  147 CONTINUE
  150 CONTINUE
C
C  FILLING ARRAY WITH VARIABLES FROM TIME 'WINDOWS'
C
      DO 155 I=1,NPTFIT
      L=LBEGIN+I-1
      X(I)=TTC(L)
      VTCSHF(I)=VTC(L)
      TTMSHF(I)=TTM(L)
      VTMSHF(I)=VTM(L)
      TFMSHF(I)=TFM(L)
      VFMSHF(I)=VFM(L)
      ARG1=ABS(VTC(L))
      IF(ARG1.LT.0.001) ARG1=0.001
      Y(I)=ALOG(ARG1)
      SIGMAY(I)=STCZRO/VTC(L)
  155 CONTINUE
      CALL LINFIT(X,Y,SIGMAY,NPTFIT,1,A,SIGMAA,B,SIGMAB,R,WT,CHISQR,
     1 CHITOT,STC)
      DO 157 I=1,NPTFIT
      YFIT(I)=A+B*X(I)
      ARG2=ABS(VTCSHF(I))
      IF(ARG2.LT.0.001) ARG2=0.001
      DIFF(I)=YFIT(I)-ALOG(ARG2)
  157 CONTINUE
C
C  FITTED VARIABLES AND ERRORS TRANSFORMED TO VARIABLES OF THE PROBLEM AND
C  THEIR ERRORS
C
      VO=EXP(A)
      VOHIGH=EXP(A+SIGMAA)
      VOLOW=EXP(A-SIGMAA)
      TAU=-1.0/B
      TAUHI=-1.0/(B+SIGMAB)
      TAULOW=-1.0/(B-SIGMAB)
```

```
      WINTAU=(TMAX-TMIN)/TAU
      WRITE(6,660) IFIT,ISET
  660 FORMAT(////,20X,'FIT',I3,' FOR DATA SET',I3,/)
      WRITE(6,605) LABEL
      WRITE(6,665)
  665 FORMAT(/,20X,'FIT DATA (ADJUSTED FOR ZERO POINT) TO STRAIGHT LINE
     1OF THE FORM Y=A+B*X, WHERE',/,25X,'X = T',/,25X,'Y = LN(VTC(T))',
     2/,25X,'A = LN(V(T=0))',/,25X,'B = -1/TAU')
      WRITE(6,670) NPTFIT,TMIN,TMAX,WINTAU
  670 FORMAT(/,20X,'ONLY',I5,' DATA POINTS WHICH SATISFY THE CRITERIA T.
     1GT.',F7.2,' SEC .AND. T.LT.',F8.2,' SEC',/,20X,'ARE INCLUDED IN TH
     2E FIT',/,20X,'THIS WINDOW IS',F6.2,' TIME CONSTANTS WIDE')
      WRITE(6,675) A,SIGMAA,B,SIGMAB,CHITOT,STD,R
  675 FORMAT(/,20X,'RESULT OF THE FIT',/,25X,'A =',F10.6,7X,'SIGMAA =',
     1 F10.7,/,25X,'B =',F10.7,7X,'SIGMAB =',F10.7,/,25X,
     2 'CHISQR =',F10.3,/,25X,'STD =',F14.8,/,25X,'R =',F8.4)
      WRITE(6,680) VO,VOLOW,VOHIGH
  680 FORMAT(/,20X,'OR, IN TERMS OF VARIABLES OF THE PROBLEM',/,25X,
     1 'V(T=0) =',F8.1,9X,'ERROR RANGE',F8.1,' TO',F8.1)
      WRITE(6,685) TAU,TAULOW,TAUHI
  685 FORMAT(25X,'TAU =',F8.3,12X,'ERROR RANGE',F8.3,' TO',F8.3,/)
C
C  CONVERTING THERMISTOR SIGNAL TO WATER TEMPERATURE (C) AND
C  FLOW METER SIGNAL TO FLOW VELOCITY (FT/SEC).
C  THERMISTOR IS VECO 3506 POTTED WITH MILLER-STEPHENSON EPOXY IN A COPPER
C  RECTANGLE BY PAUL RUNCO (8/76).  VTHSHF IS IN MV.
C
      SUMTW=0.0
      SUMFV=0.0
      ALINFM=AVOLFM*SQRT(1.0/VEXCIT)*0.4085/TUBEID**2
      NPTAVE=NPTFIT-1
      DO 160 I=1,NPTAVE
      TWATER(I)=THINT+THSLP*(0.001*VTHSHF(I))
      SUMTW=SUMTW+TWATER(I)
      FLOVEL(I)=ALINFM*SQRT(0.001*(VFMSHF(I)-VFMZRO))
      SUMFV=SUMFV+FLOVEL(I)
  160 CONTINUE
      AVETW=SUMTW/NPTAVE
      AVEFV=SUMFV/NPTAVE
C
C  STANDARD DEVIATION OF WATER TEMPERATURE AND FLOW VELOCITY OVER ANALYSIS
C  WINDOW
C
      SUMSQT=0.0
      SUMSQF=0.0
      DO 165 I=1,NPTAVE
      SUMSQT=SUMSQT+(TWATER(I)-AVETW)**2
      SUMSQF=SUMSQF+(FLOVEL(I)-AVEFV)**2
  165 CONTINUE
      STDTW=SQRT(SUMSQT/(NPTAVE-1))
      STDFV=SQRT(SUMSQF/(NPTAVE-1))
      WRITE(6,686)
  686 FORMAT(20X,'WATER TEMPERATURE AND FLOW VELOCITY DURING ANALYSIS WI
     1NDOW',//,10X,'TIME (SEC)',3X,'WATER TEMP (C)',13X,'TIME (SEC)',
```

```
      23X,'FLOW VELOCITY (FT/SEC)',/)
       WRITE(6,687) (TTHSHF(I),TWATER(I),TEMSHF(I),FLOVEL(I),I=1,NPTAVE)
  687 FORMAT(1X,F16.1,F16.3,F24.1,F19.3)
       WRITE(6,688) AVETW,STDTW,AVEFV,STDFV
  688 FORMAT(/,10X,'AVERAGE WATER TEMPERATURE IS',F8.3,' PLUS OR MINUS'
      1,F6.3,/,10X,'AVERAGE FLOW VELOCITY IS',F7.3,' PLUS OR MINUS',F6.3,
      2//)
C
C  CCN CONVERTS TAU TO H, CORRECTS H FOR HEAT LOSSES TO THE AIR AND TO THE TUBE
C  WALLS, AND NORMALIZES THE RESULT TO 70 F.
C
       CALL CCN(TAU,AVETW,AVEFV,HINTR,ACCN,BCCN,CCCN,DCCN,AKTUBE,
      1 AKCYL,RAD1,RAD2,RAD3,HAIR,ALNGTH,TTHWLL)
       WRITE(6,690)
  690 FORMAT(//,20X,'DETAILS OF FIT',//,10X,'POINT',11X,
      1 'TIME',7X,'VTC(OBS)',3X,'LN(VTC(OBS))',3X,'LN(VTC(FIT))',
      2 5X,'DIFFERENCE',9X,'WEIGHT',9X,'CHISQR',/)
       WRITE(6,695) (I,X(I),VTCSHF(I),Y(I),YFIT(I),DIFF(I),WT(I),
      1 CHISQR(I),I=1,NPTFIT)
  695 FORMAT(I15,7E15.5)
  888 CONTINUE
       GO TO 1
  999 CONTINUE
       STOP
       END
ƎI FOR LINFIT
C
C  LINFIT WAS LIFTED FROM 'DATA REDUCTION AND ERROR ANALYSIS FOR THE PHYSICAL
C  SCIENCES' BY BEVINGTON, PAGE 104
C
       SUBROUTINE LINFIT(X,Y,SIGMAY,NPTS,MODE,A,SIGMAA,B,SIGMAB,R,WT,
      1 CHISQR,CHITOT,STD)
       DOUBLE PRECISION SUM,SUMX,SUMY,SUMX2,SUMY2
       DOUBLE PRECISION XI,YI,WEIGHT,DELTA,VARNCE
       DIMENSION X(1),Y(1),SIGMAY(1),CHISQR(1),WT(1)
C
C  ACCUMULATE WEIGHTED SUMS
C
   11 SUM=0.
       SUMX=0.
       SUMY=0.
       SUMX2=0.
       SUMXY=0.
       SUMY2=0.
   21 DO 50 I=1,NPTS
       XI=X(I)
       YI=Y(I)
       IF(MODE) 31,36,38
   31 IF(YI) 34,36,32
   32 WEIGHT=1./YI
       GO TO 41
   34 WEIGHT=1./(-YI)
       GO TO 41
   36 WEIGHT=1.
```

```
      GO TO 41
   38 WEIGHT=1./SIGMAY(I)**2
      WT(I)=WEIGHT
   41 SUM=SUM+WEIGHT
      SUMX=SUMX+WEIGHT*XI
      SUMY=SUMY+WEIGHT*YI
      SUMX2=SUMX2+WEIGHT*XI*XI
      SUMXY=SUMXY+WEIGHT*XI*YI
      SUMY2=SUMY2+WEIGHT*YI*YI
   50 CONTINUE
C
C  CALCULATE COEFFICIENTS AND STANDARD DEVIATIONS
C
   51 DELTA=SUM*SUMX2 - SUMX*SUMX
      A=(SUMX2*SUMY - SUMX*SUMXY)/DELTA
   53 B=(SUMXY*SUM - SUMX*SUMY)/DELTA
      CHITOT=0.0
      DO 55 I=1,NPTS
      CHISQR(I)=WT(I)*(A+B*X(I)-Y(I))**2
      CHITOT=CHITOT+CHISQR(I)
   55 CONTINUE
   61 IF(MODE) 62,64,62
   62 VARNCE=1.
      GO TO 67
   64 C=NPTS-2
      VARNCE=(SUMY2 + A*A*SUM + B*B*SUMX2
     1 -2.*(A*SUMY + B*SUMXY - A*B*SUMX))/C
   67 SIGMAA=DSQRT(VARNCE*SUMX2/DELTA)
   68 SIGMAB=DSQRT(VARNCE*SUM/DELTA)
   71 R=(SUM*SUMXY - SUMX*SUMY)/
     1 DSQRT(DELTA*(SUM*SUMY2 - SUMY*SUMY))
      STD=SQRT((NPTS/(NPTS-2))*(CHITOT/SUM))
      RETURN
      END
21 FOR CON
      SUBROUTINE CON(TAU,TWATER,FLOVEL,HINTR,A,B,C,D,AKTUBE,
     1 AKCYL,RAD1,RAD2,RAD3,HAIR,ALNGTH,TTHWLL)
C
C  TAU IS CONVERTED TO H BY THE RELATION
C       LN(H) = A + B*LN(TAU) + C*(LN(TAU))**2 + D*LN(TAU))**3 .
C  THIS RELATION IS A FIT TO THE NUMBERS THAT WERE GENERATED BY HTAU (FETTE'S
C  TWO-CYLINDER PROGRAM)
C
      IF(TAU.LT.0.0001) RETURN
      FNTAU=ALOG(TAU)
      FNH=A+B*FNTAU+C*FNTAU**2+D*FNTAU**3
      HUNCOR=EXP(FNH)
      HWATRR=1.0/HUNCOR-HINTR
C
C  CORRECTIONS FOR HEAT LOSS TO AIR AND TO WALLS OF HEAT
C  EXCHANGER TUBE.  SEE PAGE 110 OF LAB BOOK II.
C
      HCYL=(AKCYL/RAD1*12.0)/ALOG(RAD3/RAD2)
      HCYLR=1.0/HCYL
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      HTUBE=(AKTUBE/RAD1*12.0)/ALOG(RAD2/RAD1)
      HTUBER=1.0/HTUBE
      RAIR=(HCYLR+HINTR+HTUBER+HWATRR)*HAIR*(RAD3/RAD1)
      HCORA=HUNCOR*(1.0-RAIR)
C
      HWTUWR=1.0/HCORA-HINTR
      HWTUW=1.0/HWTUWR
      WLLCON=(2.0/ALNGTH*12.0)*SQRT(AKTUBE*TTHWLL/12.0)
      RWALLS=WLLCON/SQRT(HWTUW)
      HCORAW=HWTUW*(1.0-RWALLS)
      HCORR=1.0/HCORAW+HINTR
      FCC9=1.0/HCOR9
C
C  NORMALIZE HCOR TO 70 F BY THE FACTOR (1 + .012*TWATER)
C
      ANORM=(1.0+.012*70.)/(1.0+.012*(1.8*TWATER+32.))
      HCRAWN=ANORM*HCORAW
      HCORNR=1.0/HCRAWN+HINTR
      HCORN=1.0/HCORNR
      V89=FLOVEL**(-0.8)
      WRITE(6,600)
  600 FORMAT(//,20X,'TIME CONSTANT (TAU) CONVERTED TO HEAT TRANSFER COEF
     1FICIENT (H) WITH CORRECTIONS FOR HEAT LOSS',/,20X,
     2 'TO AIR AND TO HEAT EXCHANGER TUBE WALLS')
      WRITE(6,605) HUNCOR,HINTR,RAIR,RWALLS,HCOR
  605 FORMAT(25X,'H(UNCORRECTED) =',F8.2,' BTU/(HR FT**2 F)',/,
     1 25X,'1.0/HINTERCEPT =',F9.6,' (BTU/HR FT**2 F)**-1',/,
     2 25X,'RAIR =',F8.5,/,25X,'RWALLS =',F8.5,/,
     3 25X,'H(CORRECTED) =',F8.2,' BTU/(HR FT**2 F)')
      WRITE(6,610)
  610 FORMAT(/,20X,'H(CORRECTED) NORMALIZED TO 70 F (NORMALIZATION STRIC
     1TLY NOT CORRECT SINCE THE TEMPERATURE-INDEPENDENT',/,20X,
     2 'FOULING CONTRIBUTION IS NOT SUBTRACTED FROM H(CORRECTED)')
      WRITE(6,615) ANORM,HCORN,HCORNR,V8R
  615 FORMAT(25X,'NORMALIZATION FACTOR =',F6.3,/,25X,'H(CORRECTED,NORMAL
     1IZED) =',F8.2,' BTU/(HR FT**2 F)',/,25X,'1.0/H(CORRECTED,NORMALIZE
     2D) =',F9.7,/,25X,'1.0/V**0.8 =',F7.4)
      RETURN
      END
2N XCT LABTTF
```

DATA SET 1

LAB DATA OF 07/30/77, TI 0337-76 (0.1 TUBE, FM 30K3, THERMISTOR BRIDGE NO. 1 RUN 1

TIME BETWEEN SUCCESSIVE VOLTAGE READINGS = 2.00 SECONDS

NUMBER OF VTC POINTS TAKEN BEFORE HEAT IS CUT = 6

TOTAL NUMBER OF POINTS IN THIS DATA SET = 232

| ICHAN | IDATA | ICHAN | IDATA | ICHAN | IDATA | ICHAN | IDATA | ICHAN | IDATA | ICHAN | IDATA | ICHAN | IDATA | ICHAN | IDATA | ICHAN | IDATA |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2 | 2861 | 0 | 6270 | 1 | 1941 | 2 | 2819 | 0 | 6273 | 1 | 1943 | 2 | 2856 | 0 | 6269 | 1 | 1947 |
| 2 | 2850 | 0 | 6268 | 1 | 1950 | 2 | 2830 | 0 | 6066 | 1 | 1954 | 2 | 2860 | 0 | 6262 | 1 | 1959 |
| 2 | 2843 | 0 | 4963 | 1 | 1957 | 2 | 2852 | 0 | 5143 | 1 | 1957 | 2 | 2845 | 0 | 4375 | 1 | 1961 |
| 2 | 2861 | 0 | 3708 | 1 | 1960 | 2 | 2844 | 0 | 3147 | 1 | 1961 | 2 | 2840 | 0 | 2666 | 1 | 1960 |
| 2 | 2835 | 0 | 2209 | 1 | 1957 | 2 | 2833 | 0 | 1615 | 1 | 1958 | 2 | 2816 | 0 | 1617 | 1 | 1958 |
| 2 | 2831 | 0 | 1305 | 1 | 1953 | 2 | 2840 | 0 | 1153 | 1 | 1953 | 2 | 2868 | 0 | 978 | 1 | 1953 |
| 2 | 2863 | 0 | 828 | 1 | 1948 | 2 | 2838 | 0 | 495 | 1 | 1946 | 2 | 2845 | 0 | 586 | 1 | 1944 |
| 2 | 2854 | 0 | 492 | 1 | 1941 | 2 | 2852 | 0 | 413 | 1 | 1937 | 2 | 2829 | 0 | 363 | 1 | 1936 |
| 2 | 2850 | 0 | 206 | 1 | 1931 | 2 | 2844 | 0 | 235 | 1 | 1925 | 2 | 2840 | 0 | 143 | 1 | 1927 |
| 2 | 2861 | 0 | 137 | 1 | 1924 | 2 | 2829 | 0 | 127 | 1 | 1921 | 2 | 2843 | 0 | 102 | 1 | 1917 |
| 2 | 2844 | 0 | 81 | 1 | 1913 | 2 | 2835 | 0 | 61 | 1 | 1916 | 2 | 2860 | 0 | 43 | 1 | 1913 |
| 2 | 2818 | 0 | 29 | 1 | 1906 | 2 | 2827 | 0 | 17 | 1 | 1905 | 2 | 2820 | 0 | 7 | 1 | 1903 |
| 2 | 2834 | 0 | 0 | 1 | 1900 | 2 | 2843 | 0 | -4 | 1 | 1890 | 2 | 2853 | 0 | -19 | 1 | 1895 |
| 2 | 2829 | 0 | -19 | 1 | 1890 | 2 | 2844 | 0 | -20 | 1 | 1887 | 2 | 2823 | 0 | -26 | 1 | 1887 |
| 2 | 2849 | 0 | -29 | 1 | 1882 | 2 | 2870 | 0 | -31 | 1 | 1883 | 2 | 2834 | 0 | -36 | 1 | 1877 |
| 2 | 2839 | 0 | -37 | 1 | 1876 | 2 | 2842 | 0 | -38 | 1 | 1872 | 2 | 2854 | 0 | -39 | 1 | 1869 |
| 2 | 2852 | 0 | -38 | 1 | 1868 | 2 | 2849 | 0 | -41 | 1 | 1867 | 2 | 2835 | 0 | -40 | 1 | 1864 |
| 2 | 2843 | 0 | -39 | 1 | 1861 | 2 | 2828 | 0 | -39 | 1 | 1864 | 2 | 2856 | 0 | -41 | 1 | 1854 |
| 2 | 2842 | 0 | -41 | 1 | 1853 | 2 | 2841 | 0 | -43 | 1 | 1856 | 2 | 2836 | 0 | -45 | 1 | 1850 |
| 2 | 2844 | 0 | -45 | 1 | 1847 | 2 | 2861 | 0 | -46 | 1 | 1844 | 2 | 2828 | 0 | -43 | 1 | 1842 |
| 2 | 2851 | 0 | -42 | 1 | 1840 | 2 | 2825 | 0 | -42 | 1 | 1837 | 2 | 2839 | 0 | -42 | 1 | 1836 |
| 2 | 2853 | 0 | -41 | 1 | 1836 | 2 | 2837 | 0 | -39 | 1 | 1832 | 2 | 2832 | 0 | -40 | 1 | 1832 |
| 2 | 2843 | 0 | -41 | 1 | 1828 | 2 | 2841 | 0 | -42 | 1 | 1828 | 2 | 2852 | 0 | -42 | 1 | 1824 |
| 2 | 2846 | 0 | -44 | 1 | 1824 | 2 | 2840 | 0 | -44 | 1 | 1822 | 2 | 2851 | 0 | -47 | 1 | 1817 |
| 2 | 2843 | 0 | -47 | 1 | 1816 | 2 | 2839 | 0 | -47 | 1 | 1818 | 2 | 2850 | 0 | -45 | 1 | 1814 |
| 2 | 2871 | 0 | -43 | 1 | 1809 | 2 | 2839 | 0 | -45 | 1 | 1811 | 2 | 2834 | | | | |

PRINTOUT OF SHIFTED DATA WITH NPRECM = 6 AND TINTVL = 2.0 SECONDS

CHANNEL 0 - THERMISTOR ( 72 POINTS)

| TTC | VTC | TTC | VTC | TTC | VTC | TTC | VTC | TTC | VTC | TTC | VTC | TTC | VTC |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0. | 6262. | 6. | 5963. | 12. | 5143. | 18. | 4375. | 24. | 3706. | 30. | 3147. | 36. | 2666. |
| 42. | 2606. | 48. | 1915. | 54. | 1617. | 60. | 1265. | 66. | 2153. | 72. | 970. | 78. | 628. |
| 84. | 695. | 90. | 586. | 96. | 492. | 102. | 413. | 108. | 345. | 114. | 286. | 120. | 235. |
| 126. | 195. | 132. | 157. | 138. | 127. | 144. | 102. | 150. | 81. | 156. | 61. | 162. | 43. |
| 168. | 29. | 174. | 17. | 180. | 7. | 186. | 0. | 192. | -4. | 198. | -14. | 204. | -19. |
| 210. | -24. | 216. | -26. | 222. | -29. | 228. | -31. | 234. | -36. | 240. | -37. | 246. | -34. |
| 252. | -34. | 258. | -38. | 264. | -41. | 270. | -40. | 276. | -38. | 282. | -39. | 288. | -41. |
| 294. | -41. | 300. | -43. | 306. | -45. | 312. | -45. | 318. | -46. | 324. | -43. | 330. | -42. |
| 336. | -43. | 342. | -42. | 348. | -41. | 354. | -39. | 360. | -44. | 366. | -41. | 372. | -42. |
| 378. | -43. | 384. | -44. | 390. | -44. | 396. | -47. | 402. | -47. | 408. | -47. | 414. | -45. |
| 420. | -45. | 426. | -45. | | | | | | | | | | |

CHANNEL 1 - THERMISTOR ( 72 POINTS)

| TTH | VTH | TTH | VTH | TTH | VTH | TTH | VTH | TTH | VTH | TTH | VTH | TTH | VTH |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2. | 1953. | 8. | 1957. | 14. | 1957. | 20. | 1961. | 26. | 196[illegible]. | 32. | 1961. | 38. | 1960. |
| 44. | 1957. | 50. | 1958. | 56. | 1958. | 62. | 1953. | 68. | 1953. | 74. | 1953. | 80. | 1948. |
| 86. | 1943. | 92. | 1944. | 98. | 1941. | 104. | 1937. | 110. | 1936. | 116. | 1931. | 122. | 1929. |
| 128. | 1927. | 134. | 1924. | 140. | 1921. | 146. | 1917. | 152. | 1913. | 158. | 1916. | 164. | 1913. |
| 170. | 1908. | 176. | 1903. | 182. | 1903. | 188. | 1900. | 194. | 1890. | 200. | 1895. | 206. | 1890. |
| 212. | 1887. | 218. | 1887. | 224. | 1882. | 230. | 1883. | 236. | 1877. | 242. | 1876. | 248. | 1872. |
| 254. | 1869. | 260. | 1868. | 266. | 1867. | 272. | 1864. | 278. | 1861. | 284. | 1860. | 290. | 1854. |
| 296. | 1853. | 302. | 1854. | 308. | 1850. | 314. | 1847. | 320. | 1840. | 326. | 1842. | 332. | 1840. |
| 338. | 1837. | 344. | 1836. | 350. | 1836. | 356. | 1832. | 362. | 1832. | 368. | 1828. | 374. | 1824. |
| 380. | 1824. | 386. | 1824. | 392. | 1822. | 398. | 1817. | 404. | 1817. | 410. | 1815. | 416. | 1810. |
| 422. | 1808. | 428. | 1810. | | | | | | | | | | |

CHANNEL 2 - FLOW METER ( 72 POINTS)

| TFM | VFM | TFM | VFM | TFM | VFM | TFM | VFM | TFM | VFM | TFM | VFM | TFM | VFM |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 4. | 2044. | 10. | 2052. | 16. | 2045. | 22. | 2041. | 28. | 2040. | 34. | 2040. | 40. | 2035. |
| 46. | 2035. | 52. | 2016. | 58. | 2031. | 64. | 2040. | 70. | 2068. | 76. | 2053. | 82. | 2038. |
| 88. | 2044. | 94. | 2054. | 100. | 2032. | 106. | 2029. | 112. | 2054. | 118. | 2044. | 124. | 2040. |
| 130. | 2041. | 136. | 2029. | 142. | 2043. | 148. | 2044. | 154. | 2035. | 160. | 2040. | 166. | 2010. |
| 172. | 2027. | 178. | 2020. | 184. | 2034. | 190. | 2043. | 196. | 2051. | 202. | 2029. | 208. | 2044. |
| 214. | 2025. | 220. | 2049. | 226. | 2070. | 232. | 2034. | 238. | 2030. | 244. | 2042. | 250. | 2054. |
| 256. | 2052. | 262. | 2040. | 268. | 2035. | 274. | 2045. | 280. | 2028. | 286. | 2056. | 292. | 2042. |
| 298. | 2041. | 304. | 2030. | 310. | 2062. | 316. | 2061. | 322. | 2029. | 328. | 2031. | 334. | 2025. |
| 340. | 2031. | 346. | 2033. | 352. | 2037. | 358. | 2032. | 364. | 2043. | 370. | 2041. | 376. | 2052. |
| 382. | 2044. | 388. | 2046. | 394. | 2051. | 400. | 2043. | 406. | 2030. | 412. | 2058. | 418. | 2071. |
| 424. | 2033. | 430. | 2034. | | | | | | | | | | |

ZERO POINT FOR THIS MEASUREMENT DETERMINED FROM THE LAST 10 THERMOPILE DATA POINTS = -40.60
RMS DEVIATION FROM ZERO POINT = 1.96
VARIANCE (USED IN WEIGHTING OF DATA FOR FIT) = .82

FIT 1 FOR DATA SET 1

LAB DATA OF 8/30/77, TI LS37-76 [illegible] TUBE, TFM 3003, THERMISTOR BRIDGE [illegible] RUN 1

FIT DATA (ADJUSTED FOR ZERO POINT) TO STRAIGHT LINE OF THE FORM Y=A+BX, WHERE
X = T
Y = LN(V(T)),
A = LN(V(T=0)),
B = -1/TAU

ONLY 72 DATA POINTS WHICH SATISFY THE CRITERIA T>[illegible] [illegible] SEC AND T<LT. 426.00 SEC
ARE INCLUDED IN THE FIT
[illegible] IS [illegible] TIME CONSTANTS STOP

RESULT OF THE FIT
A = [illegible] SIGMA A = .0009402
B = -.0029[illegible] SIGMA B = .0008490
[illegible] = [illegible]
[illegible] = [illegible]

R = .9936

OR, IN TERMS OF VARIABLES OF THE PROBLEM

V(T=0) = 6769.0    ERROR RANGE 6767.7 TO 6770.0
TAU = 39.201    ERROR RANGE 39.189 TO 39.214

WATER TEMPERATURE AND FLOW VELOCITY DURING ANALYSIS WINDOW

| TIME (SEC) | WATER TEMP (C) | TIME (SEC) | FLOW VELOCITY (FT/SEC) |
|---|---|---|---|
| 2.0 | 25.863 | 4.0 | 0.731 |
| 8.0 | 25.862 | 10.0 | 0.746 |
| 14.0 | 25.862 | 16.0 | 0.730 |
| 20.0 | 25.863 | 22.0 | 0.727 |
| 26.0 | 25.863 | 28.0 | 0.735 |
| 32.0 | 25.863 | 34.0 | 0.72[illegible] |
| 38.0 | 25.863 | 40.0 | 0.717 |
| 44.0 | 25.862 | 46.0 | 0.713 |
| 50.0 | 25.863 | 52.0 | 0.68[illegible] |
| 56.0 | 25.863 | 58.0 | 0.71[illegible] |
| 62.0 | 25.861 | 64.0 | 0.725 |
| 68.0 | 25.861 | 70.0 | 0.71[illegible] |
| 74.0 | 25.861 | 76.0 | 0.748 |
| 80.0 | 25.860 | 82.0 | 0.727 |
| 86.0 | 25.860 | 88.0 | 0.730 |
| 92.0 | 25.859 | 94.0 | 0.740 |
| 98.0 | 25.858 | 100.0 | 0.716 |
| 104.0 | 25.857 | 106.0 | 0.707 |
| 110.0 | 25.857 | 112.0 | 0.74[illegible] |
| 116.0 | 25.855 | 118.0 | 0.73[illegible] |
| 122.0 | 25.853 | 124.0 | 0.725 |
| 128.0 | 25.854 | 130.0 | 0.727 |
| 134.0 | 25.853 | 136.0 | 0.707 |
| 140.0 | 25.853 | 142.0 | 0.73[illegible] |
| 146.0 | 25.851 | 148.0 | 0.73[illegible] |
| 152.0 | 25.850 | 154.0 | 0.717 |
| 158.0 | 25.851 | 160.0 | 0.76[illegible] |
| 164.0 | 25.850 | 166.0 | 0.688 |
| 170.0 | 25.849 | 172.0 | 0.703 |
| 176.0 | 25.848 | 178.0 | 0.69[illegible] |
| 182.0 | 25.848 | 184.0 | 0.715 |
| 188.0 | 25.847 | 190.0 | 0.73[illegible] |
| 194.0 | 25.847 | 196.0 | 0.748 |
| 200.0 | 25.845 | 202.0 | 0.707 |
| 206.0 | 25.844 | 208.0 | 0.735 |
| 212.0 | 25.843 | 214.0 | 0.69[illegible] |
| 218.0 | 25.843 | 220.0 | 0.74[illegible] |
| 224.0 | 25.842 | 226.0 | 0.727 |
| 230.0 | 25.842 | 232.0 | 0.71[illegible] |
| 236.0 | 25.841 | 238.0 | 0.72[illegible] |
| 242.0 | 25.840 | 244.0 | 0.7[illegible] |
| 248.0 | 25.839 | 250.0 | 0.740 |
| 254.0 | 25.838 | 256.0 | 0.74[illegible] |
| 260.0 | 25.838 | 262.0 | 0.735 |
| 266.0 | 25.838 | 268.0 | 0.717 |
| 272.0 | 25.837 | 274.0 | 0.731 |
| 278.0 | 25.836 | 280.0 | 0.7[illegible]5 |
| 284.0 | 25.836 | 286.0 | 0.75[illegible] |

| | | | |
|---|---|---|---|
| 290.0 | 25.834 | 292.0 | 0.720 |
| 296.0 | 25.834 | 298.0 | 0.727 |
| 302.0 | 25.834 | 304.0 | 0.710 |
| 308.0 | 25.833 | 310.0 | 0.703 |
| 314.0 | 25.832 | 316.0 | 0.707 |
| 320.0 | 25.832 | 322.0 | 0.699 |
| 326.0 | 25.831 | 328.0 | 0.716 |
| 332.0 | 25.831 | 334.0 | 0.720 |
| 338.0 | 25.830 | 340.0 | 0.720 |
| 344.0 | 25.829 | 346.0 | 0.751 |
| 350.0 | 25.829 | 352.0 | 0.720 |
| 356.0 | 25.826 | 358.0 | 0.712 |
| 362.0 | 25.826 | 364.0 | 0.731 |
| 368.0 | 25.827 | 370.0 | 0.727 |
| 374.0 | 25.828 | 376.0 | 0.746 |
| 380.0 | 25.826 | 382.0 | 0.725 |
| 386.0 | 25.826 | 388.0 | 0.730 |
| 392.0 | 25.826 | 394.0 | 0.748 |
| 398.0 | 25.824 | 400.0 | 0.731 |
| 404.0 | 25.824 | 406.0 | 0.720 |
| 410.0 | 25.824 | 412.0 | 0.756 |
| 416.0 | 25.824 | 418.0 | 0.770 |
| 422.0 | 25.822 | 424.0 | 0.720 |

AVERAGE WATER TEMPERATURE IS 25.844 PLUS OR MINUS .013
AVERAGE FLOW VELOCITY IS 9.729 PLUS OR MINUS .050

TIME CONSTANT (TAU) CONVERTED TO HEAT TRANSFER COEFFICIENT (U) WITH CORRECTIONS FOR HEAT LOSS TO AIR AND TO HEAT EXCHANGER TUBE WALLS
U(UNCORRECTED) = 1608.59 BTU/(HR FT**2 F)
1.0/U(INTERCEPT) = .000023 (BTU/HR FT**2 F)**-1
R(AIR) = .00071
R(WALLS) = .01765
U(CORRECTED) = 1570.62 BTU/(HR FT**2 F)

U(CORRECTED) NORMALIZED TO 70 F (NORMALIZATION STRICTLY NOT CORRECT SINCE THE TEMPERATURE-INDEPENDENT FOULING CONTRIBUTION IS NOT SUBTRACTED FROM U(CORRECTED))
NORMALIZATION FACTOR = .947
U(CORRECTED,NORMALIZED) = 1490.70 BTU/(HR FT**2 F)
1.0/U(CORRECTED,NORMALIZED) = .000670
1.0/V**0.8 = .1620

DETAILS OF FIT

| POINT | TIME | U(COUNT) | LOG(U(COUNTS)) | LOG(Y(FIT)) | DIFFERENCE | WEIGHT | CHISQR |
|---|---|---|---|---|---|---|---|
| 1 | .00000 | .63900+04 | .87494+01 | .86201+01 | .29790-01 | .10906+08 | .52142+05 |
| 2 | .60000+01 | .60076+04 | .87000+01 | .86671+01 | -.33724-01 | .94425+07 | .10749+05 |
| 3 | .12000+02 | .51076+04 | .85540+01 | .85140+01 | -.40040-01 | .70407+07 | .11240+05 |
| 4 | .18000+02 | .41196+04 | .83938+01 | .83600+01 | -.33890-01 | .51163+07 | .55121+04 |
| 5 | .24000+02 | .37526+04 | .82302+01 | .82070+01 | -.23410-01 | .36842+07 | .19340+04 |
| 6 | .30000+02 | .31916+04 | .80685+01 | .80540+01 | -.14495-01 | .26550+07 | .40149+03 |
| 7 | .36000+02 | .27106+04 | .79009+01 | .79001+01 | -.31495-02 | .18223+07 | .10004+02 |
| 8 | .42000+02 | .23066+04 | .77427+01 | .77409+01 | .20570-02 | .13196+07 | .50980+02 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 9 | .48000+02 | .17596+04 | .75605+01 | .75050+01 | .5[illegible]8-01 | .10047+07 | .23114+03 |
| 10 | .54000+02 | .16616+04 | .74155+01 | .74026+01 | .2707[illegible]-01 | .72235+06 | .52937+03 |
| 11 | .60000+02 | .14096+04 | .72511+01 | .72095+01 | .36470-01 | .51905+06 | .77016+03 |
| 12 | .66000+02 | .11976+04 | .70681+01 | .71306+01 | .49941-01 | .37574+06 | .87977+03 |
| 13 | .72000+02 | .10220+04 | .69301+01 | .69836+01 | .53356-01 | .27351+06 | .77857+03 |
| 14 | .78000+02 | .87200+03 | .67715+01 | .68306+01 | .56106-01 | .19921+06 | .69105+03 |
| 15 | .84000+02 | .73900+03 | .65061+01 | .66773+01 | .71218-01 | .14311+06 | .72556+03 |
| 16 | .90000+02 | .61000+03 | .64467+01 | .65243+01 | .77579-01 | .10404+06 | .62608+03 |
| 17 | .96000+02 | .51600+03 | .62053+01 | .63712+01 | .85182-01 | .75333+05 | .55607+03 |
| 18 | .10200+03 | .43760+03 | .61260+01 | .62105+01 | .92108-01 | .54784+05 | .46559+03 |
| 19 | .10800+03 | .37760+03 | .59000+01 | .60651+01 | .10313+00 | .39305+05 | .47901+03 |
| 20 | .11400+03 | .33060+03 | .58039+01 | .59120+01 | .11114+00 | .20595+05 | .35319+03 |
| 21 | .12000+03 | .27960+03 | .56334+01 | .57690+01 | .12505+00 | .20053+05 | .32221+03 |
| 22 | .12600+03 | .23760+03 | .54706+01 | .56050+01 | .13535+00 | .14770+05 | .27006+03 |
| 23 | .13200+03 | .20160+03 | .53065+01 | .54524+01 | .14629+00 | .10633+05 | .22808+03 |
| 24 | .13800+03 | .17160+03 | .51452+01 | .52994+01 | .14890+00 | .77840+04 | .18457+03 |
| 25 | .14400+03 | .14600+03 | .49077+01 | .51490+01 | .15990+00 | .56228+04 | .14255+03 |
| 26 | .15000+03 | .12500+03 | .48331+01 | .49035+01 | .16081+00 | .41273+04 | .10666+03 |
| 27 | .15600+03 | .10560+03 | .46597+01 | .48007+01 | .18190+00 | .29175+04 | .95560+02 |
| 28 | .16200+03 | .87500+02 | .44728+01 | .46876+01 | .21482+00 | .20077+04 | .92667+02 |
| 29 | .16800+03 | .73600+02 | .42906+01 | .45395+01 | .23594+00 | .14172+04 | .70025+02 |
| 30 | .17400+03 | .61600+02 | .41207+01 | .43016+01 | .27092+00 | .99276+03 | .67577+02 |
| 31 | .18000+03 | .51000+02 | .39435+01 | .42706+01 | .24491+00 | .69460+03 | .56505+02 |
| 32 | .18600+03 | .44600+02 | .37977+01 | .40756+01 | .27769+00 | .52002+03 | .40110+02 |
| 33 | .19200+03 | .36600+02 | .36000+01 | .39223+01 | .32247+00 | .35047+03 | .36319+02 |
| 34 | .19800+03 | .31600+02 | .34210+01 | .37499+01 | .30020+00 | .24990+03 | .20712+02 |
| 35 | .20400+03 | .27600+02 | .32426+01 | .36105+01 | .37591+00 | .17146+03 | .23954+02 |
| 36 | .21000+03 | .20600+02 | .30253+01 | .34431+01 | .43706+00 | .11102+03 | .21246+02 |
| 37 | .21600+03 | .16600+02 | .29232+01 | .33101+01 | .38093+00 | .90513+02 | .15561+02 |
| 38 | .22200+03 | .13600+02 | .27473+01 | .31570+01 | .40077+00 | .63670+02 | .10651+02 |
| 39 | .22800+03 | .11600+02 | .26101+01 | .30090+01 | .30591+00 | .48391+02 | .75000+01 |
| 40 | .23400+03 | .80000+01 | .21510+01 | .28508+01 | .60940+00 | .19350+02 | .90508+01 |
| 41 | .24000+03 | .70000+01 | .20281+01 | .26070+01 | .60072+00 | .15112+02 | .67700+01 |
| 42 | .24600+03 | .60000+01 | .10671+01 | .25040+01 | .65770+00 | .11307+02 | .40324+01 |
| 43 | .25200+03 | .50000+01 | .17228+01 | .23910+01 | .66979+00 | .82047+01 | .36750+01 |
| 44 | .25800+03 | .60000+01 | .10871+01 | .22400+01 | .36103+00 | .11497+02 | .18071+01 |
| 45 | .26400+03 | .30000+01 | .12809+01 | .20030+01 | .40071+00 | .33907+01 | .21907+01 |
| 46 | .27000+03 | .60000+01 | .15261+01 | .19320+01 | .40023+00 | .55360+01 | .91453+00 |
| 47 | .27600+03 | .50000+01 | .17228+01 | .17790+01 | .56700-01 | .82047+01 | .26470+01 |
| 48 | .28200+03 | .50000+01 | .17228+01 | .16500+01 | -.96200-01 | .82047+01 | .76052+01 |
| 49 | .28800+03 | .30000+01 | .12809+01 | .14730+01 | .10299+00 | .33907+01 | .12463+00 |
| 50 | .29400+03 | .30000+01 | .12809+01 | .13200+01 | .30030-01 | .33907+01 | .59717+02 |
| 51 | .30000+03 | .10000+01 | .47000+00 | .11673+01 | .69720+00 | .66477+00 | .32526+00 |
| 52 | .30600+03 | -.40000+00 | -.91029+00 | .10143+01 | .10301+01 | .41860-01 | .15601+00 |
| 53 | .31200+03 | -.40000+00 | -.91029+00 | .86120+00 | .17775+01 | .41860-01 | .13726+00 |
| 54 | .31800+03 | -.10000+01 | .33607+00 | .70810+00 | .37107+00 | .51277+00 | .70095+01 |
| 55 | .32400+03 | .10000+01 | .47000+00 | .55500+00 | .86090-01 | .66477+00 | .40002+02 |
| 56 | .33000+03 | .20000+01 | .95551+00 | .40200+00 | -.55356+00 | .17606+01 | .15410+00 |
| 57 | .33600+03 | .20000+01 | .95551+00 | .24090+00 | -.70024+00 | .17606+01 | .80209+00 |
| 58 | .34200+03 | .20000+01 | .95551+00 | .95910-01 | -.85900+00 | .17606+01 | .13020+01 |
| 59 | .34800+03 | .30000+01 | .12809+01 | -.57110-01 | -.13391+01 | .33907+01 | .60709+01 |
| 60 | .35400+03 | .50000+01 | .17228+01 | -.21020+00 | -.19330+01 | .82047+01 | .30625+02 |
| 61 | .36000+03 | .40000+01 | .15261+01 | -.36320+00 | -.18893+01 | .55360+01 | .10701+02 |
| 62 | .36600+03 | .30000+01 | .12809+01 | -.51630+00 | -.17972+01 | .33907+01 | .10902+02 |
| 63 | .37200+03 | .20000+01 | .95551+00 | -.66930+00 | -.16249+01 | .17606+01 | .44605+01 |
| 64 | .37800+03 | .20000+01 | .95551+00 | -.82230+00 | -.17779+01 | .17606+01 | .58956+01 |
| 65 | .38400+03 | .60000+00 | -.51093+00 | -.97540+00 | -.46105+00 | .94106-01 | .20315+01 |
| 66 | .39000+03 | .60000+00 | -.51093+00 | -.11280+01 | -.61771+00 | .94106-01 | .37936+01 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 67 | +.39000+03 | -.24000+01 | .87547+00 | -.12814+01 | -.21371+01 | +.15070+01 | +.70118+01 |
| 68 | +.40400+03 | -.24000+01 | +.87547+00 | -.14384+01 | -.24191+01 | +.15070+01 | +.80452+01 |
| 69 | +.40800+03 | -.24000+01 | +.87547+00 | -.15877+01 | -.24022+01 | +.15070+01 | +.91441+01 |
| 70 | +.41400+03 | -.48000+00 | -.91529+00 | -.17940+01 | -.82497+00 | +.41860-01 | +.20045-01 |
| 71 | +.42400+03 | +.16000+01 | +.47000+00 | -.18934+01 | -.23628+01 | +.66977+00 | +.37454+01 |
| 72 | +.42000+03 | -.48000+00 | -.91029+00 | -.20464+01 | -.11306+01 | +.41860-01 | +.53546-01 |

FIT 2 FOR DATA SET 1

LAB DATA OF 8/30/76, TI 6337-76 NO.1 TUBE, EM 30A3, (JOHNSTON GAUGE NO.1 RUN )

FIT DATA (ADJUSTED FOR ZERO POINT) TO STRAIGHT LINE OF THE FORM Y=A+B*X, WHERE
X = T
Y = LN(VTC(T))
A = LN(V(T=0))
B = -1/TAU

ONLY 23 DATA POINTS WHICH SATISFY THE CRITERIA T.GT. 20.00 SEC .AND. T.LT. 157.20 SEC
ARE INCLUDED IN THE FIT
THIS WINDOW IS 3.71 TIME CONSTANTS WIDE

RESULT OF THE FIT
A = 8.879766    SIGMAA = .0002592
B = -.0270750    SIGMAB = .0000152
CHISQR = 53.846
STD = .0017202
R = -1.0000

OR, IN TERMS OF VARIABLES OF THE PROBLEM
V(T=0) = 7185.1    ERROR RANGE 7180.4 TO 7189.4
TAU = 36.934    ERROR RANGE 36.914 TO 36.955

WATER TEMPERATURE AND FLOW VELOCITY DURING ANALYSIS WINDOW

| TIME (SEC) | WATER TEMP (C) | TIME (SEC) | FLOW VELOCITY (FT/SEC) |
|---|---|---|---|
| 26.0 | 25.603 | 28.0 | 6.732 |
| 32.0 | 25.603 | 34.0 | 6.725 |
| 38.0 | 25.663 | 40.0 | 6.717 |
| 44.0 | 25.662 | 46.0 | 6.715 |
| 50.0 | 25.663 | 52.0 | 6.700 |
| 56.0 | 25.663 | 58.0 | 6.71[illegible] |
| 62.0 | 25.661 | 64.0 | 6.725 |
| 68.0 | 25.661 | 70.0 | 6.775 |
| 74.0 | 25.661 | 76.0 | 6.748 |
| 80.0 | 25.660 | 82.0 | 6.722 |
| 86.0 | 25.660 | 88.0 | 6.730 |
| 92.0 | 25.659 | 94.0 | 6.740 |
| 98.0 | 25.658 | 100.0 | 6.746 |
| 104.0 | 25.657 | 106.0 | 6.707 |
| 110.0 | 25.657 | 112.0 | 6.745 |
| 116.0 | 25.659 | 118.0 | 6.735 |
| 122.0 | 25.655 | 124.0 | 6.725 |
| 128.0 | 25.654 | 130.0 | 6.727 |
| 134.0 | [illegible] | 136.0 | [illegible] |

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| | | | |
|---|---|---|---|
| 190.0 | 25.853 | 192.0 | 0.731 |
| 196.0 | 25.851 | 198.0 | 0.734 |
| 152.0 | 25.850 | 154.0 | 0.717 |

AVERAGE WATER TEMPERATURE IS 25.858 PLUS OR MINUS .008
AVERAGE FLOW VELOCITY IS 9.727 PLUS OR MINUS .016

TIME CONSTANT (TAU) CONVERTED TO HEAT TRANSFER COEFFICIENT (H) WITH CORRECTIONS FOR HEAT LOSS TO AIR AND TO HEAT EXCHANGER TUBE WALLS

H(UNCORRECTED) = 1654.00 BTU/(HR FT**2 F)
1.0/H(UNCORRECTED) = .000023 (BTU/HR FT**2 F)**-1
RAIR = .00097
RWALLS = .01146
H(CORRECTED) = 1793.53 BTU/(HR FT**2 F)

H(CORRECTED) NORMALIZED TO 70 F (NORMALIZATION STRICTLY NOT CORRECT SINCE THE TEMPERATURE-INDEPENDENT FOULING CONTRIBUTION IS NOT SUBTRACTED FROM H(CORRECTED))
NORMALIZATION FACTOR = .947
H(CORRECTED,NORMALIZED) = 1702.56 BTU/(HR FT**2 F)
1.0/H(CORRECTED,NORMALIZED) = .000587
1.0/V**0.8 = .1620

DETAILS OF FIT

| POINT | TIME | V(CLOUDS) | LN(V(CLOUDS)) | LN(V(CALC)) | DIFFERENCE | WEIGHT | CHISQR |
|---|---|---|---|---|---|---|---|
| 1 | .24000+02 | .17526+04 | .82302+01 | .82304+01 | -.24682-03 | .36042+07 | .20953+00 |
| 2 | .30000+02 | .31916+04 | .80683+01 | .80687+01 | -.74199-03 | .26650+07 | .14674+01 |
| 3 | .36000+02 | .27106+04 | .79049+01 | .79051+01 | .16015-03 | .19223+07 | .37717-01 |
| 4 | .42000+02 | .23045+04 | .77427+01 | .77422+01 | -.47147-04 | .13896+07 | .30880-02 |
| 5 | .48000+02 | .19596+04 | .75805+01 | .75802+01 | -.33091-03 | .10047+07 | .10944+00 |
| 6 | .54000+02 | .16616+04 | .74155+01 | .74177+01 | .21787-02 | .72233+06 | .34286+01 |
| 7 | .60000+02 | .14095+04 | .72511+01 | .72553+01 | .47095-02 | .51985+06 | .91864+01 |
| 8 | .66000+02 | .11976+04 | .70881+01 | .70926+01 | .47398-02 | .37524+06 | .84249+01 |
| 9 | .72000+02 | .10226+04 | .69301+01 | .69306+01 | .26091-03 | .27359+06 | .18615-01 |
| 10 | .78000+02 | .87260+03 | .67715+01 | .67676+01 | -.35620-02 | .19921+06 | .25280+01 |
| 11 | .84000+02 | .73960+03 | .66061+01 | .66055+01 | -.60540-03 | .14511+06 | .50612-01 |
| 12 | .90000+02 | .63060+03 | .64467+01 | .64435+01 | -.32570-02 | .10404+06 | .13950+01 |
| 13 | .96000+02 | .53060+03 | .62853+01 | .62806+01 | -.46691-02 | .75133+05 | .16574+01 |
| 14 | .10200+03 | .45760+03 | .61260+01 | .61181+01 | -.78610-02 | .54784+05 | .34054+01 |
| 15 | .10800+03 | .38760+03 | .59600+01 | .59559+01 | -.43194-02 | .39305+05 | .73349+00 |
| 16 | .11400+03 | .33060+03 | .58009+01 | .57939+01 | -.70028-02 | .28595+05 | .14025+01 |
| 17 | .12000+03 | .27960+03 | .56334+01 | .56308+01 | -.25909-02 | .20853+05 | .13703+00 |
| 18 | .12600+03 | .23760+03 | .54706+01 | .54683+01 | -.23770-02 | .14770+05 | .78463-01 |
| 19 | .13200+03 | .20160+03 | .53063+01 | .53059+01 | -.40272-03 | .10633+05 | .17240-02 |
| 20 | .13800+03 | .17160+03 | .51452+01 | .51437+01 | -.17154-02 | .77040+04 | .23667-01 |
| 21 | .14400+03 | .14660+03 | .49877+01 | .49810+01 | -.67429-02 | .56224+04 | .25563+00 |
| 22 | .15000+03 | .12560+03 | .48331+01 | .48186+01 | -.14570-01 | .41277+04 | .87865+00 |
| 23 | .15600+03 | .10560+03 | .46597+01 | .46561+01 | -.36152-02 | .29175+04 | .37732-01 |

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# APPENDIX D. LABORATORY ELECTRONICS SYSTEM

D.1. Introduction. If a system of heat transfer test units is to be operated in a non-remote location, the complicated multiplexing system described in Sec. 5 may be much simplified. Here we describe such a simplified system. It is one we have used extensively in the laboratory. This system, or obvious modifications of it, may be confidently used with the heat transfer apparatus.

The system is shown in block-diagram form in Figure D-1. As shown, the outputs from only one test unit are connected. With some simple additional hardware the system can handle three units.

The operation of the system is qualitatively as follows. The three signals from the test unit are sequentially switched by the Scanner (under the control of the TTY IF) to the DMM. The DMM output is channeled to the teletype, by the TTY IF, where it is recorded.

D.2. Signal Sources. The circuitry which generates the three input signals is shown in Figure D-2. At the top right of the diagram are the terminals for the 10 input channels of the Scanner and its output. Directly below are the input terminals to the DMM. Channel 0 is connected to the thermopile signal, Channel 1 to the thermistor signal, and Channel 2 to the flow meter signal.

The DMM is used in the 0-10 mV range. The circuit design is such that the flow meter and thermistor signals are at the appropriate levels. The thermocouple output, however must be amplified (by a factor of about 10).

The arms of the flow meter bridge (120 Ω each) are strain gages mounted on the strain arm of the Ramapo flow meter described in Sec. 4. As shown in the diagram, the thermistor used is the Veco 35D7.

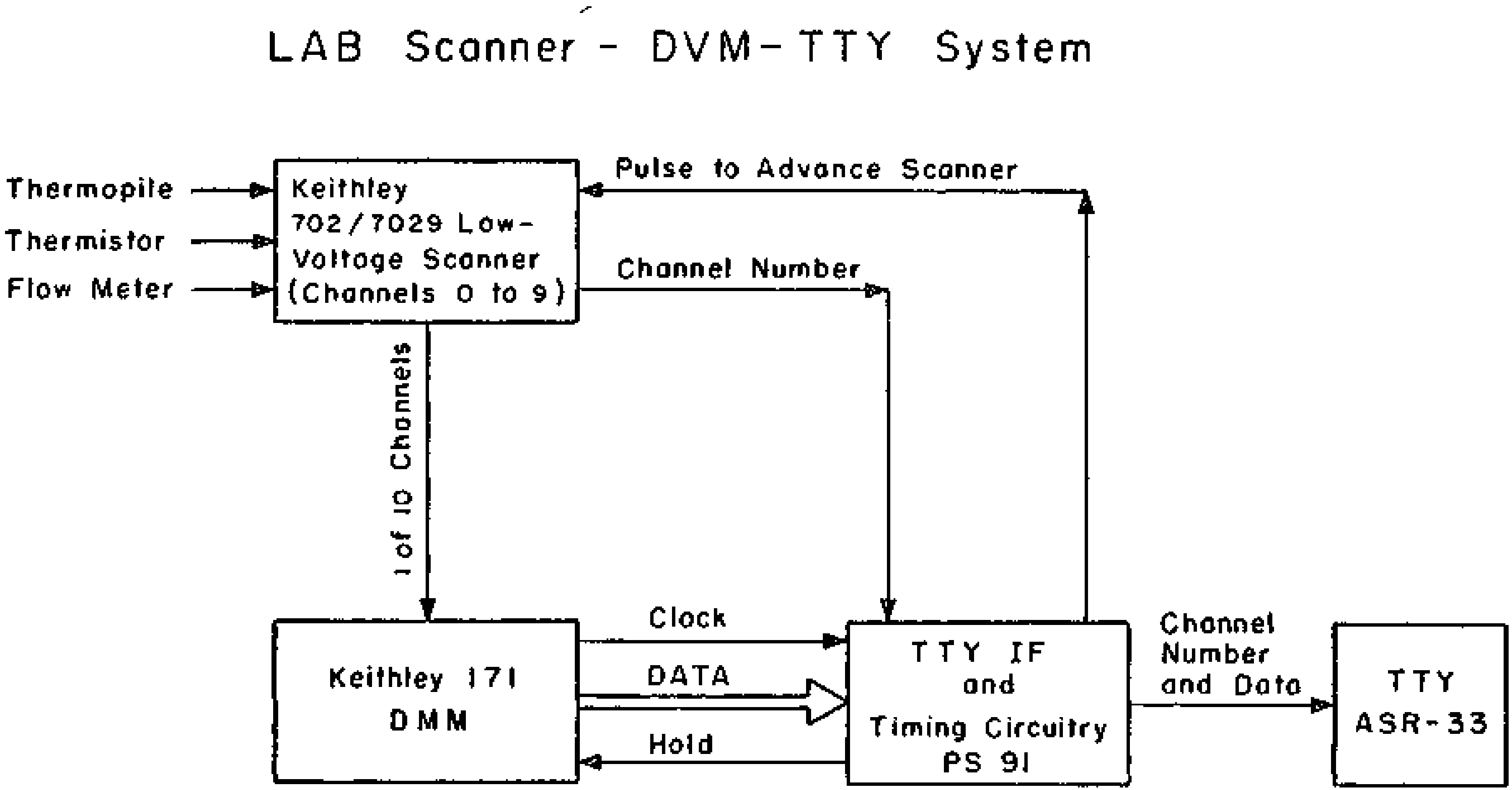



Figure D-1. Laboratory Scanner-DVM-TTY System.

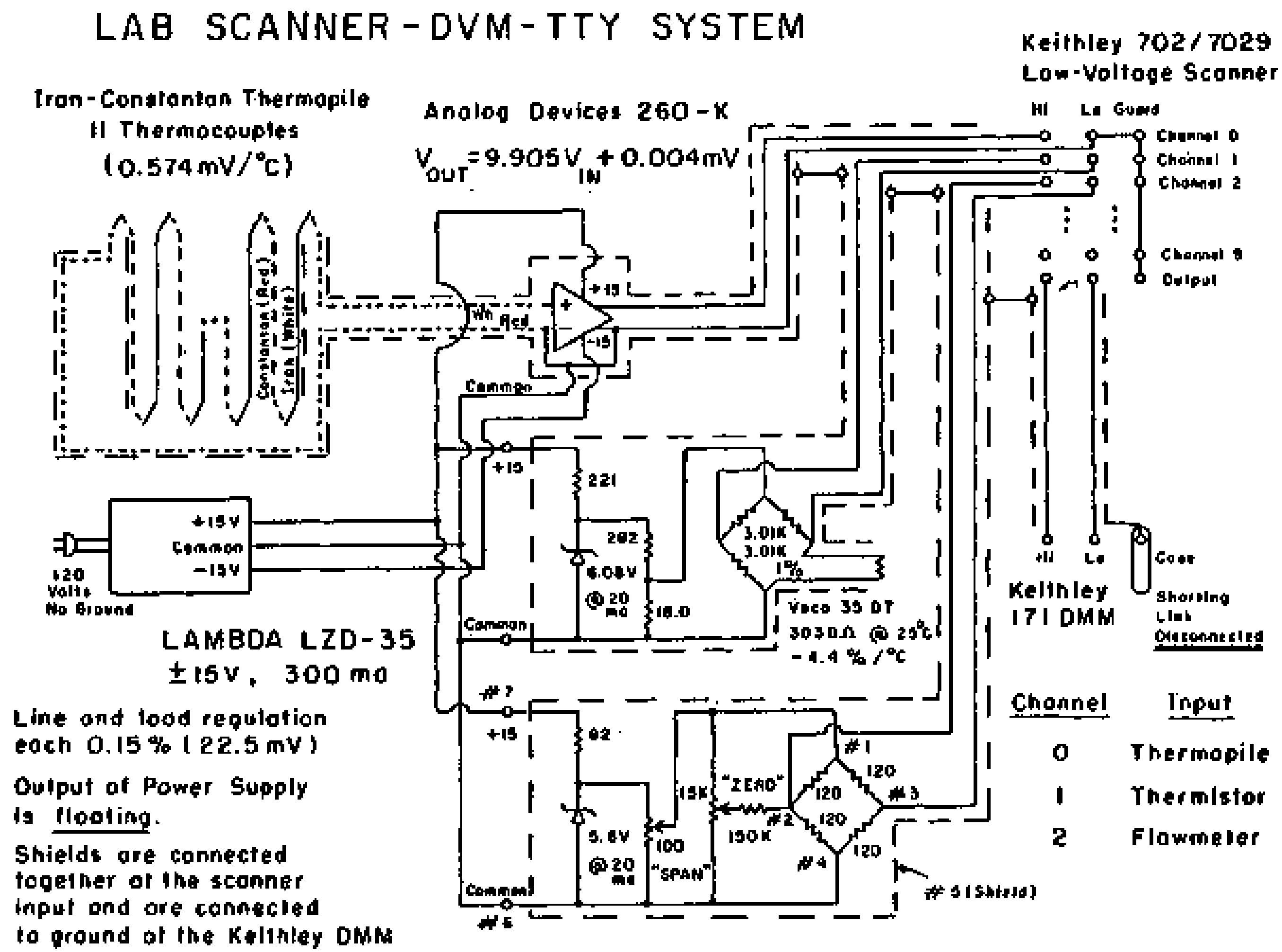



Figure D-2 Laboratory Scanner - DVM - TTY System

It is important that the lines carrying low-level signals be well shielded.

D.3. Scanner. The Scanner used is the Keithley Low-Voltage Scanner Model 702. It is available from Keithley Insturments, 28775 Aurora Road, Cleveland, Ohio, 44139 (Tel. 216-248-0400). Its characteristics are shown in Fig. D-3.

D.4. Digital Multimeter (DMM). The DMM used in this system is the Keithley Model 171. It's specifications are shown in Fig. D-4.

D.5. PS-91 DVM-TTY Interface. The PS-91 DVM-TTY Interface was designed as a back-up system for interfacing a Digital Voltmeter (Keithley Model 171) to a Teletype (ASR-33), to be used in event of breakdown of a more elaborate system, consisting of a DVM, scanner and sequencer.

The basic building blocks of the interface are two commercially available modules supplied by Analog Devices, which, along with associated electronics, comprise a complete interface. This interface allows not only a printout of the DVM readings periodically on the Teletype, but also advances a Keithley Model 702 Scanner, punches paper tape in the Teletype, and permits a type-out, in push-button command, of the voltmeter reading.

The two blocks obtained from Analog Devices are:

a) an STX-1003 Serial Transmitter, and

b) an SCL-1006 Clock Module.

The STX-1003 Serial Transmitter is a module containing a "receiver" which can receive serial ASCII from a teletype and recognize certain characters which it can then use as internal or external control signals. Also contained in the module is a "transmitter" which can take parallel input data and send it in serial ASCII form to a teletype. Further, the module contains a "controller" which programs the "receiver" and "transmitter" for the

# SPECIFICATIONS

Guaranteed for 1 year
(used with a scanner plug-in card)

**CHANNELS:** 10 channels per scanner mainframe (multiple scanner mainframes may be connected for up to 100 channels).

**CONTROL MODES** (front panel selectable):

- **All-Off:** No channel selected.
- **Manual:** Channel selected by front panel switch.
- **Scan:** Channels sequentially selected at a rate determined by front panel control. Initial channel may be preset.
- **Remote:** Channel randomly selected using 4-line BCD code, or sequentially selected at remote clock rate.

**SCAN RATE:** Variable from nominally 0.1 to 10 seconds per channel by front panel control. Scan rate using remote clock is limited only by relay closure time.

**DISPLAY:** Single digit front panel LED display identifies channel selected.

**DIGITAL INPUT AND DIGITAL OUTPUT:** TTL interface lines provide for remote channel selection, clock, and control of All-Off mode. Output data includes present channel address, mainframe identification, clock, and relay ready. The (digital) Common may be floated up to ±30 volts peak with respect to (chassis) Ground.

**ENVIRONMENT:** 0°C-50°C, 0% to 80% relative humidity up to 35°C.

**POWER:** 90-125 or 200-250 volts (switch selected), 50-60Hz, 15 watts.

**CONNECTORS:**

- **Digital Input, Digital Output (rear):** 26-pin 3M Part No. 3429-1002.
- **Common, Ground (rear):** Binding posts.
- **Scanner Plug-in Card (rear):** Internal connector mates with plug-in card edge.

**DIMENSIONS, WEIGHT:** Style M 3-1/2 in. half-rack, overall bench size 4 in. high x 8-3/4 in. wide x 15-1/4 in. deep (100 x 220 x 385 mm). Net weight 8 pounds (3,5 kg).

Fig. D-3.- Keithley Low-Voltage Scanner Specifications

# SPECIFICATIONS

calibrated at 25°C

**AS A DC VOLTMETER**

RANGE: ±1 microvolt per digit (10 mV full range) to ±1000 volts in six decade ranges. 100% overranging to 19999 on all except the 1000-volt range.

ACCURACY (90 days): ±(0.02% of reading +0.01% of range) except on the 10-millivolt range where it is ±(0.02% +0.02%).

TEMPERATURE COEFFICIENT: ±(0.003% of reading +0.001% of range)/°C.

INPUT RESISTANCE: Greater than 1000 megohms on the 10-millivolt through 1-volt ranges, 10 megohms on the 10-volt to 1000-volt ranges.

SETTLING TIME: Less than 2 seconds to rated accuracy with less than 100 kilohms source resistance.

REJECTION:

- NMRR: Greater than 70 dB, 50 Hz to 180 Hz at 10 Hz multiples.
- CMRR: Greater than 100 dB with 1 kilohm unbalance, dc to 180 Hz at 10 Hz multiples.

MAXIMUM SAFE INPUT: ±1400 volts peak momentary, 1000 V dc or rms ac continuous.

**AS A DC AMMETER**

RANGE: ±0.1 nanoampere per digit (1μA full range) to ±2 amperes in seven decade ranges. 100% overranging to 19999 on all ranges.

ACCURACY (90 days): ±(0.05% of reading +0.03% of range). Self heating due to long term application of 2 amperes will cause less than 0.1% additional error on the 1-ampere range.

TEMPERATURE COEFFICIENT: ±(0.005% of reading +0.002% of range)/°C.

INPUT VOLTAGE DROP: 100 millivolts at full range on the lower ranges increasing to approximately 500 millivolts on the 1-ampere range.

MAXIMUM SAFE INPUT: 3 amperes, internally fused beyond 3 amperes.

**AS AN OHMMETER**

RANGE: 0.1 ohm per digit (1 kΩ full range) to 2000 megohms in seven decade ranges. 100% overranging to 19999 on all ranges.

ACCURACY (90 days): ±0.05% of reading for 1-kilohm through 1-megohm ranges; ±0.2% of reading on the 10-megohm ranges; ±3% of reading on the 100-megohm range; ±20% of reading on the 1000-megohm range (±0.02% of range on all ranges).

TEMPERATURE COEFFICIENT: ±(0.008% of reading +0.002% of range +0.0003% of reading per megohm)/°C.

SETTLING TIME: Less than 2 seconds to rated accuracy up to 1 megohm.

CONFIGURATION: Two-terminal, constant current.

VOLTAGE ACROSS UNKNOWN: 100 mV for full range on the 1-kilohm to 100-kilohm ranges, 1V maximum open circuit. 1 volt for full range on the 1-megohm to 1000-megohm ranges, 5 volts open circuit.

MAXIMUM OVERLOAD: 250 volts rms on the 100-kilohm to 1000-megohm ranges. Diode clamped to protect the 1 and 10-kilohm ranges (internally fused beyond 3 amps)

**AS AN AC VOLTMETER**

RANGE: 10 microvolts per digit (100 mV full range) to 1000 volts rms in five decade ranges. 100% overranging to 19999 on all except the 1000-volt range.

ACCURACY (90 days):

- 1V-100V range ±(0.3% of reading +0.04% of range) 40 Hz-40kHz
- 100mV range ±(0.4% of reading +0.2% of range) 40 Hz-10kHz; ±3% of full range to 100kHz on the 100 mV and 1V ranges
- 1kV range ±(0.4% of reading +0.04% of range) 40 Hz-10kHz

(Average reading, calibrated in rms of a sine wave.)

TEMPERATURE COEFFICIENT: ±[0.35% of reading +0.003% of range (0.008% on 100-mV range)]/°C.

INPUT IMPEDANCE: 1 MΩ shunted by approximately 100 pF.

SETTLING TIME: Less than 3 seconds except for ac superimposed on dc.

MAXIMUM SAFE INPUT: 1000-volts dc or rms ac (1500 volts peak) 10-volt to 1000-volt range, 300 volts rms (450 volts peak) on the 100-mV and 1-volt ranges.

**AS AN AC AMMETER**

RANGE: 0.1 nanoampere per digit (1μA full range) to 2 amperes rms, in seven decade ranges. 100% overranging to 19999 on all ranges.

ACCURACY (90 days): ±(1.5% of reading +0.1% of range) 40 Hz to 10kHz on the 100-microampere to 1-ampere ranges, decreasing to 40 Hz to 120 Hz on the 1-microampere range (average reading, calibrated in rms of a sine wave).

TEMPERATURE COEFFICIENT: ±(0.04% of reading +0.005% of range)/°C.

INPUT VOLTAGE DROP: 100 millivolts at full range on the lower ranges increasing to approximately 500 millivolts on the 1-ampere range.

MAXIMUM SAFE INPUT: 3 amperes, internally fused beyond 3 amperes.

**GENERAL**

ZERO STABILITY: ±(0.0005% of range +0.3 μV)/°C.

ANALOG OUTPUT: ±1 volt at up to 1 milliampere for full range input, 100% overranging on all ranges except the 1000-volt ranges.

POLARITY: Automatic.

OFFSET CURRENT: Typically less than 10 picoamperes.

DISPLAY: 4 digits plus 1 overrange digit; appropriate decimal location; function in engineering units; polarity and overload indication; 2 readings/second.

ISOLATION: Circuit ground to chassis ground: greater than 100 megohms shunted by less than 0.02 microfarad. Circuit ground may be floated up to 500 volts with respect to chassis ground in all modes. Maximum safe voltage between input and chassis ground: 1500 volts peak.

WARMUP TIME: 45 minutes to within twice specified accuracy; 2 hours for complete stabilization.

OPERATING ENVIRONMENT: 0° to 35°C up to 80% R. H.

CONNECTORS: Input, chassis ground; binding posts. Analog output; Amphenol 80-PC2F.

POWER: 105-125 or 210-250 volts (switch selected), 50-60 Hz, 25 watts.

DIMENSIONS, WEIGHT: Style M 3-1/2 in. half-rack, overall bench size 4 in. high x 8-1/2 in. wide x 15-1/4 in. deep (100 x 217 x 385 mm). Net weight, 10 pounds (4.6 kg).

ACCESSORIES SUPPLIED: Mating output connector, spare input fuse.

Fig. D-4.- Digital Multimeter Specifications character format, such as the proper number of data bits per character, parity, etc.

The SCL-1006 module contains a clock oscillator, used for timing the system, and a -15 volt D.C. power supply, needed in the STX-1003.

In addition to the two building block modules, the system contains

a) A divider chain

b) A channel counter

c) A +5 volt power supply

d) Extra shift registers for extra characters.

The divider chain takes the precision 100 kilohertz clock pulses from the DVM and produces pulses at the following rates; one pulse-per-second, one pulse-per-two-seconds, one pulse-per-four-seconds, and one pulse-per-ten-seconds. These pulses determine, via selector switch, the rate of type-out of voltmeter readings.

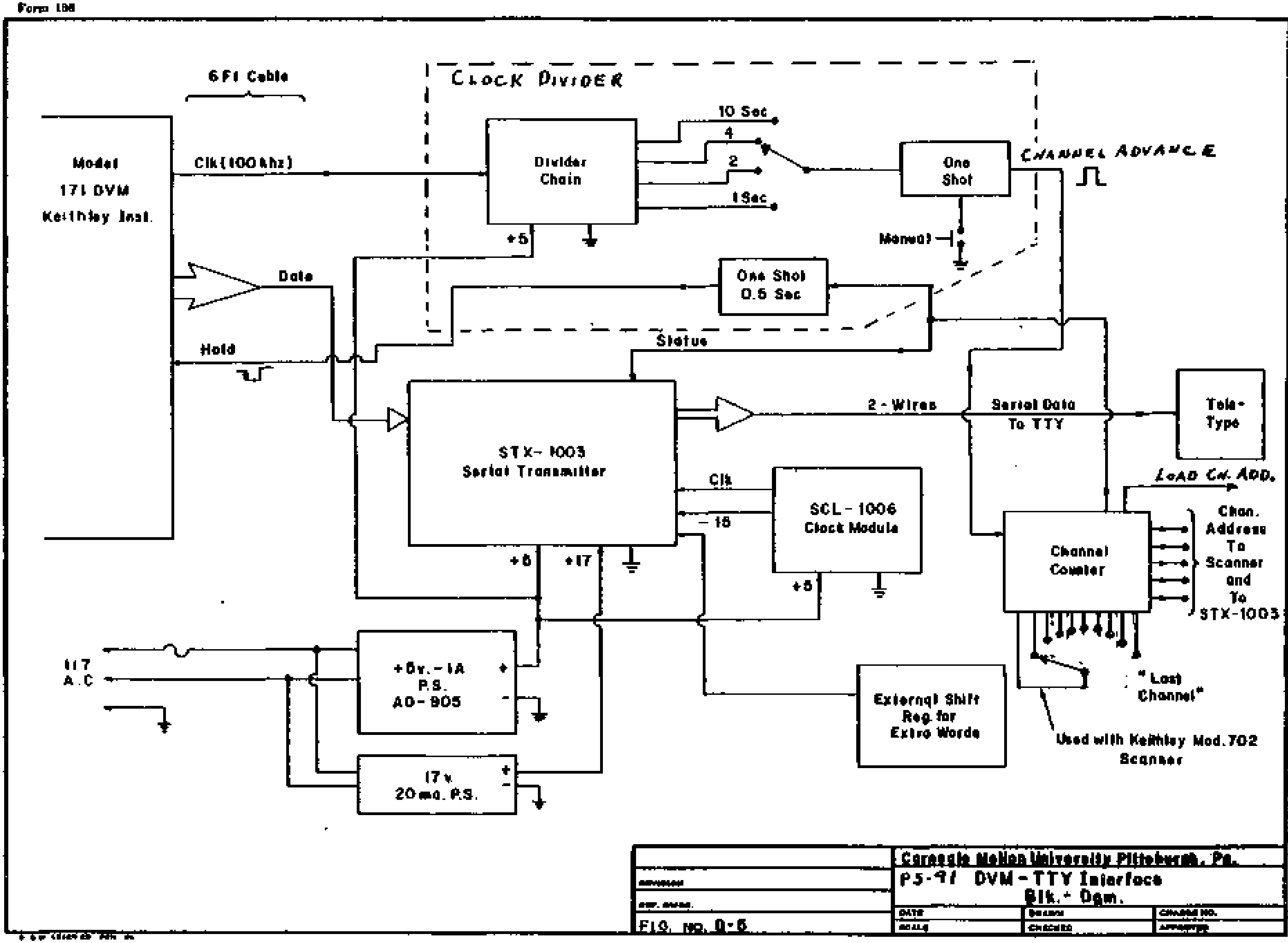
The channel counter provides the necessary pulses to allow the channel number (when used with the Model 702 Scanner) to be loaded and typed out (or punched out), and allows the operator to select the last channel to be punched, thus preventing the punching of unused channels.

The +5 volt power supply supplies the necessary 5 volts for the entire interface.

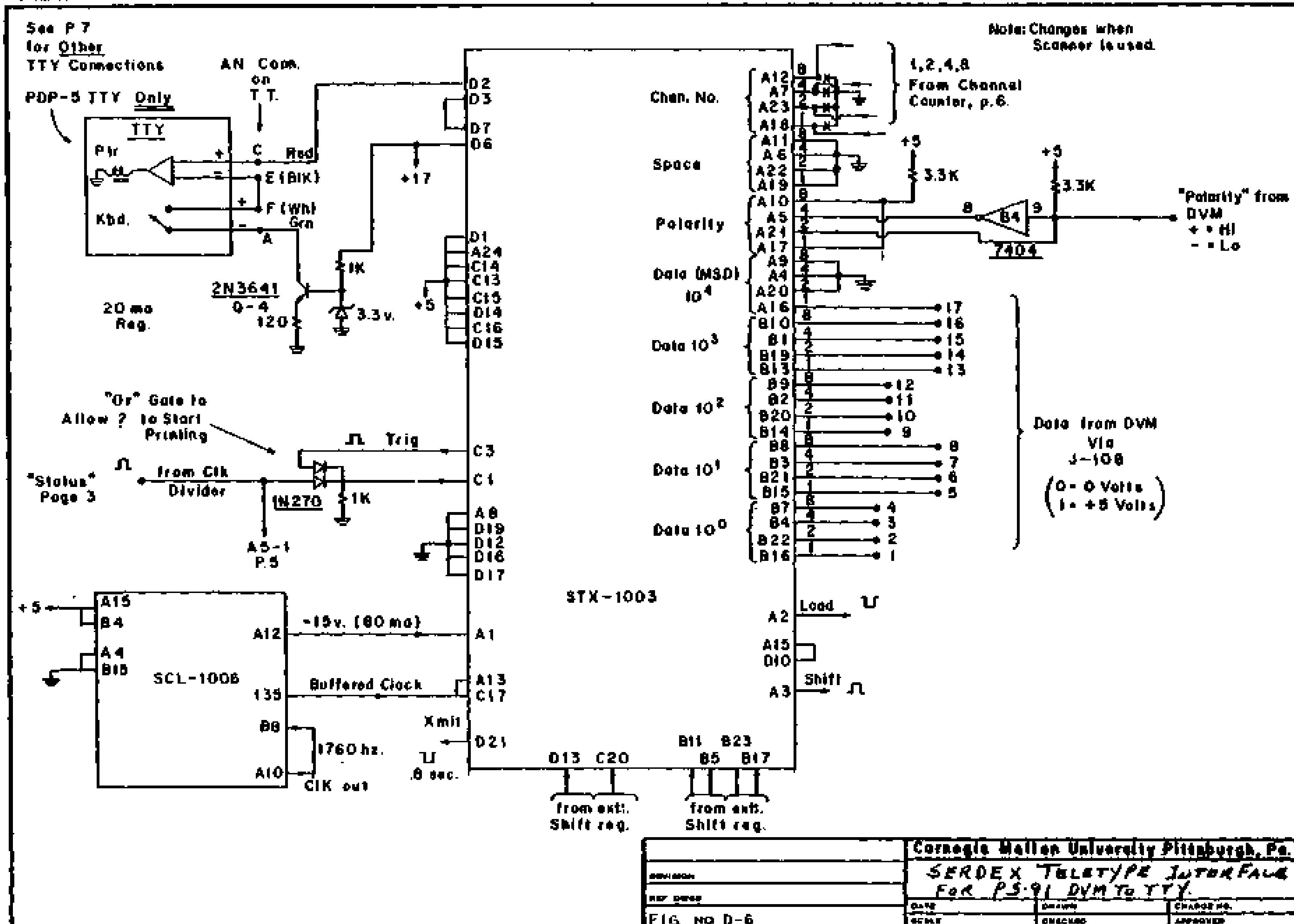
The extra shift registers provide the correct levels for the STX-1003 module (bits 5 and 6), so that extra characters may be typed. The format selected for typing is Space (or Channel number), Space, Polarity, Data (most significant bit), Data, Data, Data, Data (least significant bit), Space, and then either 3 Stop bits on all words except the eighth, where the last 3 bits are "line feed", "carriage return", and Stop. This format allows the typing of eight DVM readings on one line of paper, then a line-feed and carriage return for the next line.

A "hold" signal is sent to the DVM from the divider chain to prevent the DVM reading from changing during the actual type-out period.

The schematic diagrams for the PS-91 DVM-TTY Interface are given in Figures D-5 to D-10.


Form 108
6 Ft Cable
Clock Divider
Model
171 DVM
Keithley Inst.
Clk (100 khz)
Divider
Chain
10 Sec
4
2
1 Sec
One
Shot
Channel Advance
Manual
+5
Data
One Shot
0.5 Sec
Hold
Status
STX-1003
Serial Transmitter
2-Wires
Serial Data
To TTY
Tele-
Type
Clk
SCL-1006
Clock Module
-18
+5
+17
+5
Load Ch. Add.
Chan.
Address
To
Scanner
and
To
STX-1003
Channel
Counter
"Last
Channel"
Used with Keithley Mod. 702
Scanner
117
A.C
+5v.-1A
P.S.
AO-905
17 v.
20 ma. P.S.
External Shift
Reg. for
Extra Words
Carnegie Mellon University Pittsburgh, Pa.
PS-91 DVM-TTY Interface
Blk. Dgm.
FIG. NO. D-5

Form 106


See P 7 for Other TTY Connections
PDP-5 TTY Only
AN Conn. on T.T.
TTY
Ptr
Kbd.
C Red
E (Blk)
F (Wh) Grn
A
+17
2N3641 Q-4
1K
3.3 v.
120
20 ma Reg.
D2
D3
D7
D6
D1
A24
C14
C13
C15
D14
C16
D15
+5
"Or" Gate to Allow ? to Start Printing
Trig
C3
C1
"Status" Page 3
from Clk Divider
1N270
1K
A5-1 P.5
A8
D19
D12
D16
D17
STX-1003
SCL-1006
A15
B4
A4
B15
+5
A12
-15v. (80 ma)
A1
135
Buffered Clock
A13
C17
B8
1760 hz.
A10
Clk out
Xmit
D21
.8 sec.
D13 C20
from ext'l. Shift reg.
B11 B23
B5 B17
from ext'l. Shift reg.
Note: Changes when Scanner is used.
Chan. No.
A12
A7
A23
A18
1,2,4,8 From Channel Counter, p.6.
Space
A11
A6
A22
A19
Polarity
A10
A5
A21
A17
+5
3.3K
B4
7404
"Polarity" from DVM
+ = Hi
- = Lo
Data (MSD) 10^4
A9
A4
A20
A16
Data 10^3
B10
B1
B19
B13
Data 10^2
B9
B2
B20
B14
Data 10^1
B8
B3
B21
B15
Data 10^0
B7
B4
B22
B16
Data from DVM Via J-108
(0 = 0 Volts
1 = +5 Volts)
A2 Load
A15
D10
A3 Shift
Carnegie Mellon University Pittsburgh, Pa.
SERDEX Teletype Interface For PS-91 DVM to TTY
FIG. NO D-6

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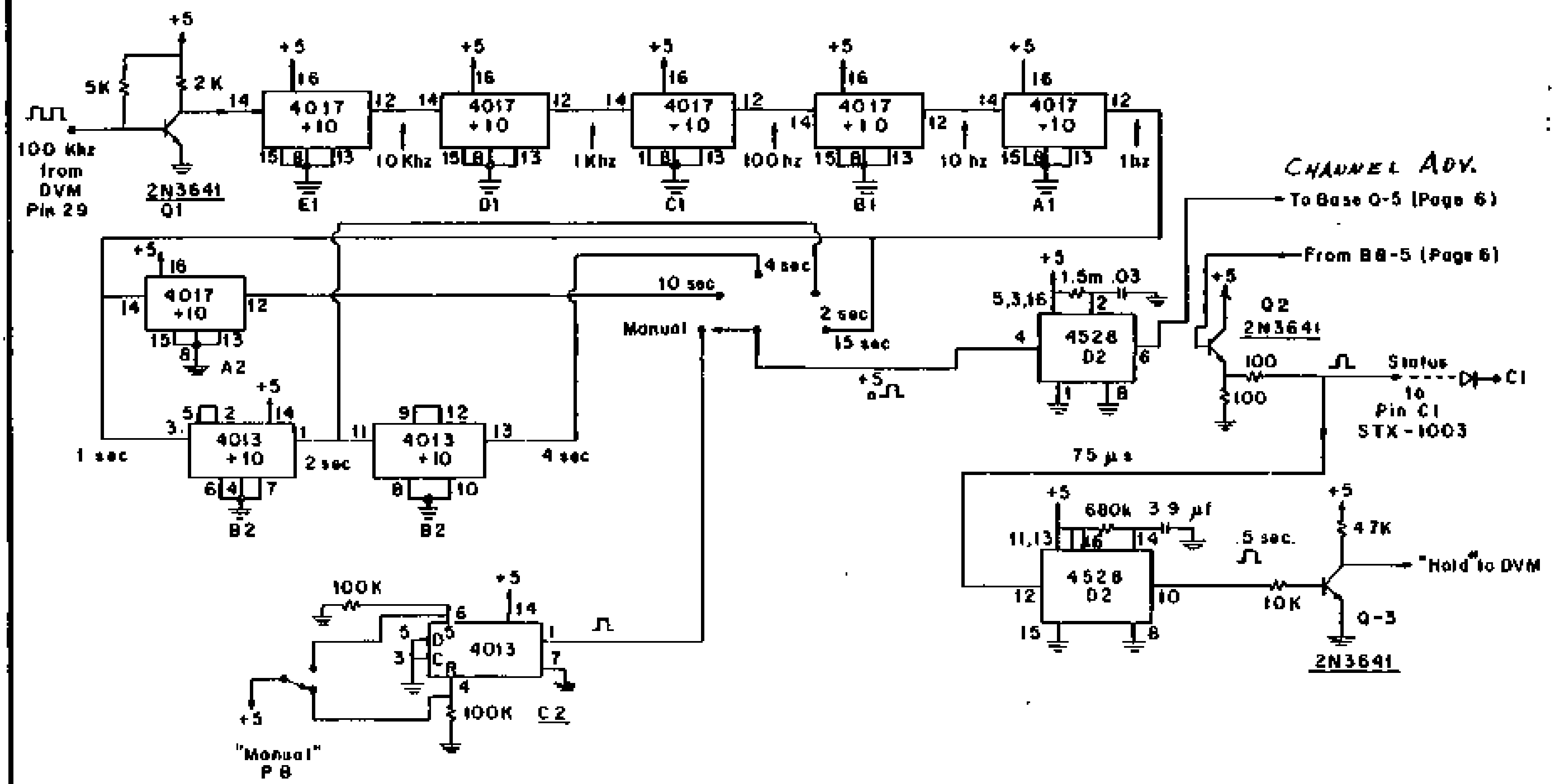
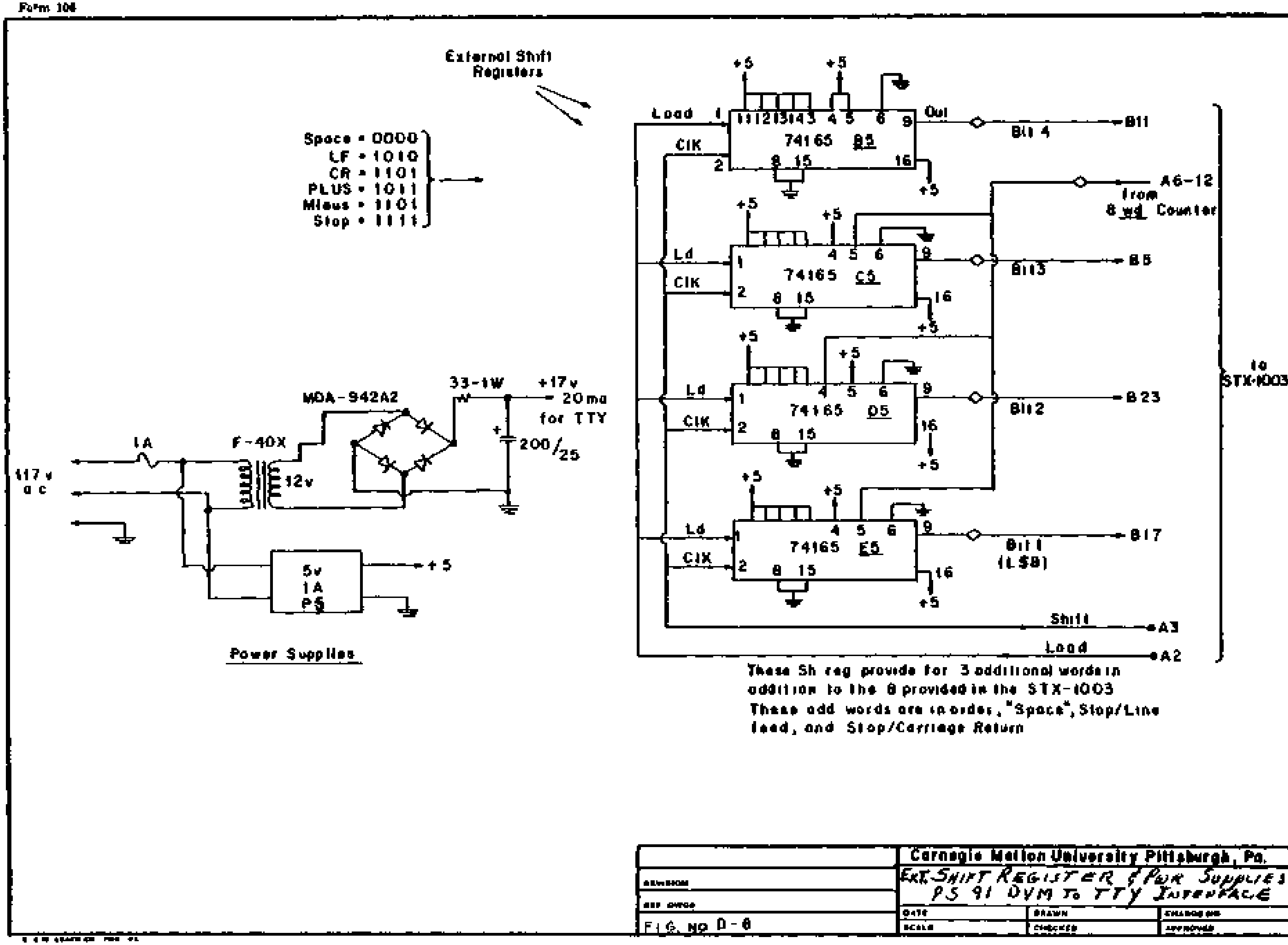
Form 106



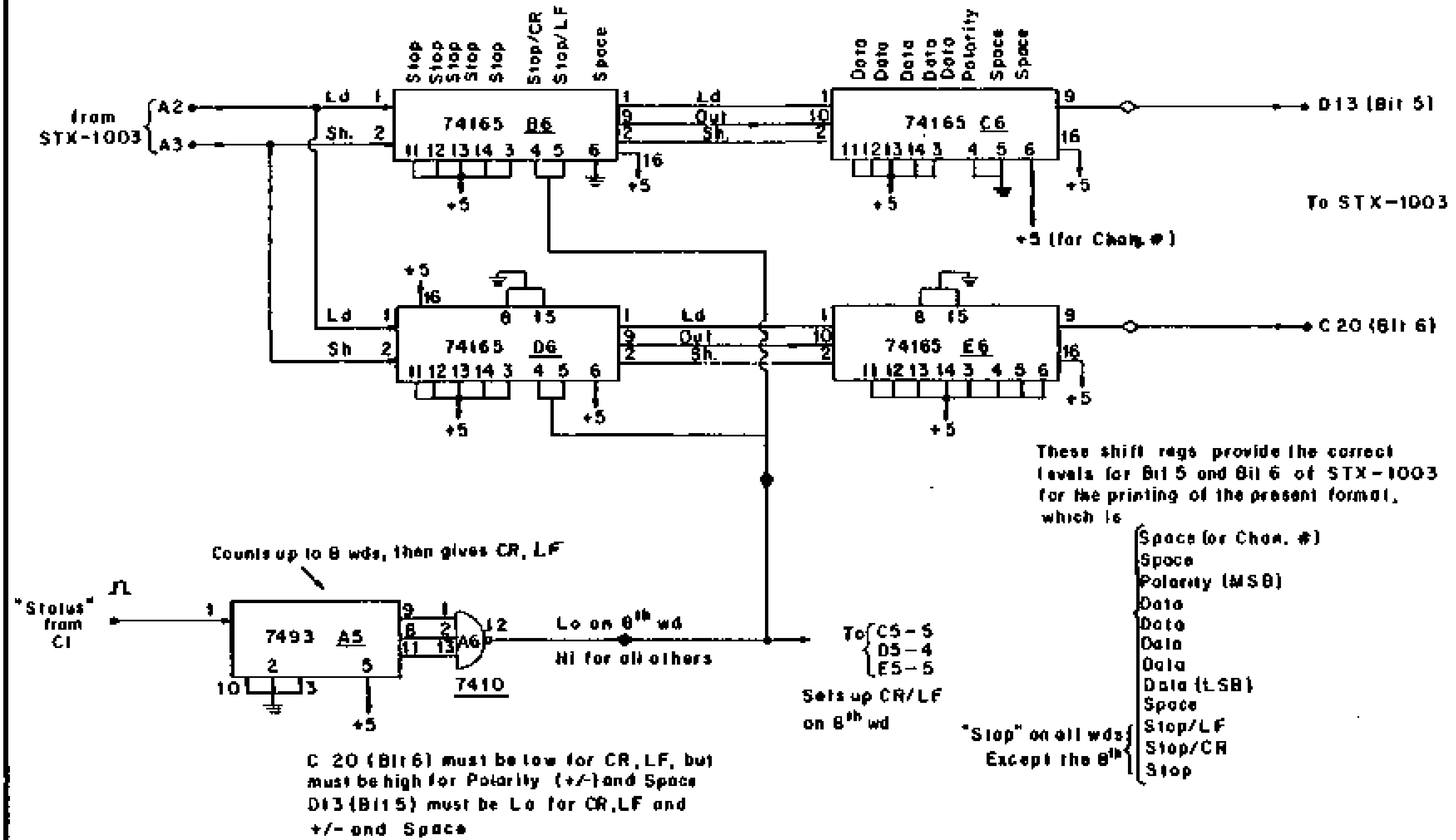

| | |
|---|---|
| | Carnegie Mellon University Pittsburgh, Pa. |
| REVISION | PS-91 CLOCK DIVIDER CHAIN |
| REF. DWGS. | DATE / DRAWN / CHANGE NO. |
| FIG. NO. D-7 | SCALE / CHECKED / APPROVED |

Form 106


External Shift Registers
Space = 0000
LF = 1010
CR = 1101
PLUS = 1011
Minus = 1101
Stop = 1111
Load
Clk
74165 B5
Out
Bit 4
B11
A6-12
from
8 wd Counter
Ld
74165 C5
Bit 3
B5
74165 D5
Bit 2
B23
74165 E5
Bit 1
(LSB)
B17
Shift
A3
Load
A2
to
STX-1003
+17 v
20 ma
for TTY
33-1W
MDA-942A2
200/25
1A
F-40X
12v
117 v
a c
5v
1A
PS
+5
Power Supplies
These Sh reg provide for 3 additional words in addition to the 8 provided in the STX-1003
These add words are in order, "Space", Stop/Line feed, and Stop/Carriage Return
Carnegie Mellon University Pittsburgh, Pa.
Ext. Shift Register & Pwr Supplies
PS 91 DVM to TTY Interface
REVISION
REF DWGS
FIG. NO D-6
DATE
SCALE
DRAWN
CHECKED
CHARGE NO
APPROVED

233

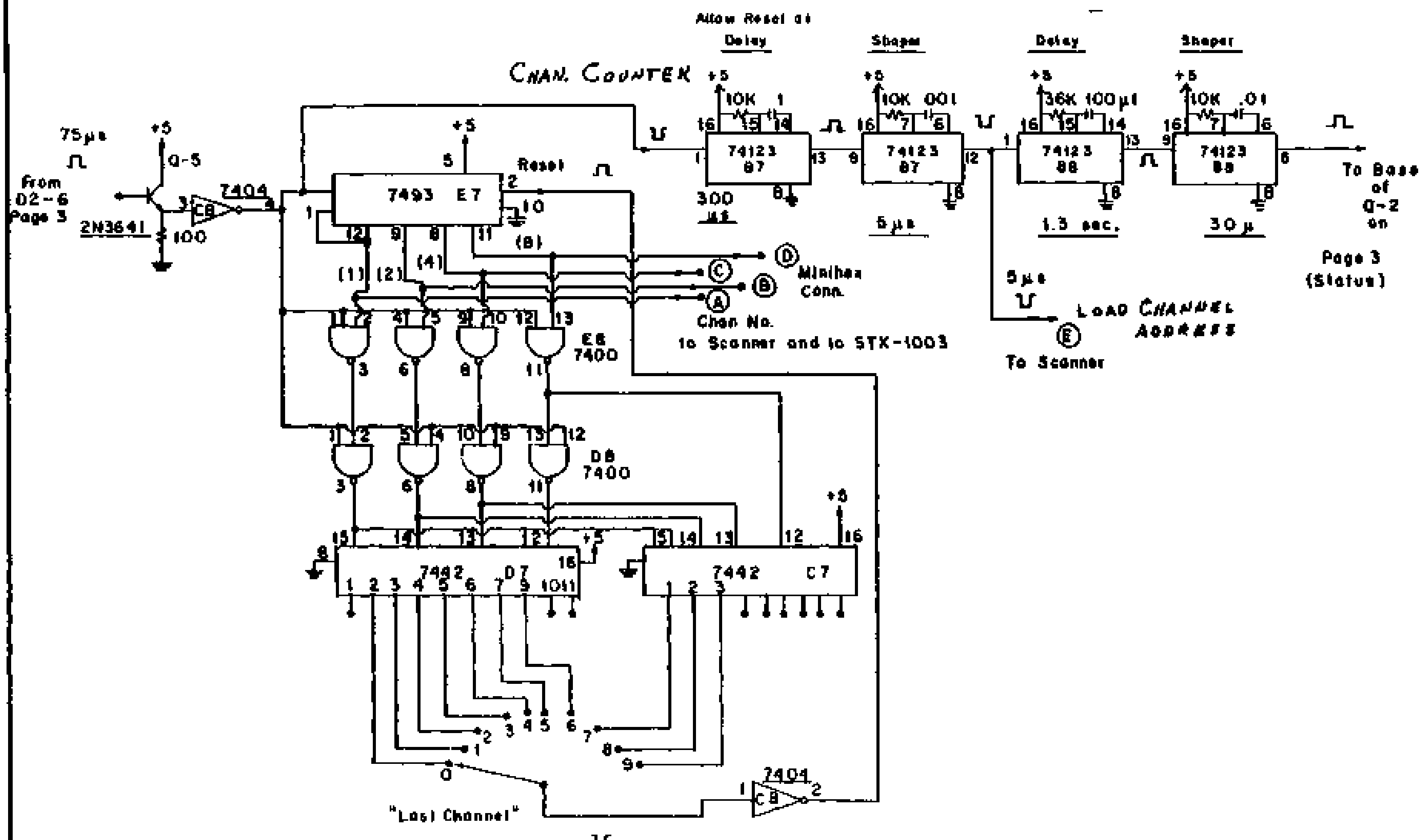
Form 108




Carnegie Mellon University Pittsburgh, Pa.

SHIFT REGISTER
PS-91 DVM To TTY INTERFACE

FIG. NO. D-9




Carnegie Mellon University Pittsburgh, Pa.

1591 CHANNEL COUNTER AND DECODER

FIG NO D-10

# APPENDIX E. NOI'I OPERATING PROCEDURE

Table of Contents

## INTRODUCTION

This is a detailed operating manual for use of the OTEC Biofouling apparatus aboard the NOI'I anchored at Keahole Point, Island of Hawaii.

The data taking system consists of 6 separate modules all of which are electrically interconnected and which have specific functions to perform. We describe the general purpose of each module, then give a detailed description of each along with its constrols. Then we describe the standard procedure for taking data.

These instructions were written for the use of technicians in the field in the operation of a specific data acquisition system (that used aboard the Research Vessel NOI'I , and described in Sec. 5.). With a different data acquisition system (for example that described in App. D), the details will be different. These instructions will not be of use with a system using different electronics. They are presented here merely to illustrate the procedures.

# CHAPTER 1

## SYSTEM DESCRIPTION

### 1.1. Experimental Units.

There are 2 experimental units on board NOI'I. The starboard unit (right side when facing bow of ship) is named Unit 2 and the port unit (left side facing bow of ship) is named Unit 3. These units are identical in major details but the experiments being performed with these two units are different in some important parameters.

These units are housed in 6 inch PVC housings which are designed to be waterproof at depths of up to 100 feet of seawater, and are designed to be mounted on a sub-surface buoy where they will operate unattended for periods up to a year. Figure 4-1 shows a sketch of the working parts of a unit.

The experiment being performed with these units is to pump ocean water through the simulated heat exchanger tube and to determine the severity of the corrosion and biological growth that accumulates in the heat exchanger tube as the water is pumped and its effect on the heat transfer between the tube and the water flowing through the tube. We do this by directly measuring the heat transfer coefficient h between the inside wall of the tube and the flowing water. h is measured in units of BTU/hr $ft^2 {}^\circ F$ or in units of watts/$cm^2 {}^\circ C$.

h is measured in the following manner. An AC voltage is applied to the heater windings on the Cu heater cylinder and the temperature of the cylinder is then raised slightly above the temperature of the flowing water. This temperature difference is measured by the thermopile in which one set of 11 junctions is embedded in the Cu reference cylinder which remains nearly at the temperature of the flowing water, and the other set of 11 junctions is at the temperature of the heater cylinder. For a given heater power, the system will come to a steady state in which all the heat put into the heater cylinder is carried away by the flowing water and the temperature of the heater blocks is no longer increasing. At this point recording of the thermopile voltage is begun. This recording is continued for 1 minute with the heater on. After 1 minute the heater is turned off and the temperature of the Cu heater cylinder begins to cool as the heat stored in it is carried away by the flowing water. Recording of the thermopile voltage is continued for 10 time constants (~10 minutes with flow velocity of 3 ft/sec) as the Cu heater cylinder cools. It cools according to Newton's law of cooling which predicts that the temperature of the block should have the following form:

$$T(t) = T_o e^{-t/\tau} \quad ,$$

where T is the temperature difference between the Cu heater cylinder and the flowing water, $T_o$ is some initial temperature, t is time and $\tau$ is the characteristic time constant of the decay. Since the thermocouple voltage is linearly related to the temperature difference between the Cu heater cylinder and the Cu reference cylinder (which is at the temperature of the flowing water), the thermocouple voltage will have this mathematical form, namely

$$V(t) = V_o e^{-t/\tau} \quad .$$

Here V is thermocouple voltage, $V_o$ its initial value, t is time and $\tau$ the same time constant given above.

This voltage is recorded vs. time on punched paper tape. These tapes are then sent to Pittsburgh where computer fits are made to the data and $\tau$ is determined.

Knowing the dimensions of the Cu heater cylinder and the thickness of the heat exchanger tube, it is possible to determine a relationship between $\tau$ and h.

In a clean tube at a certain water temperature h depends only on the velocity of the water passing through the tube. This dependence has the form:

$$h = K\ V^{0.8}\ ,$$

where V is water velocity and K depends on water temperature and the degree of smoothness of the tube.

As a biological fouling layer (or any other kind, for instance scale precipitated from the water) builds up in the tube, its effect is to decrease the efficiency with which heat is transferred between the tube and the water and K is decreased.

With this as background, the general philosophy of the NOI'I experiments, and the later subsurface buoy experiments can be stated.

With a clean tube we begin pumping water through the tube at a certain fixed velocity. This velocity is 3 ft/sec for Unit 2 and 6 ft/sec for Unit 3. We then measure h at this velocity at periodic intervals. As the fouling develops we see a change in h that is related to the development of the fouling layer.

When a cooling curve is taken, two other parameters are recorded simultaneously with the thermopile voltage. These are the flow meter output, which gives the water velocity through the tube, and the thermistor output, which gives the temperature of the water flowing through the tube. It is necessary to record the flow velocity because of its effect on h. Small variations in flow velocity from run to run must be taken into account in determining the degree of fouling. We have also found that there are sudden changes in water temperature of the order of 0.1°C. These changes affect the Cu heater cylinder slightly differently than they do the Cu reference cylinder. Thus they are reflected in the thermopile voltage, and must be taken into account during analysis of the data.

1.2. Buoy Control

The buoy control is designed to be mounted on the subsurface buoy.

It takes in low level signals from the experimental units, amplifies them and transmits them through a cable to recording apparatus on shore. It is designed to require no maintenance when in operation and has no controls to be worked by an operator. On the NOI'I the cable through which it transmits is a bundle of 6 coaxial wires. The box containing the buoy control is sealed and should not be opened without consulations with Pittsburgh.

1.3. Beach Control

The beach control is designed to take in amplified signals from the buoy control and output them to the Digital Voltmeter (DVM) to be punched on paper tape. The beach control also sends signals down the cable to the buoy control to tell it which input to connect to which amplifier. There are also other controlling functions that are preformed by the beach control and buoy control combination. These will be explained later. The best description of the relationship between the beach control and the buoy control is a master-slave relationship with the beach control telling the buoy control what to do.

1.4. Digital Voltmeter (DVM)

The DVM has several components which allow it to take in up to 20 different signals and punch any one of them onto paper tape.

1.4.1. DVM Scanner

The scanner is the part of the DVM that determines which voltage is recorded on the paper tape. The input to the scanner is up to 20 channels of information, each channel containing a DC voltage in the range $-10 \leq V \leq 10$. The output of the scanner is one of these voltages. The scanner is a passive device, containing only switches and the logic to drive them. The scanner can be made to output a particular channel continuously or to automatically advance from one channel to another in a controlled sequence.

### 1.4.2. DVM Digital Indicator

The input to the digital indicator is the voltage output by the scanner. It takes this voltage and converts it into a digital signal of the form A.BCD. This digital signal is then displayed on a Nixie tube readout on the front of the digital indicator and is routed to the paper tape punch where it can be recorded in a permanent, computer readable manner.

### 1.4.3. DVM Paper Tape Punch

The paper tape punch takes the output of the digital indicator and punches it onto paper tape. The frequency with which it punches is controlled by the Beach Control. This signal to punch from the Beach Control passes through the scanner where it also causes the scanner to advance.

### 1.4.4. DVM Other Components

There are other parts of the DVM which are either not a part of the data transmission path, or whose operation is transparent to the operator.

#### 1.4.4.1. DVM Clock

The DVM has a digital clock. This clock is run off the 60 Hz line frequency. This frequency is not very well regulated aboard NOI'I, so the clock does not keep reliable time. It can be useful nevertheless.

#### 1.4.4.2. DVM Comparators

These perform no function and are not used in the NOI'I operation.

#### 1.4.4.3. DVM Adams-Smith Instrument Interface

This unit, whose operation is transparent to the operator, takes in the signals from the digital indicator and puts them out to the paper tape punch in the correct format.

## 1.5. Thermistor Bridge Switch

The beach and buoy control were designed to handle only one thermistor. Early on in the NOI'I operation we realized the necessity for taking water temperature measurements with each cooling curve. In order to do this we had to build a new thermistor bridge and switch circuit. The thermistor bridge takes power from the buoy control and produces a signal which depends on the temperature of the thermistor which is connected to the bridge via the switch circuit. The switch can handle up to 6 thermistors, though only 3 are now in use.

## 1.6. Marker Potentiometers

We would like to be able to analyse the tapes produced by the DVM with as little human manipulation as possible. To do this we punch on the tape a number of Markers which convey information about date, time, run number, unit number and type of information. These markers are a series of voltages ($0 \leq V \leq 10$) which are input to DVM channels 14-19. These voltages are controlled by 6 one-turn potentiometers (pots). The code for using these pots will be explained later.

## 1.7. Chassis Designations

The following units, all of which are controlled by the operator, are called chassis. They will often be referred to by abbreviations. Their names and abbreviations are:

Beach Control: (BC)

Digital Voltmeter: (DVM)

Thermistor Switch Box: (TM)

Marker Potentiometers: (MP) and

Hewlett-Packard Digital Multimeter: (HPMM)

See Figs. E-1 thru E-9 for a sketch of each chassis panel.

# CHAPTER 2

## DESCRIPTION OF OPERATOR CONTROLS

### 2.1. Beach Control

When the overall design parameters of the subsurface buoy were fixed we decided upon a maximum of 6 units in place on the buoy. This meant that our electronics system must be able to handle 6 thermocouples, 6 heaters, 6 flow meters, and 6 pumps, in addition to other pieces of information such as water temperature.

In order to multiplex all these signals for transmission along a few lines, the Buoy Control and Beach Control electronics are based on ring counters. Ring counters are the electronic equivalent of stepping switches. Basically these devices have several outputs $Q_o$ - $Q_n$. At any given time only one of these outputs can be in the logic 1 state, that is , have a voltage greater than 3.5 V. (Logic 0 state is indicated by a voltage less than 1.8 V.) Upon receiving an "advance" pulse the ring counter advances the logic 1 state from $Q_m$ to $Q_{m+1}$. ($Q_o$ follows $Q_n$ or it wouldn't be called a ring counter.) Upon receiving a reset pulse the ring counter resets the logic 1 state from $Q_m$ to $Q_o$. It is important for understanding the operation of the Beach Control and Buoy Control that one understand that a ring counter can do only 2 things.

(1) Advance from $Q_m$ to $Q_{m+1}$ and

(2) Reset from $Q_m$ to $Q_o$.

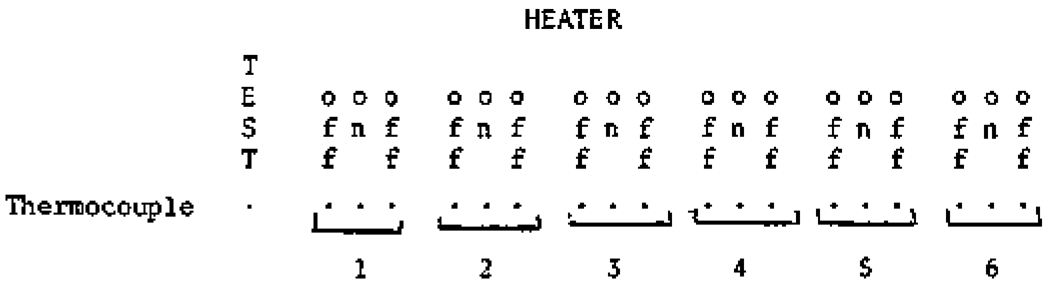
When the ring counter brings its logic 1 signal to a certain output ($Q_m$), this signal is used in other parts of the Buoy Control or Beach Control to perform the function desired.

On the front panel of the Beach Control will be observed 6 rows of light emitting diodes (LED's), 3 switches and 2 red push buttons.

Each of these rows of LED's corresponds to 2 identical ring counters. One is contained in the Beach Control, the various outputs of which drive the LED's on the panel: and the other is contained in the Buoy Control where its outputs perform switching functions.

2.1.2. Thermocouple LED's

The first row of LED's is labelled Thermocouples and contains 19 LED's. They are arranged as indicated below:




Thermocouple LED's

---

The position of the lighted LED indicates which of the 6 possible thermocouples is connected to the thermocouple amplifier in the buoy control, and whether the heater associated with that thermocouple is on or off. This output of the thermocouple amplifier is transmitted up the cable to the Beach Control, and then to channel 1 of the DVM. The position of the lighted LED is advanced to the right one step at a time by pressing the red button marked STEP with the upper right hand switch (Marked SWITCH) set to the STEP THERMOCOUPLE position. For the n$^{th}$ thermocouple (TCn) there are 3 positions for the lighted LED.

1. TCn connected to the TC amplifier, heater n OFF.
2. TCn connected to the TC amplifier, heater n ON.
3. TCn connected to the TC amplifier, heater n OFF.

The reset position, reached by pressing the red button marked RESET ALL is called TEST and connects the emplifier to a voltage generated inside the buoy control. This voltage simulates a thermocouple voltage.

In order to make a cooling curve on Unit 3, the operator would do the following. (Remember the LED's on the Beach Control just mimic the action of a ring counter in the Buoy Control which does all the actual switching).

1. Set the DVM to Scan between Ch 1 and Ch 3 (This will be described later).
2. Push RESET ALL once.
3. Set SWITCH to STEP THERMOCOUPLE.
4. Press STEP 8 times to advance lighted LED to thermocouple 3 (TC3) heater on (now it will be noted that the voltage indicated by Ch 1 is decreasing (getting more negative).
5. When the voltage stops decreasing, the heater block has reached its steady state temperature. Press STEP once. This moves the lighted LED to TC3 heater off.

(Now the Ch 1 voltage will increase as the block cools.)

This describes how the thermocouple part of the Beach Control is used to generate a cooling curve.

2.1.3. Flow Meters

The second row of LED's is labelled Flow Meters and numbered 1-6. The lighted LED is advanced to the right in this row by pressing STEP with the SWITCH in the STEP FLOW METER position. It is reset by the RESET ALL button. (All rows of LED's are reset simultaneously by RESET ALL). The lighted LED indicated which flow meter is connected to the flow meter amplifier in the Buoy Control. The output of this amplifier is transmitted up the cable to the Beach Control, and then to channel 3 of the DVM.

## 2.1.4. Function and Control

The third row of LED's is labelled FUNCTION and has a somewhat different role than the previous two rows. The fourth row of LED's is labelled ELECTROLYSIS, the fifth row labelled PUMP OFF and the sixth row HEATER POWER. The lighted LED's in these rows are advanced to the right by using the SWITCH positions STEP FUNCTION and STEP CONTROL in conjunction.

### 2.1.4.1. Electrolysis

Our original design called for using electrolytically generated chlorine as a fouling prevention method. We thus designed into the Beach Control and Buoy Control the capability of monitoring the current and voltage being used by the electrolysis circuit. The CURRENT and VOLTS positions on the FUNCTION line and the ELECTROLYSIS line are connected with this system. This system is not in use aboard NOI'I, but for completeness we will describe its operation. This will also describe the mode of operation of STEP FUNCTION and STEP CONTROL, and make later descriptions easier.

In general STEP FUNCTION doesn't actually do anything but rather enables the operator to do something by using STEP CONTROL. When the FUNCTION lighted LED is at CURRENT (VOLTS) a signal proportional to current (voltage) in the $\ell^{th}$ ($1 \le \ell \le 5$) electrolysis circuit is connected to the Miscellaneous amplifier in the Buoy Control. The output of this amplifier is transmitted up the cable to the Beach Control, and then to Ch. 2 of the DVM. The value of $\ell$ above, that is, the position of the lighted LED in the ELECTROLYSIS line, is advanced to the right by punching the STEP button with the SWITCH set to STEP CONTROL. Thus with the FUNCTION lighted LED in either the CURRENT or VOLTS position, STEP CONTROL moves the lighted LED in the ELECTROLYSIS line. Again the RESET ALL moves the lighted LED to the extreme left in all lines.

2.1.4.2. Pumps

Each of the 6 units will have a pump associated with it. We need to be able to control these 6 pumps using the Beach Control and the Buoy Control. The way we chose to do this is to turn off an individual pump and leave the rest of the 6 running. When the FUNCTION lighted LED in the PUMPS position, operating STEP with the SWITCH in the STEP CONTROL position advances the PUMPS OFF lighted LED from 1 to 6, turning off the indicated pump. The RESET position is no pumps turned off. This system is not in use on NOI'I.

2.1.4.3. Heater Power

We included in the Buoy Control and Beach Control the capability of using either of two different voltages to power the heater windings. When the FUNCTION lighted LED is in the HEATER POWER position, operating the STEP button with the SWITCH set to STEP CONTROL advances the HEATER POWER lighted LED from LOW to HIGH. On NOI'I Unit 2 is run at LOW power, Unit 3 at HIGH power.

2.1.4.4. Ball

The BALL position of the FUNCTION lighted LED is projected for use with a fouling control system which has not yet been designed.

2.1.4.5. Thermistor

As indicated above in paragraph 1.5 we have included in the Beach Control and Buoy Control, the capability of handling a water temperature measuring thermistor. The signal from the thermistor bridge and switch described in paragraph 1.5 goes into the Buoy Control. When the FUNCTION lighted LED is in the THERMISTOR position, the Miscellaneous amplifier is connected to the thermistor bridge. This amplifier's output is transmited up the cable to the Beach Control and then to Ch. 2 of the DVM. The reading at Ch. 2 is then related to the temperature of the sea water flowing through the unit in question.

2.1.5. DVM Scan Interval

In order to get a correct time constant from our cooling curves we need to punch out the individual data points with the time between points controlled as accurately as possible. The Beach Control contains a quartz clock. We take pulses from this quartz clock and use them to drive the DVM Scanner and Punch. The DVM SCAN INTERVAL switch controls the timing with which these pulses arrive at the DVM. The normal timing for the NOI'I operation is the 2 SEC setting. This should never be changed.

2.1.6. Manual or Auto Switch

We plan to use the DVM to automatically monitor the flow meters on each unit on the subsurface buoy. To do this the Beach Control and Buoy Control must automatically scan from one flow meter to the next. In the MANUAL setting, no automatic advances take place and the advancement to the right of the Flow Meter lighted LED is controlled by the STEP button as described in paragraph 2.1.3. In the AUTO position the STEP button is disabled for the SWITCH position STEP FLOW METER and the flow meter lighted LED advances to the right each minute or every 10 minutes depending on the position of the MANUAL/AUTO switch.

2.1.7. Manipulation of Beach Control for Taking Data From Unit 2

To set up the Beach Control to take data from Unit 2, follow the steps below. Explanation of the rationale for some of the steps, where it is not obvious from above, is offered after the enumeration of the steps.

Instruction

1 | Push RESET ALL

2 | Set SWITCH to STEP THERMOCOUPLE

3 | Push STEP 5 times

4 | Set SWITCH to STEP FLOW METER

5 | Push STEP 1 time

6 | Set SWITCH to STEP FUNCTION

7 | Push STEP 5 times

8 | Set SWITCH to STEP THERMOCOUPLE

9 | Set thermistor switch (on external switch box) to 2

Notes

Instruction Explanation

3 | Turns Unit 2 heater on

5 | Connects DVM Ch. 3 to flow meter for Unit 2.

7 | Connects DVM Ch. 2 to thermistor output

8 | When STEP is pushed after steady state is reached we want to STEP THERMOCOUPLE, not something else. This instruction insures that.

2.1.8 Manipulation of Beach Control for Taking Data from Unit 3

To set up the Beach Control to take data from Unit 3 follow the steps below. Again the rationale follows where necessary.

Instruction

1 | Push RESET ALL

2 | Set SWITCH to STEP THERMOCOUPLE

3 | Push STEP 8 times

4 | Set SWITCH to STEP FLOW METER

5 | Push STEP 2 times

6 | Set SWITCH to STEP FUNCTION

7 | Push STEP 2 times

8 | Set SWITCH to STEP CONTROL

9 | Push STEP 1 time

10 | Set SWITCH to STEP FUNCTION

11 | Push STEP 3 times

12 | Set SWITCH to STEP THERMOCOUPLE

13 | Set thermistor switch to 3

| Instruction | Notes Explanation |
| --- | --- |
| 3 | Turns Unit 3 heater on |
| 5 | Connects DVM Ch. 3 to Flow Meter 3 |
| 7 | Puts FUNCTION lighted LED at HEATER POWER |
| 9 | Sets HEATER POWER to HIGH |
| 11 | Connects DVM Ch. 2 to thermistor |
| 12 | Beach Control is ready to turn off heater |

2.1.9. Power Switch

The Beach Control has a power switch. The RESET ALL circuitry is arranged so that a few milliseconds after the switch is turned on, a RESET ALL pulse is generated. This insures that every thing "wakes up" reset. On NOI'I, the power switch for the DVM also controls the Beach Control in series with the Beach Control's own power switch.

2.2. DVM Operator Controls

In general the DVM controls are clearly marked and their functions quite easily determined from their names, but a short description of each control is in order so that this manual is complete and self-sufficient.

2.2.1. POWER SWITCH

There is a white, circuit-breaker type power switch on the lower left of the DVM rack. This controls all power to the DVM and, on NOI'I, power to the Beach Control (but not to the Buoy Control). Sometimes when this switch is thrown the DIGITAL INDICATOR ends up in a confused state. The indication of this is a reading (usually) displaying 8.XYZ where X, Y and Z may vary and the Nixie tube for z (usually) displays more than one number at a time. The only cure is to turn the switch off and back on again. Should nothing happen when this switch is turned on, check to see that the switch at the outlet where the DVM is plugged in is on, and also check that the breaker marked AFT OUTLET is on (the breaker box is located in the aft head (rest room) on NOI'I).

2.2.2. Clock

The DVM clock does not keep accurate time because it works off line frequency which is not well controlled by the portable generator aboard the NOI'I, but it can be useful from time to time. The clock is set by turning the SET/RUN switch to SET. Then the buttons above each digit cause the digit to change at the rate of 1 numeral/sec. When the proper setting is reached, return SET/RUN switch to RUN.

2.2.3. Comparators

The thumb switches on the comparators are of no use and perform no function in the NOI'I operation.

The ALARM RESET button does nothing.

The MANUAL RECORD button does nothing.

The AUTO RECORD button turns the paper tape punch on and off. Press once and the punch works and the button is lighted, press again and the punch is off.

2.2.4. Digital Indicator

Normally the operator does not use any of the controls on the DIGITAL INDICATOR. In the event of some inadvertent change of these controls their symptoms will be described.

If the digital indicator reads 9.ABC, and does not respond to changing voltages at the input (changing the setting on a marker pot for instance) or to changing channels, try pushing the calibrate button. It should normally be out.

If power is turned off to the digital indicator alone, the Adams-Smith Instrument Interface must be turned off via a small switch in the rear of the interface. The digital indicator has a neon tube to the extreme left of the display. When lighted this indicates the DVM is in overrange condition (V>10 volts).

2.2.5. Scanner

The controls associated with the scanner perform most of the control functions for the DVM.

2.2.5.1. Int/Ext Switch

When the INT/EXT switch is in the EXT position the scan rate of the scanner and the punch rate of the punch is controlled via the DVM SCAN INTERVAL switch on the Beach Control. This is the normal position and should not be changed.

In the INT position the scan and punch timing is controlled internally in the scanner and adjusted by the SCAN RATE potentiometer on the front of the scanner.

2.2.5.2. Initial Channel/Final Channel Thumbswitches

These switches set the limits of the automatic scan on the scanner. They refer to channel numbers. Their normal setting is INIT CHANNEL = 1, FINAL CHANNEL = 3 for cooling curves, and INIT CHANNEL = 14, FINAL CHANNEL = 19 for tape markers.

2.2.5.3. Push Switch Row

This row of seven switches labelled

| | | | | | | |
|---|---|---|---|---|---|---|
| Power | Random Access | Single Scan | Cont Scan | Start | Step | Reset |

are the heart of the DVM controls. The function of each will be explained.

POWER

Turns power on and off to the scanner, normally left in the on position.

RANDOM ACCESS

With this switch pushed, the scanner does not change channels automatically. The channel displayed (The Nixie tube display on the scanner indicates which channel is input to the digital Indicator.) is the Initial channel when START is pressed and advances by 1 when STEP is pressed.

SINGLE SCAN

With the SINGLE SCAN button pressed the scanner goes to the initial channel when START is pressed and advances at the scan rate indicated by the DVM SCAN INTERVAL switch of the Beach Control until it reaches the final channel. It then returns to the initial channel and stops scanning. If the AUTO RECORD button is pushed the punch punches just before the scanner scans.

CONT SCAN

If the CONT SCAN button is pushed the scanner goes to the initial channel when START is pushed and advances at the rate indicated by the DVM SCAN INTERVAL until it reaches the final channel. At the final channel it returns to the initial channel and continues scanning. If AUTO RECORD is pushed, the punch punches just before the scanner scans.

START

In either RANDOM ACCESS, SINGLE SCAN or CONT SCAN, pressing START makes the scanner go to the intial channel. When AUTO RECORD is pressed an automatic start command is given.

STEP

In RANDOM ACCESS (STEP does not work in SINGLE SCAN or CONT SCAN) STEP advances the scanner 1 channel. If the scanner is on the final channel, when step is pressed it returns to the initial channel.

RESET

Pressing RESET causes the scanner to go to channel 00. This channel contains no information and is not used in the NOI'I operation.

2.2.6. Punch

There are two buttons on the punch which are used in the NOI'I operation. One is labelled REEL MOTOR and switches on or off the motor which drives the take-up reel for the punched tape. The other is labelled TAPE FEED, and causes the punch to punch feed sprocket holes in the tape and run tape through the machine. The REEL MOTOR is normally on, and the TAPE FEED is used to put blank deliniating spacers on the tape.

2.2.7. Setting Up the Scanner to Record a Tape Marker

| Instruction | Action |
|---|---|
| 1 | Set INIT CHANNEL to 14 |
| 2 | Set FINAL CHANNEL to 19 |
| 3 | Push SINGLE SCAN |
| 4 | Push AUTO RECORD |

When AUTO RECORD is pushed the scanner will go to the initial channel (just as if START were pressed) and begin punching and scanning until the final channel is reached, at which point AUTO RECORD is pushed again to turn off the punch.

2.2.8. Setting Up the Scanner to Record a Cooling Curve

| Instruction | Action |
|---|---|
| 1 | Set INIT CHANNEL to 1 |
| 2 | Set FINAL CHANNEL to 3 |
| 3 | Push CONT SCAN |
| 4 | Push AUTO RECORD |

When AUTO RECORD is pushed the scanner will go to the initial channel and begin punching and scanning 1-2-3-1-2-3 ... until AUTO RECORD is pushed again.

2.3. Thermistor Bridge

The thermistor bridge control has only one switch which has 6 positions. Positions 1-3 are used and Position 4-6 are not used.

| Position | Function |
|---|---|
| 1 | Air temperature thermistor - Unit 2 |
| 2 | Water temperature thermistor - Unit 2 |
| 3 | Water temperature thermistor - Unit 3 |

Position 1 is used in the standard data-taking sequence to record information of value to the data analysis.

Positions 2 and 3 are used whenever a cooling curve is taken as explained in paragraph 1.5. The operator must make certain that the thermistor switch is set to 2(3) when cooling curves are taken with Unit 2(3).

2.4. Marker Pots

The marker pots are used to put identifying markers on the paper tapes produced by the DVM. They operate on channels 14-19. These pots put onto channels 14-19 a voltage that can be varied between 1-10 volts. The digital indicator always displays (and the punch punches) voltages in the format A.BCD. For the markers in Ch. 14-19 the digits C and D are ignored. Thus all the codes explained below use only the digits A and B.

The code is as follows.

| Channel | Meaning |
|---|---|
| 14 | Month of year (1-12) |
| 15 | Day of month (1-31) |
| 16 | Hour of day (0-24) |
| 17 | Minute of hour (0-59) |

| | |
|---|---|
| 18 | Run number (1-99) |
| 19 Digit A | Unit number (0-9) |
| 19 Digit B | Identifying code for type of Data (code follows) |

Code for Digit B of Ch. 19

We generate several different kinds of data in the NOI'I operation. A marker consisting of voltages punched out in Ch. 14-19 preceeds each group of data. The value of Digit B tells the kind of data according to the following code.

| Value | Meaning |
|---|---|
| 0 | Thermocouple test voltage follows |
| 1 | Flow meter zero data follows |
| 2 | Cooling curve follows |
| 3 | Air temperature thermistor data follows |
| 4-9 | Future use |

At the beginning (end) of each sequence of 4 cooling curves a begin (end) sequence marker is placed. These consist of Ch. 14 - Ch. 17 as above and in Ch. 19 0.0 (9.9).

2.5. H-P DMM

The HPMM has 6 buttons marked power, ⎓ ∿, V, A, KΩ and scale auto hold' and has 4 positions for the input leads. These positions are marked V, Ω, com and A. The switches have the following meaning:

POWER: Switch down, power on; switch up, power off.

V: Switch down, measure voltage between V and com. connection

A: Switch down, measure current between A and com. connection

KΩ: Measure resistance between Ω and com. connection.

⎓ ∿, scale auto hold: These switches have a line like this ¯|_ on their face. In the up position the line points to one option, in the down position to another. ⎓ means DC voltage or current, ∿ means AC volts or current, Auto means automatic range selection, hold means it stays at present range selection. Fuses and manual are with instrument.

# CHAPTER 3

## GENERAL DATA TAKING PROCEDURES

### 3.1. Manual

We have made every effort to make this manual complete in every respect. We must be CERTAIN that things are done precisely according to instructions. This manual gives complete instructions for taking data and handling the experiment. If it seems necessary to do something in the experiment that is not covered by this manual, DO NOTHING until you have checked with one of the following

Phone Numbers: All area codes (412)

| | Work | Home |
|---|---|---|
| Glenn Grannemann | 571-2748 | 421-4850 |
| John Fetkovich | 578-2771 | 963-7394 |
| Dan Meier | 578-2772 | 683-1259 |

Call anytime day or night.

### 3.2. Integrity of the Experiment

In general, ANY change in experimental conditions may adversely effect the experiment. If a change seems necessary, contact one of the above before doing anything. The ONLY thing an operator should do is to take data according to the method given in this manual. Most especially the water velocity in the units should not be changed.

### 3.3. Operator Care Necessary

It is imperative that utmost care be exercised when taking the data. Small deviations from the data-taking scheme outlined in this manual can make data analysis and interpretation very difficult or impossible. When using the DVM be certain that all the inputs are in their nominal range and the correct input is being read. When making observations and writing them in the log, note down ANYTHING you observe. Our philosophy is that much too much data is infinitely preferable to even a little too little.

3.4. Data Wanted

Based upton past experience we have devised the following scheme for taking data. The scheme repeats on a two week schedule.

Week 1:

A one day visit to boat. Operator will take 4 or 8 cooling curves with each unit. (Cooling curves will always be taken in groups of 4.) This visit will be to insure that everything is normal.

Week 2:

A two day visit to boat. Operator will take 16-24 cooling curves with each unit. This visit will be to produce data that has high statistical significance. (Again all cooling curves are done in groups of 4.

3.5. Logs for Use with the Experiment

The information written down by the observer is at least as important as that punched by the DVM. We therefore employ an extensive log system while taking data. These logs are kept in 4 separate notebooks. Each test unit has its own log. In addition we have a general log and a tape log. A major part of an operator's duties is to keep up these logs in the manner specified. We have found their format to be intelligible and indispensable to data analysis. Any deviation from the standard log format puts in jeopardy a whole day's effrot at data taking and also a whole day's worth of data. Again, much too much data is better than a little too little. Try to confine writing to an 8-1/2 by 11 space for ease of phtocopying.

3.5.1. Unit Logs

All information pertaining to only one unit is logged in that unit's log. This log has two parts. The first part (FRONT) contains data that pertains to each run. These are arranged in columns, the headings of which are enumerated and explained below

| Heading | Explanation |
|---|---|
| Recorder | Who takes the data |
| Date | |
| Time | Time accurate to ±5 minutes. |
| Run | Runs are numbered sequentially from 1 for each unit for each day |
| Tape | Tapes are numbered according to the following system. Month-day-year-sequential number for that day. For example, Tape 9-1-76-2, is the second tape taken on September 1, 1976 |
| FMZ | Flow meter zero reading |
| FMR | Flow meter reading |
| Volts | AC line voltage as measured by H-P DMM |
| Power | Heater power setting of beach control |
| Bottle Fill Seconds | Time to fill bottle used for absolute flow velocity measurements |
| TC Test | Thermocouple test voltage |
| Air Temp. Thermistor | Air temperature thermistor reading |
| Air Temp. | Mercury thermometer reading |
| $TCR_{30\ sec}$ | Thermocouple reading 30 sec. after heater turned off |
| $TCR_{60\ sec}$ | Thermocouple reading 60 sec. after heater turned off |
| $TCR_{\infty}$ | Thermocouple reading when asymptotic value reached |
| $\tau$ | Time constant calculated from $TCR_{30\ sec}$, $TCR_{60\ sec}$, $TCR_{\infty}$ |
| Comment | |

These items are recorded before and during a run. The work of 30 and 31 Aug. may be used as an example of how data are to be taken.

The second part of the Unit log is to be found in its back pages. Here are kept any observations that pertain only to the unit in question. The pages are divided into 5 columns with the headings: Recorder, Date, Time, Previous Run and Observations. The insertion of the previous run column makes it clear when a particular observation was taken relative to the day's runs. Again the data of 30 and 31 Aug. may be taken as Examples. Some of the kinds of things that might be recorded in the unit logs are any unusual happenings while taking data, changes in water temperature noted while cooling curves are run, indications of sea and boat roll conditions.

3.5.2. General Log

In the general log are kept any observations that pertain to all the experiments aboard NOI'I. The pages are divided into the following columns: Recorder, Date, Time, Observations. We record here things like sea state, ships roll state, weather conditions, power plant outages, observation of creatures near the ship, current direction and speed. Again the general log for 30-31 Aug. may be helpful.

3.5.3. Tape Log

The third log we keep is a tape log. In this log are kept notes which help to understand what is on a particular tape generated by the DVM. Again the Recorder, Date, Time, Observation column shceme is used. This manual describes a standard sequence of 4 cooling curves. This sequence calls for placing several items on the tape. At the start of a sequence a tape log entry should be made to indicate that a sequence is being started. Give the Tape number, the run numbers, and the unit number. As the sequence proceeds any errors or deviations from standard procedure should be noted in the log. At the end of the sequence another note should be entered saying the sequence was finished.

This completes the descriptions of the logs.

## 3.6. System Frailties

By design and in practice the whole system is pretty rugged. There is little an operator can do which would damage it.

The potentially most damaging thing would be to turn the heater on to a particular unit when the water flow is turned off. This could wreck a heater cylinder by getting it too hot and shorting out the heater.

Before the ONAN generator is turned off or on, the operator should make certain that all circuit breakers are in the OFF position. The generator should start and stop under no-load conditions.

Of course the normal care exercised around 110 VAC power should be enforced. Remember that the ocean is near, and salt water on hands, carpets, etc., can make them more conductive than normal.

## 3.7. Description of a Standard Sequence of 4 Cooling Curves

In order to increase the statistical significance of the data, we take four identical runs in rapid succession without changing anything about the apparatus. Along with the four cooling curves several other items are recorded.

These are:

(1) Air-temperature thermistor output.

(2) Thermocouple test voltage.

This voltage tells us things about the stability of the electronics.

(3) Flow meter zero.

The flow meter reading with no flow is an important parameter in our analysis.

(4) Four cooling curves for the unit in question.

(5) Repeat flow meter zero

(6) Repeat Thermocouple test

(7) Repeat air temperature thermistor

# CHAPTER 4

## HOW TO TAKE DATA

This chapeter is, of course, the heart of the manual. The things that have come before are really only background so that when things are done according to these instructions, the operator will understand both what he is doing and why it is done. See Fig. E-1 thru E-9 for a sketch of each chasis panel. Abreviations with reference to DVM:

RA: random access

SS: single scan

CS: continuous scan

AR: auto record

IC: initial channel

FC: final channel

### 4.1. Instruction for Initial Set-up and Checks

(1) Check to see that all things are as you left them last time you were at the ship. Paragraph 4.4. p.279 gives instructions about how to leave the apparatus. If things are not as you left them, determine from the crew what has caused the change. If cause cannot be determined, or if something appears to be wrong or damaged, consult with one of those named on p.260 before continuing

(2) Check visually to see that both pump discharges appear normal

(3) Fill absolute-velocity measuring jug from the discharge of each Unit. Adjust fill time for Unit 2 to be between 1 min. 50 sec. and 2 min. Adjust fill time for Unit 3 to be between 55 and 65 seconds.

(4) Check with the crew to see if any unusual incident has occured, and log anything they report (in General Log).

(5) Log a description of sea and weather state observed on the way from Honokahau to the ship (in General Log).

(6) Set H-P DMM to AC volts [HPMM:ACV]

(In the red boxes following each instruction appears first the chassis abbreviation (see p.243) and then a list of controls to be adjusted on that chassis. The format is this: chassis abbreviation: action).

(7) Plug input of HPMM into AC line

(8) Set DVM Clock [DVM: clock]

(9) Reset Beach Control [BC: Reset]

(10) Set DVM Scanner Initial Channel = 1, Final Channel = 3
(IC = 1, FC = 3) [DVM:IC,FC]

(11) Press Random Access, then Start [DVM:RA,Start]

(12) Value of Thermocouple Test voltage (TC Test) Should be - -3.3

(13) Step Thermocouple (Step TC) 4 times to heater off Unit 2
[BC: Switch,Step]

(14) Value should be - -.7

(15) Step thermocouple 1 time to heater on Unit 2 [BC:Step]

(16) Value should decrease (become larger negative) as Cu heater cylinder heats up

(17) Step TC 2 times to heater off Unit 3 [BC:Step]

(18) Value should be - -.7

(19) Step TC 1 time to heater on Unit 3 [BC:Step]

(20) Value should decrease as Cu heater cylinder heats up

(21) Reset Beach Control [BC:Reset]

(22) Step DVM Scanner 1 time to Ch 2 [DVM:Step]

(23) Step Function 5 times to thermistor [BC:Swtich,Step]

(24) Set Thermistor Switch to TM#1 [TM:Switch]

(25) This value can vary between -2.5 and -9.0 depending on whether or not Unit 2 is in the sun.

(26) Set Thermistor switch to TM#2 [TM:Switch]

(27) This value should be ~ -3.5

(28) Set Thermistor switch to TM#3 [TM:Switch]

(29) This value should be about -3.5

(30) Step DVM Scanner 1 time to Ch 3 [DVM:Step]

(31) Step Flow Meter 1 time to FM2 [BC:Switch, Step]

(32) Flow Meter 2 is damaged so this value may be erratic or even positive.

(33) Step Flow Meter 1 time to FM3 [BC:Step]

(34) This value should be about -1.5

(35) Set DVM Scanner IC=14 FC=19 Random Access, Start [DVM:IC,FC,RA,Start]

(36) Turn Pot 14, see that value changes, Set to month [MP:14]

(37) Step DVM Scanner 1 time to Ch 15 [DVM:Step]

(38) Turn Pot 15, see that value changes, set to day [MP:15]

(39) Step DVM Scanner 1 time to Ch 16 [DVM:Step]

(40) Turn Pot 16, see that value changes, set to hour [MP:16]

(41) Step DVM Scanner 1 time to Ch 17 [DVM:Step]

(42) Turn Pot 17, see that value changes, set to minute [MP:17]

(43) Step DVM Scanner 1 time to Ch 18 [DVM:Step]

(44) Turn Pot 18, see that value changes, set to 0.0 [MP:18]

(45) Step DVM Scanner 1 time to Ch 19 [DVM: Step]

(46) Turn Pot 19, see that value changes, set to 0.0 [MP:19]

(47) Log in General Log that this procedure has been completed.

Note any problems or any unexpected happenings or values.

If these voltages are all within normal ranges, (see Paragraph 5.5, p.283 ) and all the controls work properly, the whole system should be working correctly. Things to watch for: a voltage >0 in Ch 1-3 (except possibly when FM 2 is being read, Ch 2 may go >0 when lighted LED not at Thermistor) indicates trouble somewhere. If such a voltage is observed, learn as much as you can about it (value, turn power on and off to see if it changes, vary input to see if it reponds) then call for advice ( p.260 )

## 4.2. Instructions for Taking a Standard Set of 4 Cooling Curves

Abbreviations used below:

| | | | |
|---|---|---|---|
| Step TC | means set Beach Control Switch to | | Step Thermocouple |
| FM | " | " | Step Flow Meter |
| Function | " | " | Step Function |
| Control | " | " | Step Control |

and push Step button.

IC=x means set DVM Scanner Initial Channel to x

FC=y means set DVM Scanner Final Channel to y

" " Things in quotes are to be written by hand on blank spaces of the tape. Run through -8 in. of tape using DVM Tape Feed button for each blank. Blanks are used to separate different kinds of data on the tape.

SIU means Special Instructions for Unit U.

After the DVM punches 6 pieces of information it inserts a carriage return and line feed on the tape. These are control characters for the tape reading device. We attempt to end all strings of data with a carriage return. They can be recognized by the sound as the punch punches a few extra holes, or by noting a unique punch on the tape just past the punch head.

What follows are step by step instructions for all things pertaining to the Beach Control, the DVM, the thermistor switch, the Marker Pots, and the Units. I will make the instructions general for both units. When there are differences between the units, I will note them in the instructions. The instructions are identified by paragraph numbers and titles. When setting up the marker pots remember the following association of Ch # and information:

| Ch 14 | Ch 15 | Ch 16 | Ch 17 | Ch 18 | Ch 19 |
|---|---|---|---|---|---|
| Month | Day | Hour | Minute | Run # | U.C |

In Ch. 19 U (the first digit) is Unit # and C (the second digit) is a code. The code is explained in Paragraph 2.4 p.258. In what follows, whenever a marker is called for, we write Ch 19 = U.C, where U is to be determined by the operator and we write down the proper C. Best setting of Pots is -A.850.

4.2.1. Measure Current and Ship's Heading

There is aboard NOI'I, a barrel stave with a 3/8 shackle on one end and a line on the other. From the bow of the ship throw the stave in water holding on to the line. Note the time for the current to carry it the length of the boat, and record it in the General log. Take a reading from the ship's compass (crew can help if necessary), and record in the General Log. Also record in Unit Log: sea conditions, wind conditions and state of roll of ship.

4.2.2. Load and Label Tape

The proper way to thread the tape through the punch is illustrated in Fig. E-5. The tape is put over the rollers as indicated and the loose end taped to the take up post. Care should be taken to be certain that on the supply side the spring tension of the rollers helps to smooth the tape feed. To put tape in the punch, lift the cover on the toothed sprocket wheel, and put the tape under the cover and under the lever on the left of the punch. (The punch will not operate unless the tape is under this lever.) Make certain that the tape is as far into the punch (as far star-board) as it will go. The tape goes ~2 mm into a metal notch. Close the cover and press Tape Feed while pulling on the tape until the sprocket holes are uniformly spaced. Continue running through tape until it can be attached to the take up post (or reel). Two things to be careful of are:

(1) The tape must be all the way into the punch or the last row of punches will be misplaced;

(2) The supply tension system must be right or the punch will place one bit of information on top of another, ruining both.

Both these problems have ruined data in the past so BE CAREFUL!! Careful inspection of the tape as it comes out will reveal either of these faults if they exist.

Finally, write the tape number on the tape. Tape number is month-day-year-tape # for that day (e.g., Tape 9-12-76-3). Also write on the tape what runs are expected to be on the tape (4 runs/tape) and the Unit #.

Press Reel Motor switch to start take-up post turning.

4.2.3. Begin Sequence Marker

(1) Enter in Tape log that sequence is beginning

(2) Run through tape "Mark" [DVM:Tape Feed]

(3) Set DVM Scanner IC=14, FC=19, Random Access, Start [DVM:IC,FC,RA,Start]

(4) Set pots for Marker, Ch 18 = 0.0, Ch 19=0.0 [MP:Set ALL]

(5) Set DVM Scanner, Single Scan, Start, Check for correct values [DVM:SS,Start]

(6) Press Auto Record, Stop after 6 punches [DVM:AR]

NOTE: For the markers associated with Air Temp., Data, TC test Data and FM Zero Data that precede the first cooling curve of a sequence (cooling curve α) use the appropriate run number for α as the run number in Ch 18. This number will be 1, 5, 9, 13, 17 etc. depending on which sequence of the day it is.

4.2.4. Air Temperature Thermistor Marker and Data

(7) Run through tape, "Mark" [DVM:Tape Feed]

(8) Set DVM Scanner IC=14, FC=19, Random Access, Start [DVM:IC,FC,RA,Start]

(9) Set Pots Ch 19=U.3 [MP:Set All]

(10) Set DVM Scanner, Single Scan, Start, Check for correct values [DVM:SS, Start]

(11) Press Auto Record, Stop after 6 punches [DVM:AR]

(12) Run through tape "Air Temp" [DVM:Tape Feed]

(13) Set DVM Scanner IC=2*; Random Acces, Start [DVM:IC,RA,Start]

(14) Reset Beach Control [BC:Reset]

(15) Step Function 5 times to TM [BC:Switch, Step]

(16) Set Thermistor switch to 1 [TM:Switch]

(17) Press Auto Record, Stop after 12 punches [DVM:AR]

(18) Record value in Unit log (front)

(19) Set Thermistor switch to proper value for unit in use [TM:Switch]

4.2.5. TC Test Marker and Data

(20) Run through tape, "Mark" [DVM:Tape Feed]

(21) Set DVM Scanner IC=14, FC=19, Random Access, Start [DVM:IC,FC,RA,Start]

(22) Set Pots Ch 19=U.0 [MP:Set All]

(23) Set DVM Scanner, Single Scan, Start, Check for Correct Values

* It is all right to leave FC=19 at this point. With Random Access Pushed and readings taken from only one channel, the Final Channel does not come into play.

DVM:SS,Start

(24) Press Auto Record, Stop after 6 punches DVM:AR

(25) Run through tape "TC Test" DVM:Tape Feed

(26) Set DVM Scanner IC=1, Tandom Access, Start DVM:IC,RA,Start

(27) Reset Beach Control BC:Reset

(28) Press Auto Record, Stop after 12 punches DVM:AR

(29) Record value in Unit Log (front)

4.2.6. FM Zero Marker and Data

(30) Run through tape, "Mark" DVM:Tape Feed

(31) Set DVM Scanner, DVM:IC,FC,RA,Start

(32) Set Pots Ch 19=3.1 MP:Set All

(33) Set DVM Scanner, Single Scan Start, check for correct values DVM:SS,Start

(34) Press Auto Record, Stop after 6 punches DVM:AR

(35) Run through tape, "FM Zero Unit 3" DVM:Tape Feed

(36) Set DVM Scanner IC=3, Random Access, Start DVM:IC,RA,Start

(37) Reset Beach Control BC:Reset

(38) Step FM 1 time for unit 2 - 2 times for Unit 3 to appropriate value for Unit in use BC:Switch,Step

(39) Close valve on pump discharge for Unit 3. There are 2 valves on each Unit. One to control flow velocity, the other to turn the flow on and off. The control valves have had their handles removed. Their settings should only be changed at the beginning of a day (see p.266, Instruction 3). The on/off valves must be completely on except when FM Zero Data is being taken or when the generator is shut down.

(40) Press Auto Record, Stop after 12 punches DVM:AR

(41) Immediately after stopping punch, open valve on pump discharge. Pump can lose prime if discharge is closed too long. Auto record button can be reached from deck without going down steps into cabin. This saves a few seconds.

(42) Check to see that flow is re-established

(43) Record value of FM Zero in Unit Log (front). It is more important that the pump not lose prime, than that the number be wirtten down. If you can't do both, make sure the pump gets turned back on and neglect recording the value in the log.

NOTE: Unit 2 Flow Meter does not work, and Flow Meter electronics are arranged so that only Flow Meter 3 can be read so make all Flow Meter zero measurements on Unit 3.

4.2.7. Cooling Curve $\alpha$

(44) Complete as much as possible of the run data in the front of the unit log for the appropriate Unit. Note in the back any observations you have made pertaining to this Unit. Note in the General log any observations you have made about the whole shipboard system or about sea conditions.

(45) Check for water flow in both units.

(46) Reset Beach Control [BC:Reset]

(47) Step TC 5 times for Unit 2; 8 times for Unit 3 to heater on appropriate Unit [BC:Switch,Step]

(48) Step FM 1 time Unit 2 - 2 times Unit 3 to appropriate value for Unite in use [BC:Switch, Step]

(49)(S12) Step Function 5 times to thermistor [BC:Switch,Step]

[Special Instructions for Unit 3]

(50)(S13) Step Function 3 times to Heater Power [BC:Switch,Step]

(51)(S13) Step Control 1 time to High Power [BC:Switch,Step]

(52)(S13) Step Function 2 times to Thermistor [BC:Switch, Step]

[Instructions for Both Units]

(53) Check that thermistor switch is set to proper value for Unit in use [TM:Switch]

(54) Return Beach Control switch to Step TC. Do Not operate Step Button [BC:Switch]

(55) Run through tape, "Mark" [DVM:Tape Feed]

(56) Set DVM Scanner, IC=14, FC=19, Random Access, Start [DVM:IC,FC,RA,Start]

(57) Set Pots Ch 19=U.2 [MP:Set All]

(58) Set DVM Scanner, Single Scan, Start, Check for correct values [DVM:SS,Start]

(59) Press Auto Record, Stop After 6 punches [DVM:AR]

(60) Run through tape, "Date, Run#, Unit #" [DVM:Tape Feed]

(61) Set DV, Scanner, IC=1, FC=3 cont., Scan Start [DVM:IC,FC,CS,Start]

(62) Observe Ch 1 voltage, wait until it has reached a steady state

(63) When steady state has been reached, Press Auto record as DVM clock switches from 59 sec to 00 sec. (Timings that follow can be made with DVM clock, it is accurate enough for a short time.) [DVM:AR]

(64) Record time to nearest minute in unit log (front) column marked Heater Off.

(65) After punching for 1 minute, Step TC 1 time to heater off appropriate unit [BC:Step]

(66) After 30 sec record Ch 1 reading in $TCR_{30\ sec}$ column of Unit log (front). This is fairly easily done in the following way: Watch DVM clock until 30 sec appears, then shift gaze to scanner readout. You should see 03 displayed. The punch will punch in a few tenths of a second, and the scanner will now display 01. Shift gaze to digital indicator display. Note and record the first 3 figures of the display just before the punch punches. You can practice these readings at 6, 12, 18 and 24 seconds.

(67) After 60 seconds record Ch 1 reading in $TCR_{60\ sec}$ column.

(68) Go to stern swim platform and measure the time necessary to fill the jug from pump discharge of the unit in use.

(69) Record the fill time in the Unit log (front).

(70) Record $TCR_{\infty}$ value from Ch 1 at least 5 minutes after the time in instruction (64). Try to pick a time when the water temperature, as indicated by the TM output in Ch 2, is not changing.

(71) Record in Unit log (back) any observations not covered by the run data in Unit log front.

(72) Calculate from $TCR_{30,60,\infty}$ values.

$\tau = 30\ sec/[\ln(TCR_{30}-TCR_{\infty}) - \ln(TCR_{60}-TCR_{\infty})]$

(73) At least 10 minutes after time recorded in instruction (64), stop punch. Try to stop it after a carriage return.

(74) Compare jug fill time with previous runs taken that day and runs taken on other days. If there is greater than a 10% difference, try to acertain the cause (on/off valve not open completely, faulty timing, etc.) if no cause can be found call someone (p.260)

(75) Compare calculated $\tau$ with $\tau$'s from other runs and other days.

If there is greater than a 20% difference try to acertain the cause (on/off valve, faulty timing, faulty calculation, etc.). If no cause can be found and condition persists for 2 more cooling curves, call someone.

4.2.8. Cooling Curve β

(76) Reset Beach Control [BC:Reset]

(77) Set DVM Scanner, IC=1, Random Access, Start [DVM:IC,RA,Start]

(78) Record value of TC Test in Unit Log (front)

(79) Step Function 5 times to Thermistor [BC:Switch, Step]

(80) Step DVM Scanner 1 time to Ch 2 [DVM:Step]

(81) Set Thermistor switch to TM#1 [TM:Switch]

(82) Record value of Air Temperature thermistor in Unit Log (front)

(83) Return thermistor switch to proper value for Unit in use [TM:Switch]

(84) Repeat instruction of Paragraph 4.2.7.

NOTE: When setting up the marker pots for run β be sure to set the Run # with pot 18 to correct value for Run β. This number will be 2, 6, 10, 14, 18, etc. depending on which sequence of the day is being run .

4.2.9. Cooling curve γ

(85) Repeat the instructions of Paragrpah 4.2.8.

NOTE: Correct run # for marker will be 3, 7, 11, 15, 19, etc.

4.2.10. Cooling Curve δ

(86) Repeat instructions of Paragraph 4.2.7.

NOTE: Values of TC Test and Air Temperature Thermistor will be recorded after this run when these values are again recorded on tape.

NOTE: The correct Run # for maker is 4, 8, 12, 16, etc.

4.2.11. Flow Meter Zero Marker and Data

(87) Repeat instructions of Paragraph 4.2.6

NOTE: The correct Run # for marker for FM Zero, for TC Test marker and Air temperature thermistor marker is 4, 8, 12, 16, etc.

4.2.12. TC Test Marker and Data

(88) Repeat instruction of Paragraph 4.2.5.

NOTE: Correct Run # 4, 8, 12, 16, etc.

4.2.13. Air Temperature Marker and Data

(89) Repeat instructions of paragraph 4.2.4.

NOTE: Coreect run # 4, 8, 12, 16, etc.

4.2.14. End Sequence Marker

(90) Run through tape, "Mark" [DVM:Tape Feed]

(91) Set DVM Scanner IC=14, FC=19, Random Access, Start [DVM:IC,FC,Start]

(92) Set Pots Ch 18=9.9, Ch 19=9.9 [MP:Set All]

(93) Set DVM Scanner, Single Scan, Start, Check for Correct values [DVM:SS,Start]

(94) Press Auto Record, Stop after 6 punches [DVM:AR]

(95) Record in Tape Log that sequence has ended, and note any errors made in making the tape.

(96) Label the end of the tape with tape number, run numbers and Unit number.

4.2.15. Unload Tape

To get tape into most convenient form for shipment and analysis, do the following: Break the tape on the supply side of the punch after sufficient tape (-12 in.) has been run through to make a good trailer section. Remove the supply roll from the reel and put reel back on the supply post. Bring tail of tape over to the reel and rewind the tape onto the reel. It can be wound quite tightly by holding the tape and gently but firmly turning the reel. Finally remove tape from reel by disassembling the reel and use scotch tape (if it turns out not to leave glue on the tape) and rubber bands to insure that it doesn't unroll.

4.3. Comments

This is the ONLY format in which data can be taken. All data are to be taken in sequences of 4 cooling curves without changing conditions between curves. On check visit days 1-2 such sequences/unit should be taken. On high statistics visits 4-6 such sequences should be taken for each unit.

4.4. Before Leaving Boat

1. Remove tape from punch
2. Turn off Reel Motor [DVM:Reel Motor]
3. Empty chad catcher on punch
4. Unplug the 110 VAC line that is input to the H-P DMM
5. Turn off H-P DMM
6. Reset Beach Control [BC:Reset]
7. Set DVM Scanner IC=0, FC=0, Random Access, Start [DVM:IC,FC,RA,Start]
8. Set Thermistor switch to TM 1 [TM:Switch]
9. Set All marker pots to zero [MP:Set all to zero]
10. Leave power ON to Beach Control.
11. Check for flow in both Units.
12. Tidy up aft cabin.
13. Take all punched tape and log books off boat with you. Take Jiffy bags along to mail data in. (They are in bag under table in aft cabin.)

## 4.5. Getting Data to Pittsburgh

When you get off the ship make photo copies of all log entries and send them along with the paper tape to:

Dan Meier
Physics Department
Carnegie-Mellon University
Pittsburgh, Pa. 15213

# CHAPTER 5

# MAINTENANCE AND TROUBLESHOOTING

## 5.1. Generator Oil Change

The crew knows how to change oil in the generator. Let them do it. In the Diesel Log is noted the time of the last oil change. Be aware of this time and in consulation with the crew and Professor Munchmeyer, decide when to change oil.

## 5.2. Priming Units

Unit 2 and Unit 3 are primed differently. The crew has heldped prime both units and knows how it is done. Unit 2 has retained its prime since early July.

### 5.2.1. Unit 2 Priming

Unit 2 has a foot valve at the end of the intake hose which makes priming easier. Before priming, be certain that pump needs to be primed. (Is discharge valve tunred off?) First turn pump off and close discharge valve. Then rig the priming pump in the following way: Intake: over the side, discharge into garden type faucet on starboard rail. Then open the main pump discharge valve and start priming pump. When a good flow is established, gradually close discharge valve but never close it completely. Then climb to the top of the A frame on which the units are mounted and open and close the air bleed valve at the top of the unit several times. Do this enough to purge the air from the system. At this point turn the main pump on and open the discharge valve. Pump will now be drawing water through inlet and through priming pump. Shut off power to priming pump. Now slowly close the valve on the garden faucet, the main pump should pass some air but continue to pump.

## 5.2.2. Unit 3 Priming

Unit 3 is different from Unit 2 in that it has no foot valve, but instead has a PVC gate valve at the water's surface. To start priming, open the gate valve to make certain that the part of the hose which is in the water is filled with water, then close it. The fitting of the priming pump and the bleeding of air proceeds as above for Unit 2. When this is complete the discharge valve is opened and the main pump is started. The priming pump is now stopped and the garden-type faucet closed WHILE the PVC gate valve is opened.

## 5.3. More on Priming

If trouble is experienced in priming, call Prof. Munchmeyer for advice.

## 5.4. Troubleshooting

If a problem arises, try to learn as much as you can about it without changing any experimental conditions. Then call someone (p.260). Glenn Grannemann is probably the prime person to discuss these problems with.

There are some problems that can be corrected in the field, however.

If Step Flow Meter does not work, and all other operations on the Beach Control appear to be normal, the problem is probably in the Auto/Manual switch. See paragraph 2.1.6.

If you get all twisted around using the Beach Control, push RESET ALL and start all over.

If the Scanner appears not to do what you want, push START and see if that helps. If that doesn't help, check to see that you haven't set the Initial channel larger than the final channel.

Sometimes the DVM gets stuck in a strange state when turned on. This is explained in Paragraph 2.2.1. Turn it off and back on. See also Paragraph 2.2.4.

If the DVM doesn't punch when Auto Record is pressed, the tape may not be under the lever to the left of the punch head. Lift this lever and press Tape Feed. It should now work.

Finally, the data-taking instructions in Chapter 4 have been tested. They work exactly as they are written. If something does not work, check to see that you are following instructions exactly. If you confirm that you are, and it still doesn't work, call someone (p.260).

## 5.5. Representative Voltages

Here is a list of nominal values of voltages appearing at the DVM. The ranges are pretty broad so any value even slightly out of range is cause for concern. Any value well out of range is cause for a call for help (p.260).

Power line voltage (Measured w/H-P)

90 - 120 VAC

TC Test - 3.0 ↔ -4.0 V

FM Zero - .010 ↔ -.200

FM Reading -1.0 ↔ -3.0

TM#1 Reading -1.5 ↔ -9.9

TM#2 Reading -2.5 ↔ -5.5

TM#3 Reading -2.5 ↔ -5.5

TC Reading (no heat, either unit) -.010 ↔ -2.0

TC Reading (Steady state either Unit) -3.0 ↔ -9.9

Ch 14 - Ch 19 Pot Voltage -0.10 ↔ +9.9

If you find any of these greater than zero, except just after punch punches, Please call

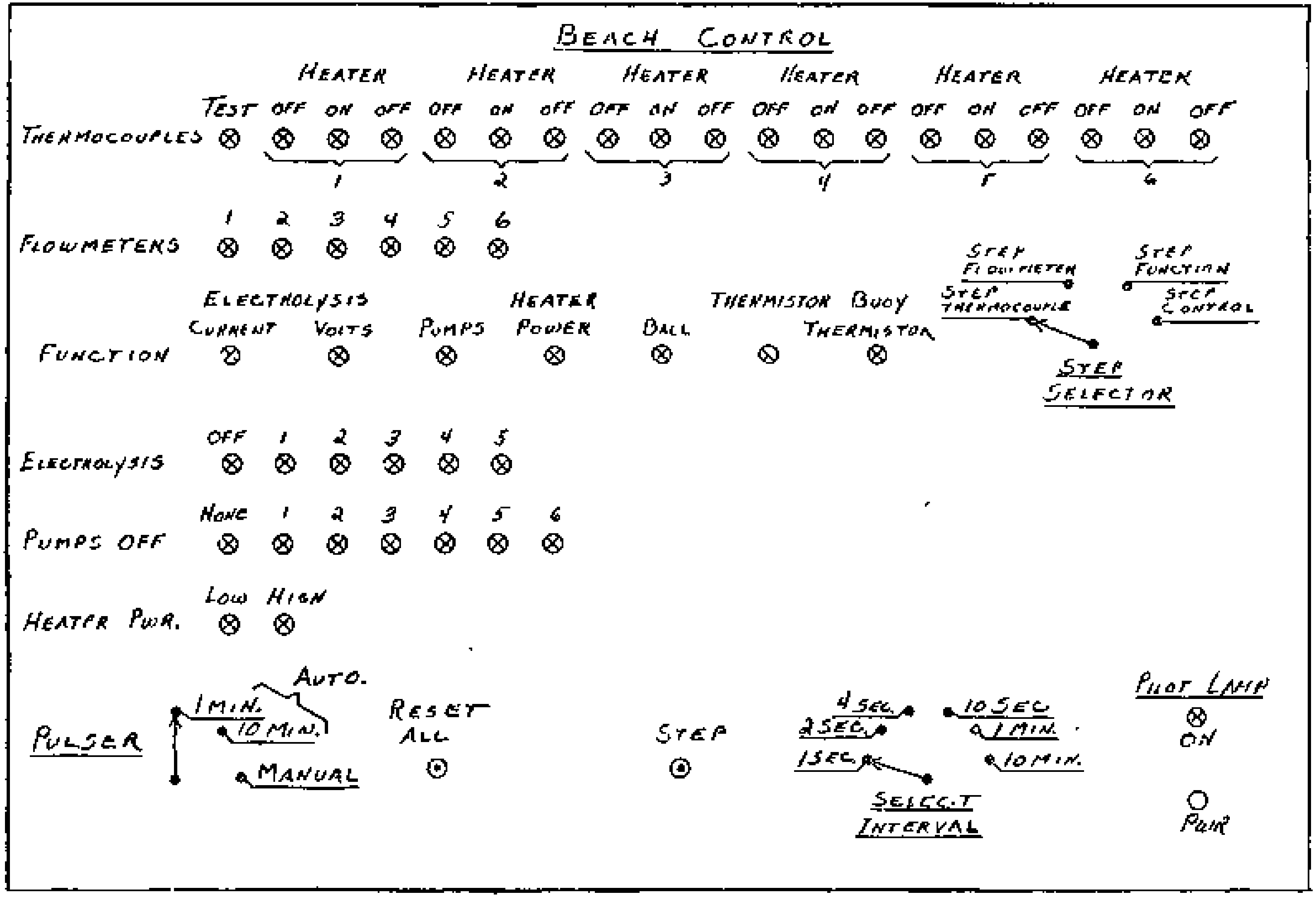



Fig. E-1. Beach Control

# DVM General Layout

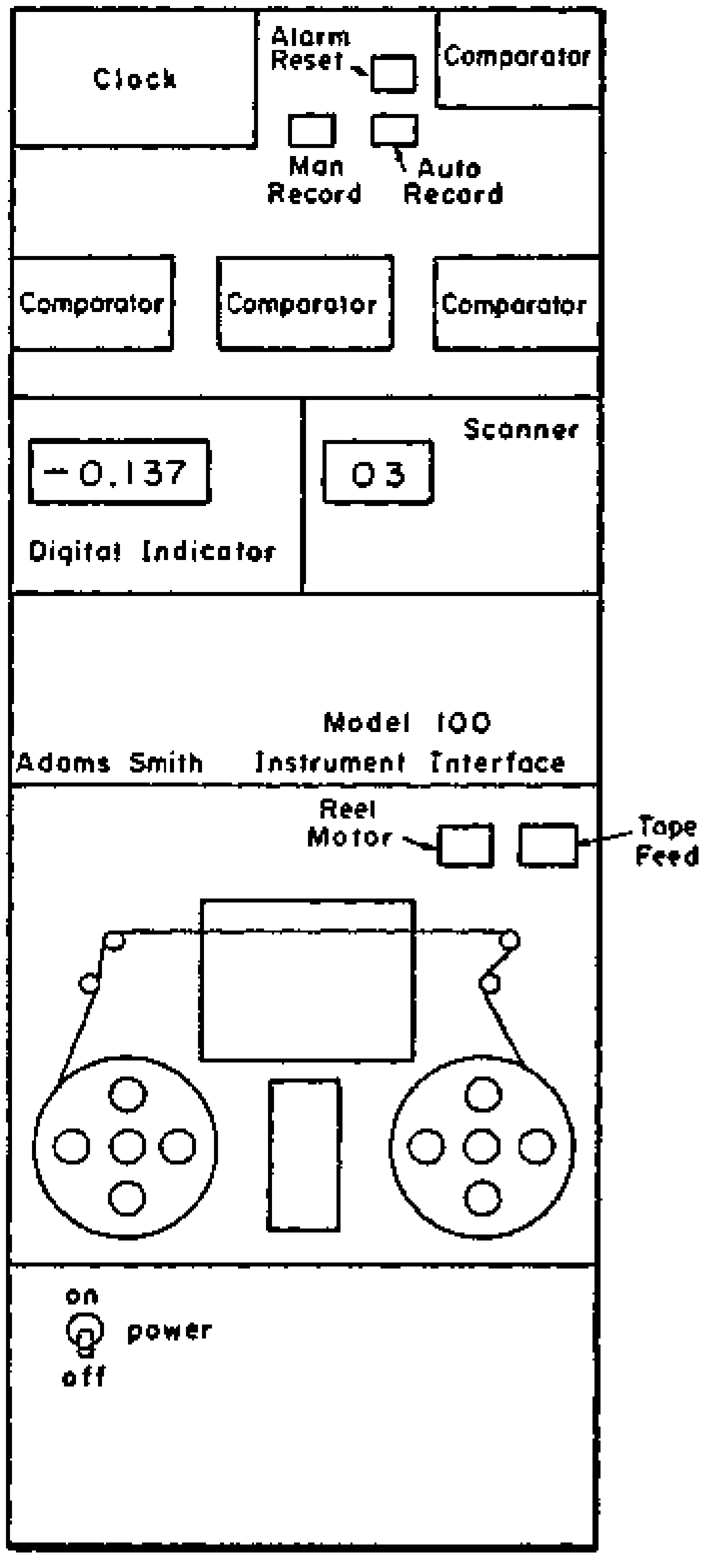



Figure E-2

# DVM Digital Indicator

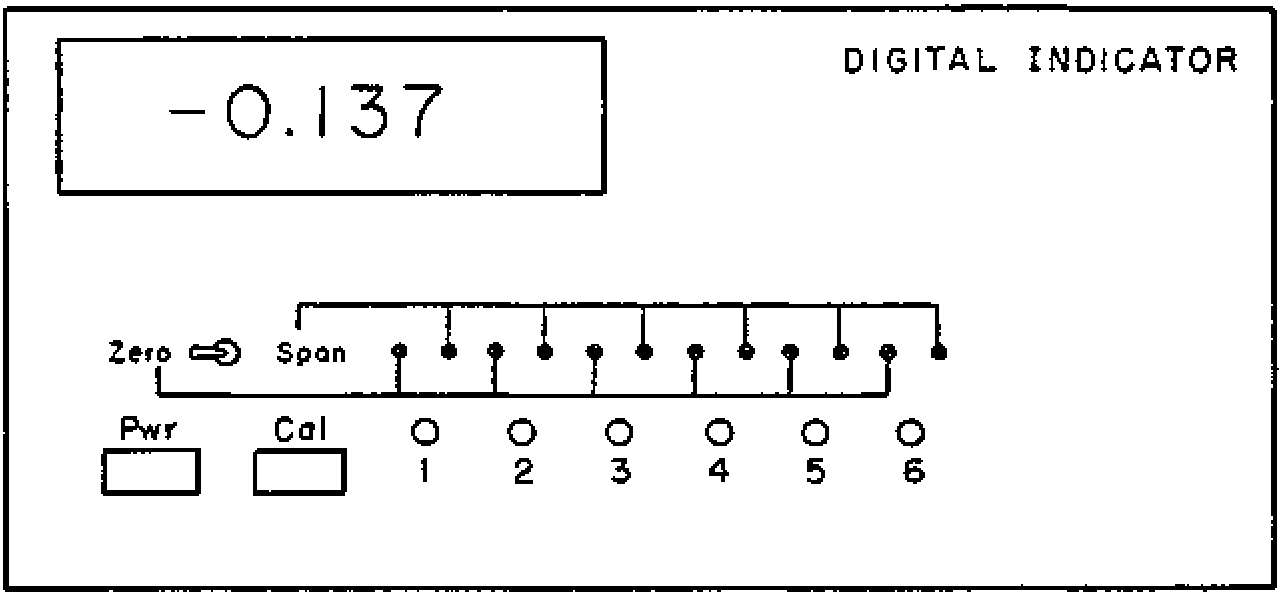



Figure E-3

No operator controls on the digital indicator. Power and cal are push switches which stay where they are put. Power is normally down, cal normally up. When cal is down, Digital indicator reads 9.4xx and does not respond to inputs. Lighted LED indicates which signal processing unit inside the digital indicator is in use. It should always indicate 4. Its position is controlled by the scanner and is transparent to the operator. Leave the toggle switch pointing to right.

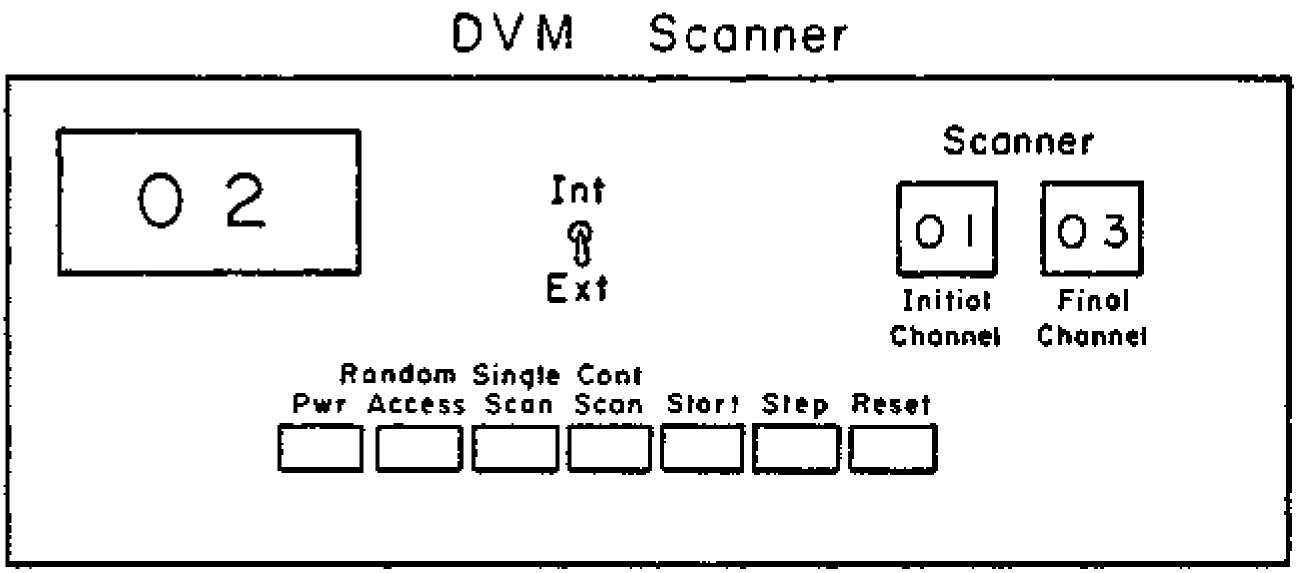



Figure E-4

Power is a press once on press again off switch. Normally it is in the down (on) position. Random Access, Single scan, and Cont scan, are switches that cancel each other when one is pressed. Start, step, and reset are momentary on switches. Int/Ext toggle switch that controls where scan interval information comes from, is normally in the EXT position.

# DVM Punch

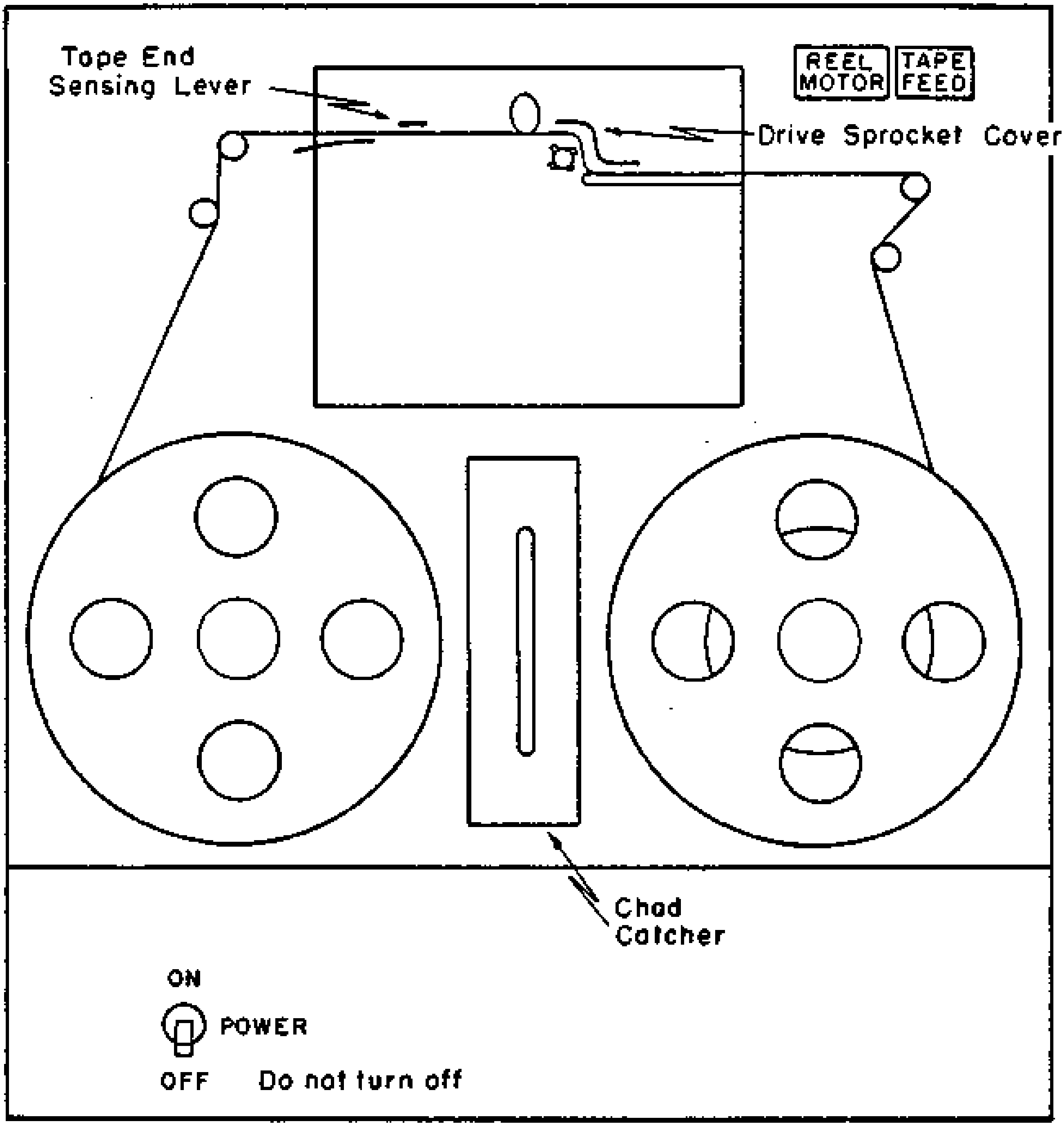



Figure E-5

Shows proper way to thread tape. Reel motor shown on and lighted red.

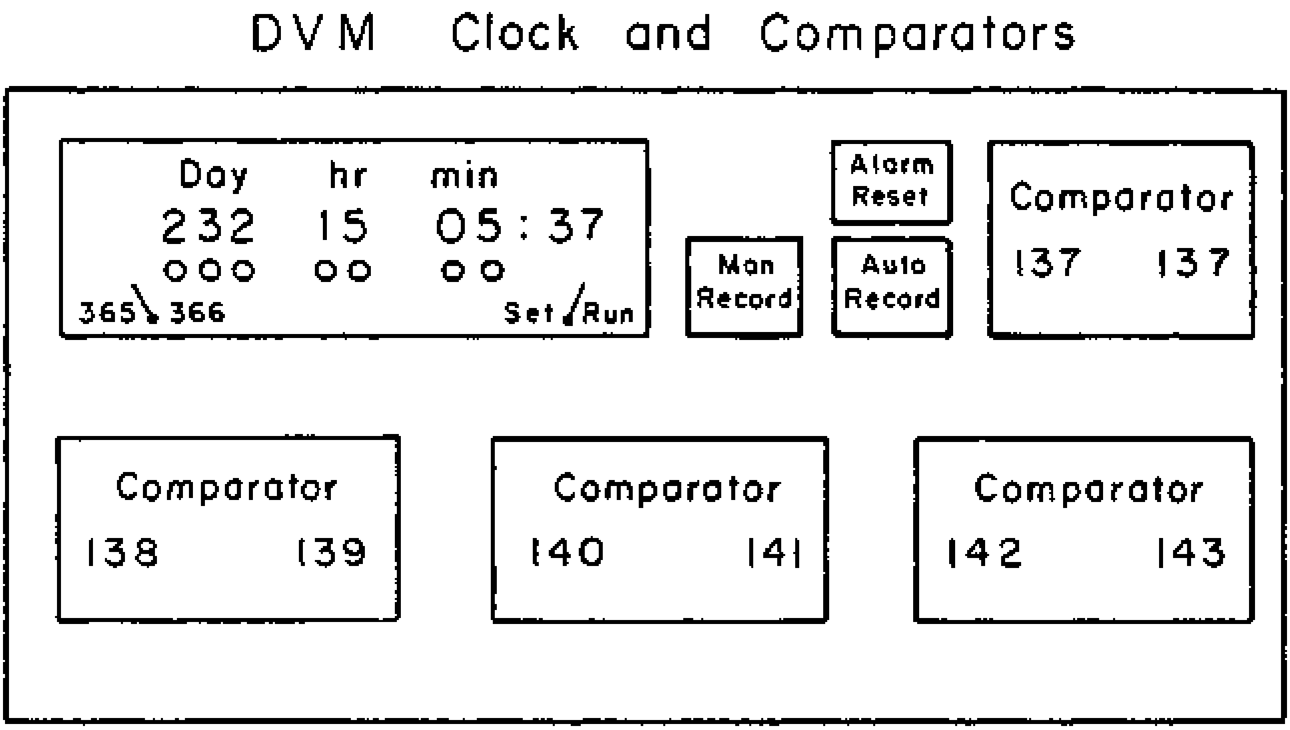



Figure E-6

Comparators, alarm reset and mañual record not in use. Only thing used is auto record and clocks.

## Thermistor Switch Box

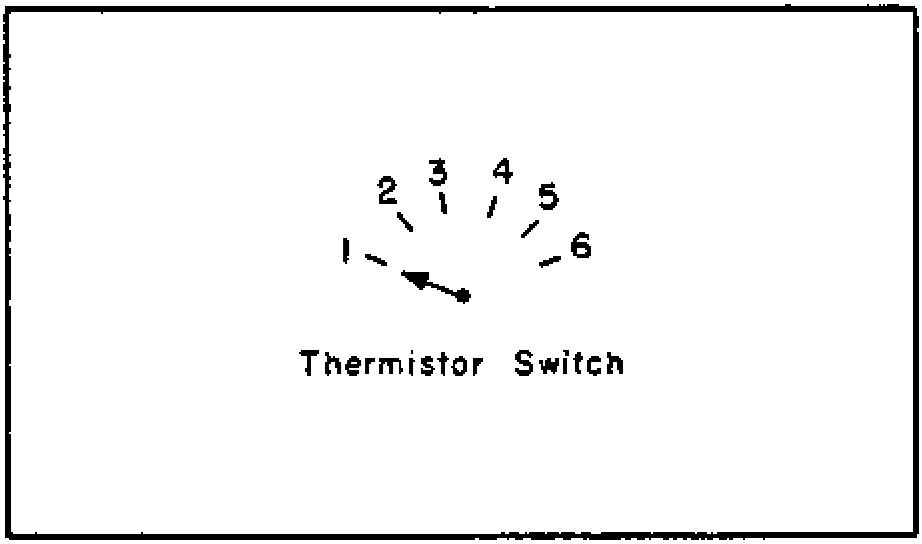



Figure E-7

Only positions 1, 2 and 3 are in use. There is nothing connected to positions 4, 5, 6.

1. Air temperature thermistor.
2. Unit 2 Water temperature.
3. Unit 3 Water temperature.

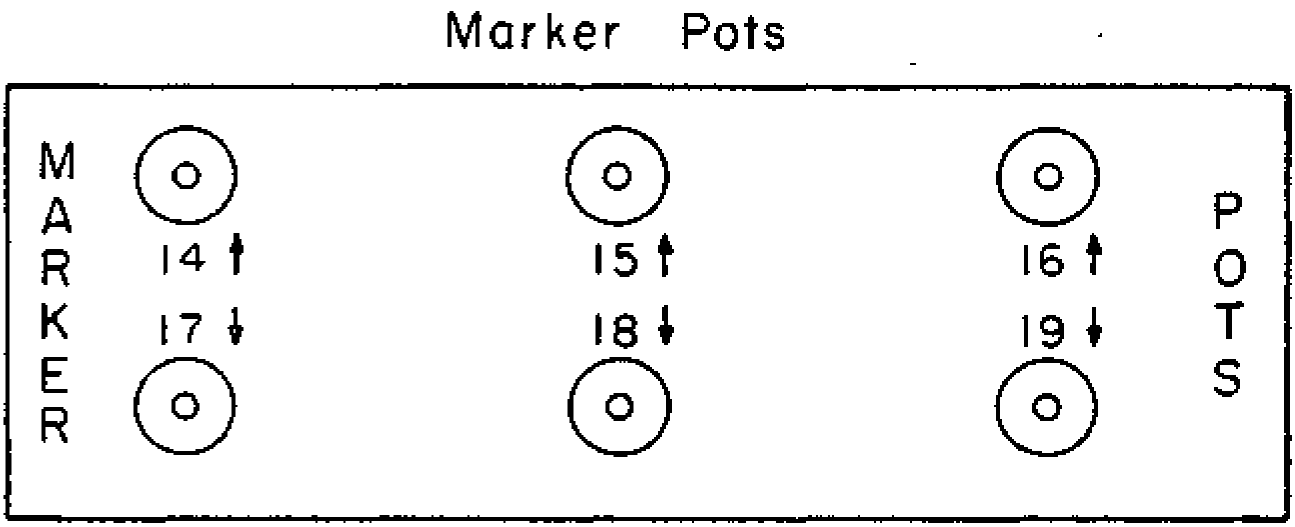
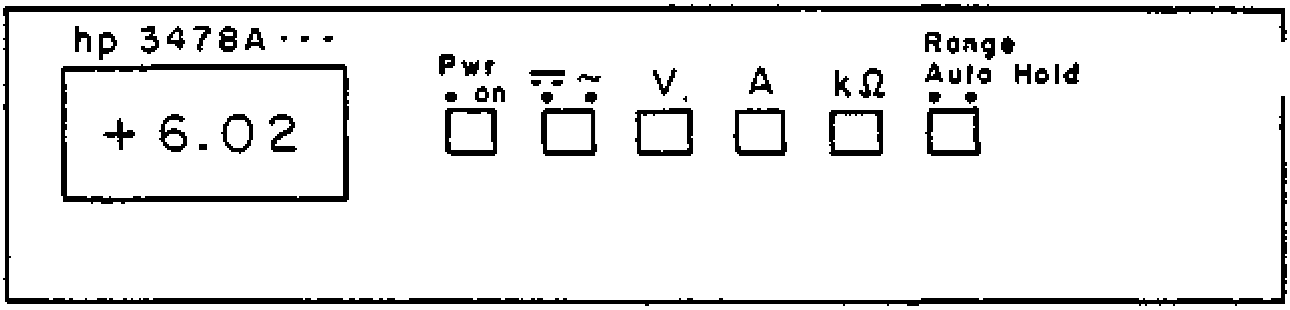



Figure E-8

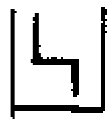
These are 1 turn pots; the knobs are markers 0 - 10.

# Hewlett - Packard DMM



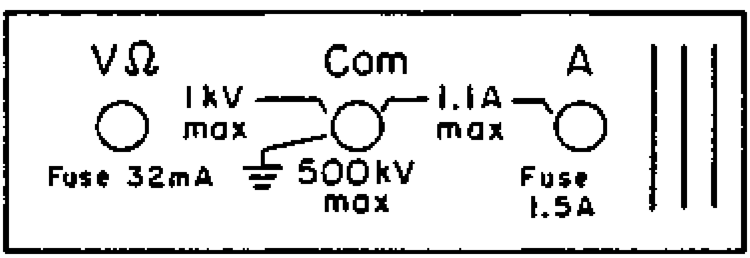

Power, ⎓ -,and Range buttons are press once down, press again up.

The top side of button is marked like this ( Button from top):



Depending on whether button is down or up indicator points to one dot or another, indicating setting.

V, A and kΩ are self cancel.




Slide plastic plate → to reveal fuses. 32 mA taped to Unit.

Put red lead in V, Ω, black in com. for normal use aboard NOI'I.

Figure E-9

## APPENDIX F. THEORY OF OPERATION OF THE THERMOPILE

The thermopile action may best be illustrated by adding the Seebeck Emf's for each segment of the thermal circuit of Fig. 4-2a[1]. The output Emf of the thermopile is thus given by:

$$E_{AB} = (E_A - E_1) + (E_1 - E_2) + (E_2 - E_3) + (E_3 - E_4) + \ldots$$

$$+ (E_{20} - E_{21}) + (E_{21} - E_{22}) + (E_{22} - E_{23}) + (E_{23} - E_B) \ .$$

$$= \int_{T_R}^{T_{RC}} \epsilon_{Cu} dT + \int_{T_{RC}}^{T_{HC}} \epsilon_{Fe} dT + \int_{T_{HC}}^{T_{RC}} \epsilon_{con} dT$$

$$+ \int_{T_{RC}}^{T_{HC}} \epsilon_{Fe} dT + \ldots$$

$$\ldots + \int_{T_{HC}}^{T_{RC}} \epsilon_{con} dT$$

$$+ \int_{T_{RC}}^{T_{HC}} \epsilon_{Fe} dT + \int_{T_{HC}}^{T_{RC}} \epsilon_{con} dT$$

$$+ \int_{T_{RC}}^{T_R} \epsilon_{Cu} dT \ .$$

Or:

$$E_{AB} = 11 \int_{T_{RC}}^{T_{HC}} (\epsilon_{Fe} - \epsilon_{con}) dT \doteq 11(\epsilon_{Fe} - \epsilon_{con})(T_{HC} - T_{RC})$$

Here $\epsilon_{Cu}$, $\epsilon_{Fe}$, and $\epsilon_{con}$ are the Seebeck coefficients for copper, iron and constantan, and $T_R$, $T_{HC}$, $T_{RC}$ are the temperatures of the room, heater cylinder, and reference cylinder. Note that the copper leads to the thermopile have no net effect on the thermopile output voltage provided the temperature distributions along the two copper leads are the same. The output voltage is 11 times that due to a single iron-constantan thermocouple. At 70°F, $(\epsilon_{Fe}-\epsilon_{con})$ is 28.6 μV/°F, so the overall sensitivity of the thermopile is 0.314 mV/°F.

Reference:

1. Heat and Thermodynamics, Mark W. Zemansky, 5th ed., McGraw-Hill, 1968 (p. 414).

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