VERTICAL DISPLACEMENT MEASUREMENTS IN CENTRAL CALIFORNIA WITH A LONG-BASELINE TWO-FLUID TILTMETER

Howard C. Merchant

Department of Mechanical Engineering
University of Washington FU-10
Seattle, Washington 98195

USGS CONTRACT NO. 14-08-0001-18224
Supported by the EARTHQUAKE HAZARDS REDUCTION PROGRAM

OPEN-FILE NO. 81-885

U.S. Geological Survey
OPEN FILE REPORT

Summary: Final Report

Contract No. 14-08-0001-18224

April 17, 1981

VERTICAL DISPLACEMENT MEASUREMENTS IN CENTRAL CALIFORNIA

WITH A LONG-BASELINE TWO-FLUID TILTMETER

Howard C. Merchant
Department of Mechanical Engineering
University of Washington FU-10
Seattle, Washington 98195

A two-fluid multiple leg tiltmeter has been assembled and installed at a test sight near San Juan Bautista, California. The system consists of two legs at 75° with lengths of 243 meters and 193 meters. Each leg has two-fluid lines which are both exposed to the same temperature environment, one containing methyl ethyl ketone and one containing N-butyl alcohol. The fluid and tubing sizes were selected using a number of criteria including accuracy for thermal compensation, dynamic response characteristics, safety, and cost. The reservoirs are supported on thermally compensated piers embedded approximately 4 meters.

The dynamic responses of the system measured in the field compare well with theory. The measurement of tilt at the test site for times of geophysical interests will be carried out in a follow-on program.

Summary: Final Report

Contract No. 14-08-0001-18224

April 17, 1981

VERTICAL DISPLACEMENT MEASUREMENTS IN CENTRAL CALIFORNIA WITH A LONG-BASELINE TWO-FLUID TILTMETER

Howard C. Merchant
Department of Mechanical Engineering
University of Washington FU-10
Seattle, Washington 98195

A two-fluid multiple leg tiltmeter has been assembled and installed at a test sight near San Juan Bautista, California. The system consists of two legs at 75° with lengths of 243 meters and 193 meters. Each leg has two-fluid lines which are both exposed to the same temperature environment, one containing methyl ethyl ketone and one containing N-butyl alcohol. The fluid and tubing sizes were selected using a number of criteria including accuracy for thermal compensation, dynamic response characteristics, safety, and cost. The reservoirs are supported on thermally compensated piers embedded approximately 4 meters.

The dynamic responses of the system measured in the field compare well with theory. The measurement of tilt at the test site for times of geophysical interests will be carried out in a follow-on program.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Introduction

The need for a water-tube tiltmeter and the details of its operation were covered by Eaton [1]* in 1959. Since that time more modern instrumentation has allowed modification and further development beyond the basic single-tube fluid tiltmeter with a mechanical surface sensor. A number of instruments are discussed in connection with thermal errors in a paper by Bevan and Bilham [2] including one due to Huggett, et al. [3]. This particular instrument, the two-fluid tiltmeter, is the subject of this project. A laboratory single leg prototype developed by Terra Technology Corporation [4] was modified and expanded for use in a field test site in central California.

The two major differences in this fluid tiltmeter are the use of two parallel tubes filled with fluids of different thermal properties experiencing the same thermal environment and the design of the level sensors in the reservoirs. The latter being piezoelectric acoustic drivers (sonar type transducers) submerged in the liquid which detect the change in the surface height in the reservoirs.

Thermal Compensation

The use of two fluids with different expansion coefficients allows the elimination of temperature effects assuming the same thermal environments for both fluids over the complete tiltmeter circuit [3,4]. The basic principle can be demonstrated by considering the simple two-tube, two-fluid system shown in Figure 1. Assume there are different fluids in A and B which have a linear variation in density with temperature. Considering fluid Column A first and let

ρ_{AO} = Density at reference temperature,

$\rho_A(T)$ = Density at temperature T,

and

α_A = linear density coefficient.

---

*Numbers in brackets [ ] refer to references.

Then

$$\rho_A(T) = \rho_{AO}(1+\alpha_A T)$$

and the pressure point p (P_p) is (1)

$$P_p = \int_o^{h_1} \rho_A(T)gdx = g\rho_{AO}(h_1+\alpha_A I_1) \quad (2)$$

where $I_1 = \int_o^{h_1} Tdx$.

Also

$$P_p = \int_o^{h_3} \rho_A(T)gdx + \int_{h_3}^{h_2+h_3} \rho_A(T)dx =$$

$$g\rho_{AO}[(h_2+h_3)+\alpha_A I_{2+3} \quad (3)$$

where $I_{2+3} = \int_o^{h_2+h_3} Tdx$.

Equating (2) and (3)

$$h_1 - h_2 = h_3 + \alpha_A(I_{2+3} - I_1) = \Delta A. \quad (4)$$

Similarly for fluid B

$$H_1 - H_2 = H_3 + \alpha_B(I_{2+3} - I_1) = \Delta B. \quad (5)$$

The terms $I_{2+3} - I_1$ are identical in (4) and (5) if both fluid columns see the same thermal environment. Therefore:

$$(\Delta A - h_3)/\alpha_A = (\Delta B - H_3)/\alpha_B.$$

If the fluid columns are on the same base $H_3 = h_3$ and

$$h_3 = (\Delta A\alpha_B - \Delta B\alpha_A)/(\alpha_B - \alpha_A). \quad (6)$$

Thus by measuring the differences in the fluid heights in the two legs, ΔA and ΔB, and knowing the density (or expansion) coefficients for the two fluids the elevation change between the two stations can be determined without requiring a knowledge of the thermal profile along the fluid columns. The effect of nonlinearities in the fluid density is discussed below under fluid selection.

Fluids

Thermal and Safety Considerations

In the previous section the ideal operation of the two-fluid system was described using a linear variation in density with temperature for each of the fluids. The density-temperature behavior is actually better described by a polynomial. The coefficients for a quadratic variation with temperature are available for some fluids (5). Using this information the density can be more accurately described as

$$\rho = \rho_o(1 + \alpha T + \beta T^2) \cdot \quad (7)$$

Repeating the analysis in the previous section with the additional term

$$\Delta A = \bar{h}_3 + \alpha_A I + \beta_A J \quad (8)$$

$$\Delta B = \bar{H}_3 + \alpha_B I + \beta_B J \quad (9)$$

where $I = I_1 - I_{2+3}$

$J = J_1 - J_{2+3}$

and $J_i = \int_o^{h_i} T^2 dx$.

The elevation change based on the nonlinear temperature variation is

$$\bar{h}_3 = \Delta A - [(\Delta B - \Delta A)(\alpha_A I + \beta_A J)]/[(\alpha_B - \alpha_A) + (\beta_B - \beta_A)] \quad (10)$$

and is related to the linear result by:

$$h_3 = \bar{h}_3 + J(\alpha_B \beta_A - \alpha_A \beta_B)/(\alpha_A - \alpha_B). \quad (11)$$

J is a function of the unknown temperature variation along the tiltmeter but the last term is eliminated if

$$\alpha_A/\alpha_B = \beta_A/\beta_B \quad (12)$$

with the result that the correct elevation change is given by the linear estimate which is independent of the temperature variation along the fluid line. Therefore the fluids were selected so that α_b and α_a the linear coefficients were well separated to avoid a problem with the denominator in equation (6) but the ratios of the linear quadratic terms were selected to satisfy equation (12) as closely as possible. Other temperature aspects of the fluids considered were freezing and boiling points, viscosity, and the magnitude of the linear expansion coefficient. The minimum operating range (freezing to boiling) was taken as -5°C to 70°C. The viscosity effect is discussed below in connection with the dynamic response. The ratio of the expansion coefficients was controlled by equation (12) but the magnitudes were controlled by the desire to avoid draining or adding fluid to the reservoirs to accommodate seasonal changes. Twenty degrees centigrade was used as the minimum range.

A computer program was written to compare fluid properties and a listing of the program (FLUIDPH) is given in Appendix A. Three hundred and sixty-nine fluid combinations were considered. An excerpt from the output is also shown in Appendix A where melting point (MP), boiling point (BP) and the ratios of the linear coefficients (A) and quadratic coefficients (B) are shown for the two fluids. The error coefficient caused by an inability to exactly satisfy equation (12) is also given. The magnitude of the linear and quadratic coefficients, the reference densities at 0°C, and the viscosity variations as a function of temperature are also given in Appendix A.

Other considerations were cost and safety factors. The fluids selected were methyl ethyl ketone and N-butyl alcohol. Appendix B shows the hygienic guides for the two fluids. NIOSH/MSHA approved respirators were used when handling the fluids. The description of the respirator used (3M #8712) is also given in Appendix B.

Dynamic Response Considerations

The dynamic response of the two leg tiltmeter was an important design parameter. The response is a function of the tube and reservoir diameters, the tubing length, and the density and the viscosity of the fluid as a function of temperature. The dynamic response for a triangular closed three leg array and a two leg array were discussed in a previous report [6]. A set of coupled second order differential equations, with fluid heights in the reservoirs as dependent variables, result for each leg (fluid) of the tiltmeter. The natural frequencies (eigenvalues) and critical damping ratios for each mode can be computed from the linearized equations. To provide an adequate time constant (time to 1/e of the initial distrubance) the damping ratio was kept near the critical value. The equations for dynamic response were programmed to find the natural frequencies, damping ratio and settling time of the tiltmeter as a function of tube diameter, length, and temperature for the fluids selected above.

Appendix C gives a listing of the computer program (DYNAM) and a typical output for the pipe diameters selected. The pipe diameter selected for methyl ethyl ketone was 1.905 cm. (0.75") and N butyl alcohol of 3.175 cm. (1.25").

TEST SITE INSTALLATION

TEST SITE

Background information on the test site selection in the Hollister-San Juan Bautista area was covered in a previous technical report [6]. The final installation site is shown in figure 2. It is located in San Benito County California between Rocks Road and the San Juan lateral on the property owned by L. E. Schumaker* and leased by W. L. Caldera**. The actual geometry of the site is shown in figure 3.

Tubing diameters were 1.9 centimeters (0.75 inches) for the methyl ethyl ketone and 3.2 centimeters (1.25 inches) for the N-butyl alcohol. The lengths of the lines were 243 meters for the North-South leg and 193 meters for the East-West leg. The burial depth was 46 centimeters (18 inches). Figure 4 is a view South along the leg between piers 1 and 2 and figure 5 is a view North along the same leg showing the metal enclosure for pier 2. The tubes were placed side by side at the edge of the trench with the conductors on top. Strain relief covers for the joints in the tubes were made of 6 foot sections of 4 inch diameter PVC pipe cut in half and placed over the joint (Figure 6). Figures 7 and 8 show the valves and tubing layouts for the methyl ethyl ketone and N-butyl alcohol respectively.

The data logger was located at the center pier and the electronics to drive the surface sensing transducers at piers 2 and 1 or 3, depending on the leg being tested. Note that the three reservoir sets are all complete with transducers and connectors but only two driving units are available for the transducers. One leg was tested at a time linking one to two or three to two. Each reservoir contains both a reference transducer focusing on a surface target and a surface detecting transducer. Therefore, each station contains

* 1145 Fifth Street, P. O. Box 4345, Denver, CO 80204

** 9 Rocks Road, San Juan Bautista, CA 95045

4 transducers, two for each of the fluids, Figure 9. The data logger samples the transducers in pairs so that the reference transducer is always sampled with the associated surface transducer [4,6].

PIER

The bases of the piers were placed at approximately 4.2 meters below the surface to obtain good foundation material and to obtain a stable temperature environment. The piers are compensated for vertical temperature variations by using reentrant concentric tubes of materials with different expansion coefficients. Aluminum and steel were used in the configuration shown in Figure 10.

The inner pipe which extends from the base to the top of the pier is made of steel which has an expansion coefficient of about one half that of aluminum. The center aluminum pipe between the two steel pipes extends from the top of the pier down to within 10.2 cm (4 inches) of the bottom of the footing. The outer steel pipe extends from the bottom of the aluminum pipe to the top of the pier again. The platform is clamped to the outer steel pipe. The combination of the two lengths of steel pipe and the single length of aluminum pipe gives an effective expansion coefficient about 1/21.5 that of a single steel pipe. Change in length (Δ) due to thermal expansion is:

$$\Delta = L\alpha\Delta T \tag{13}$$

Where:

L = Length of tube

α = Expansion coefficient

ΔT = Temperature Change

The total length change in the composite pier is:

$$\Delta_T = (L_{SO} + L_{SI})\alpha_S - L_A\alpha_A \approx 20\ \alpha_S \text{ cm} \tag{14}$$

since $\alpha_A = 2\ \alpha_S$

$L^*_{SO} \simeq L_{SI} \simeq L_A + 10$ cm

---

*Depends on the table adjustment

Where the subscripts are:

SO = Steel outer cylinder

SI = Steel inner cylinder

S = Steel

A = Aluminum

The length change in an uncompensated steel pier would be

$\Delta_S = L_{SI}\ \alpha_S = 430\ \alpha_S$ cm.

The ratio of compensated to uncompensated expansion of the pier for the configuration in Figure 10 is therefore 1/21.5 as noted above.

The table is carried on a split tube which slides over the outer support tube and is clamped in place by a collar. Lateral stability for the pier is given by the nylon glides between the respective pipes (Figure 10) and support braces cast in concrete attached with turn buckles to the clamping collar for the table. Figure 11 is a photograph of the pier in place with the table, clamping collar, turn buckles and support braces removed. Figure 12 shows pier one complete with the reservoirs, valves and associated tubing installed. The reference target for the height sensing system can be seen in the front bell jar (methyl ethyl ketone). Figure 13 shows pier two, the center pier, with the associated valves and manifolds for allowing single or multiple leg operation of the system.

The pier was tested in the laboratory for temperature compensation by enclosing the pier in an insulated duct and using an electric heater and fan to pass heated air axially along the pier. Thermocouples were used to measure temperature at six places on the three tubes. Dial indicators were used to measure the expansion over the complete, compensated pier and the expansion of the central steel pipe alone for comparison. Heating and cooling rates were too rapid to obtain quasi equilibrium conditions but the data in Appendix D shows that the pier configuration does compensate thermally for the expansion even in a transit condition. The tests were performed the day before the pier was to be transported to

California for installation so the tests could not be repeated at slower heating and cooling rates.

RESPONSE

The system was tested at the site in California by using one leg at a time since only two remote transducer units were available as noted above. All units were operated successfully in pairs. Dynamic response data were taken for comparison with the theoretical predictions. To perturb the system, one reservoir platform was raised with the line valves closed. After equilibrium had been reached, the valve was opened thus putting a displacement step function into the system.

The initial height was obtained by using the data from the logger. Because of the sampling rate limit [6] the time history response was obtained by visually observing the change in the height of the fluid in the reservoirs with scales attached to the bell jars. CB radios were used to coordinate readings taken at both ends of the line for averaging purposes.

The results of the initial tests indicated that there were bubbles trapped in the valves and possibly one of the lines. The valves were purged by cycling fluids back and forth between the reservoirs. During this process two important operational features were noted. First, it is important to have clear tubing, or at least clear tubing sections, near valves or other places where bubbles may be trapped. This makes it possible to observe the effect of the purging process to remove the bubbles. Also, flexing of the pipes or flexible joints must be provided to allow changes in elevation and angle for effective purging of these areas.

Tubing failure was noted over one of the serrated male tube connectors at a valve where the tubes were flexed and rotated. A longitudinal failure in the tubing occurred where the tubing passes over the serrations rather than at the end of the tube. This indicates that the flexing and rotation of the tubing due to the purging process may have initiated the rupture. Ruptures originating in the pipe, rather than at the end of the pipe, were not observed in laboratory operations with shorter pipe sections where purging problems with valves were not encountered.

After purging, readings were obtained which show excellent correlation with the predicted response. Table 1 gives the results of the response measurements for the methyl ethyl ketone and Table 2 for the N-butyl alcohol. The methyl ethyl ketone line was predicted to be an underdamped system with the result that the height of the reservoir should behave according to the following equation:

$$R = H/Ho = e^{-\rho\omega t}[(\rho/\sqrt{1-\rho^2})\mathrm{Sin}(\omega\sqrt{1-\rho^2})t + \mathrm{Cos}(\omega\sqrt{1-\rho^2})t], \quad (15)$$

where

H = fluid height relative to the equilibrium position

Ho = the initial height

ω = the undamped natural frequency

ρ = the critical damping ratio.

The predicted values of the parameters are:

$\omega = (2gA_T/LA_R)^{1/2} = 0.0327$ rad/sec

$\rho = 4\pi\mu/\omega dA_T = 0.08363$ (dimensionless)

where

g = acceleration of gravity

A_T = area of a tube for the fluid

A_R = area of the reservoir

L = length of fluid tube

d = fluid density

μ = fluid viscosity.

Using these values in the above equation, the fluid heights for the response of the methyl ethyl ketone were predicted and are also shown in Table 1. Note the time constant (time to 1/e of the original amplitude) is predicted to be 36.5 seconds.

The N-butyl alcohol line is predicted to be overdamped and therefore, the governing equation is

$$R = H/Ho = e^{-\rho\omega t}[(\rho/\sqrt{1-\rho^2})\sinh(\omega\sqrt{1-\rho^2})t + \cosh(\omega\sqrt{1-\rho^2})t], \tag{16}$$

where the variables are defined in equation (15) above.

The predicted values of the parameters are:

$\omega = 0.0613$ rad/sec

$\rho = 2.489$.

Table 2 shows the predicted values for the N-butyl alcohol with a time constant of 82 seconds.

The determination of the tilt requires the conversion of four pairs of frequencies recorded on the data logger, using the system geometry, in a digital computer program. Ideally, this computation would be done with a microcomputer at the test site. However, the data logger was constructed so that long term data may be stored in memory and then the data logger disconnected from the system and brought to the laboratory for interrogation. Field tilt data was not analyzed since the system was turned over to the Geological Survey after the dynamic test runs. Sample runs were made previously in the laboratory.

Appendix E gives a listing of a computer code (TILT) run on a PDP 1143 computer to compute the tilt for a single or multiple leg system. The details of the computer code are explained in the comment cards within the code. Note that the frequency (counts) for the different transducers are compared with bounds based on the reference target counts to automatically detect malfunctions in the transducers. A copy of the data as obtained from the data logger and used directly by the computer program for tilt calculations is also given in Appendix D for reference.

CONCLUSIONS AND RECOMMENDATIONS

The two fluid tiltmeter system has been successfully installed in the test site at San Juan Bautista, California. The dynamic response can be accurately determined theoretically using linear theory as demonstrated by field experiments on both methyl ethyl ketone and N-butyl alcohol legs of the system.

The thermally compensated pier performs satisfactorily in a laboratory test and can be assembled and installed with minimal effort at a remote test site. Computer codes needed to evaluate field combinations based on thermal error conditions and dynamic response are available. A computer program to determine tilt from the recorded frequencies obtained from the measurement system and data logger is operational.

It is recommended that a third reservoir, transducer driver package be constructed and appropriate modifications made to the data logger so that both legs of the system can be operated simultaneously. Long-term tilt data must be taken to supplement the response data already taken to qualify the instrument.

REFERENCES

1. Eaton, J. P., "A Portable Water-Tube Tiltmeter", Bull. Seismol. Soc. Amer., 49, 301-316, 1959.

2. Bevan, J., Bilham, R., "Thermally Induced Errors in Fluid Tube Tiltmeters", Journal of Geophysical Research, Vol. 82, No. 9, 5699-5704, 1977.

3. Huggett, G. R., Slater, L. E., and Pavlis, G., "Precision Leveling with a Two-Fluid Tiltmeter", Geophysical Research Letters, Vol. 3, No. 12, 754-756, 1976.

4. Huggett, G. R., "Two-Fluid Tiltmeter", Final Report USGS Contract No. 14-08-0001-16818, Terra Technology Corporation, Redmond, Washington 98052, July 2, 1979.

5. International Critical Tables of Numerical Data, Physics, Chemistry, and Technology, McGraw-Hill, New York, 1928.

6. Merchant, H. C., Slater, L. E., "Vertical Displacement Measurements in Central California with a Long-Baseline Two-Fluid Tiltmeter", Semi-Annual Report USGS No. 14-08-0001-18224, December, 1980.

TABLE 1

RESPONSE TO AN INITIAL DISPLACEMENT

Methyl Ethyl Ketone

Time(sec)	Fluid Height (cm) Measured	Fluid Height (cm) Predicted	Ratio H/Ho
0	13.36	-----	-----
15	13.11	12.96	0.664
28	12.85	12.72	0.465
36.5	-----	-----	0.369
38	12.60	12.60	0.354
53	12.34	12.46	0.235
71	12.09	12.36	0.143

TABLE 2

RESPONSE TO AN INITIAL DISPLACEMENT

N-Butyl Alcohol

Time(sec)	Fluid Height (cm) Measured	Fluid Height (cm) Predicted	Ratio H/Ho
0	13.77	-----	-----
10	13.51	13.54	0.92
17	13.26	13.31	0.84
26	13.00	13.06	0.75
33	12.75	12.85	0.68
47	12.50	12.55	0.57
75	12.24	12.07	0.40
82	-----	-----	0.364

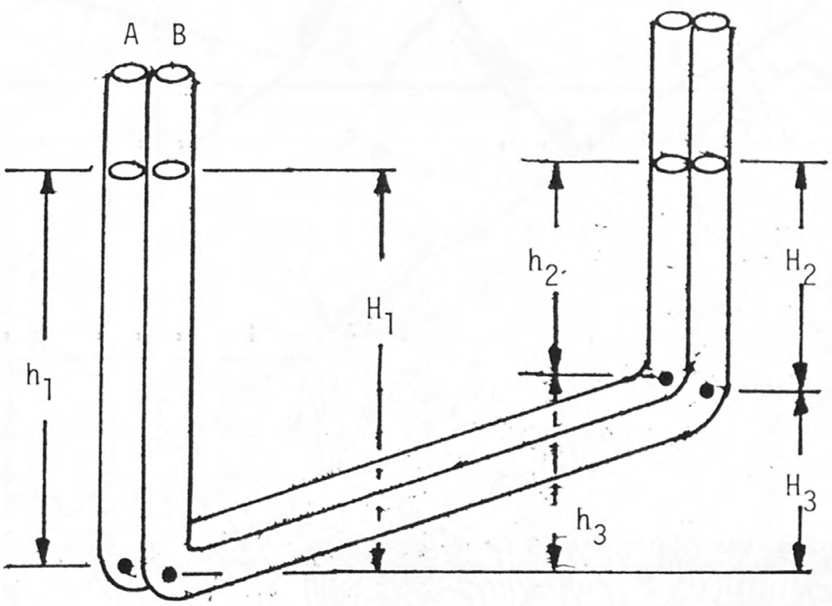


Figure 1

Thermal Compensation Schematic

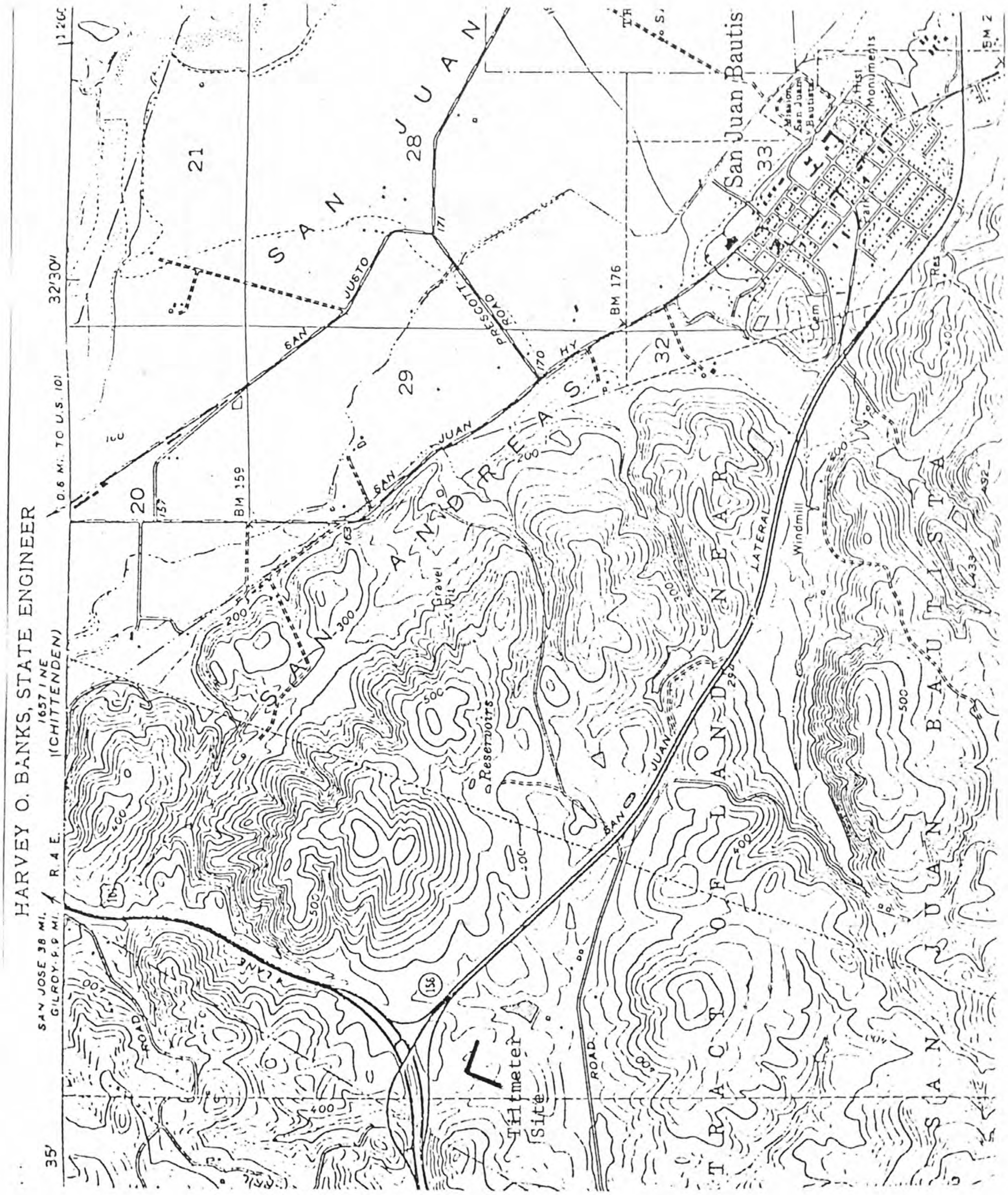


Figure 2

Tiltmeter Site

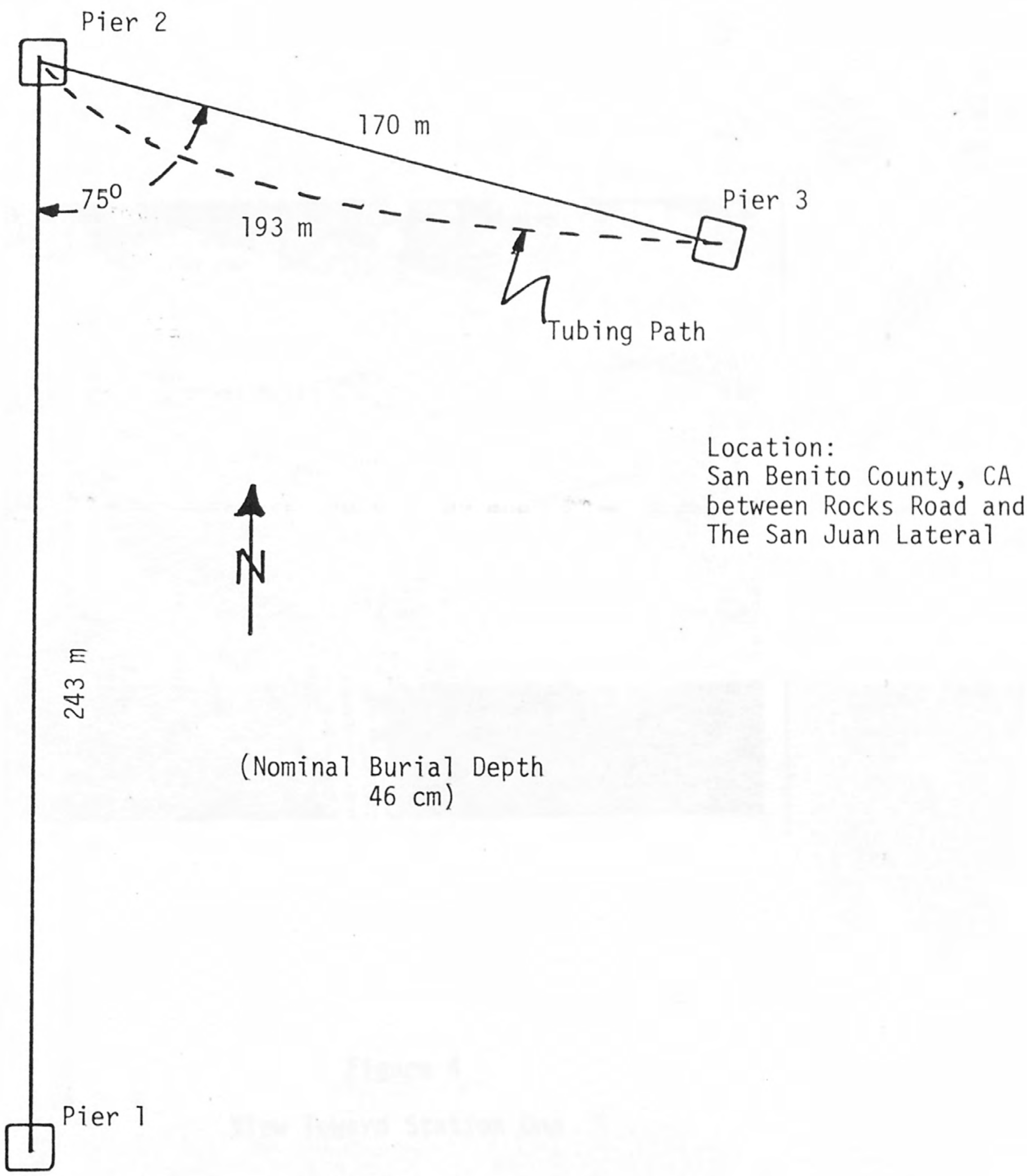


Figure 3

Tiltmeter Geometry

Figure 4

View Toward Station One

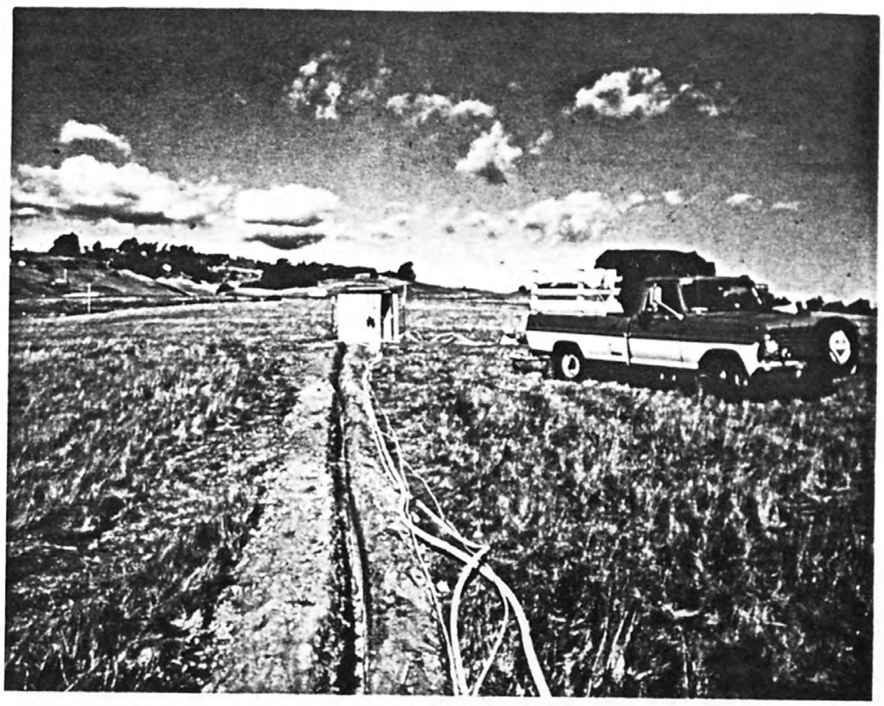


Figure 5

View Toward Station Two

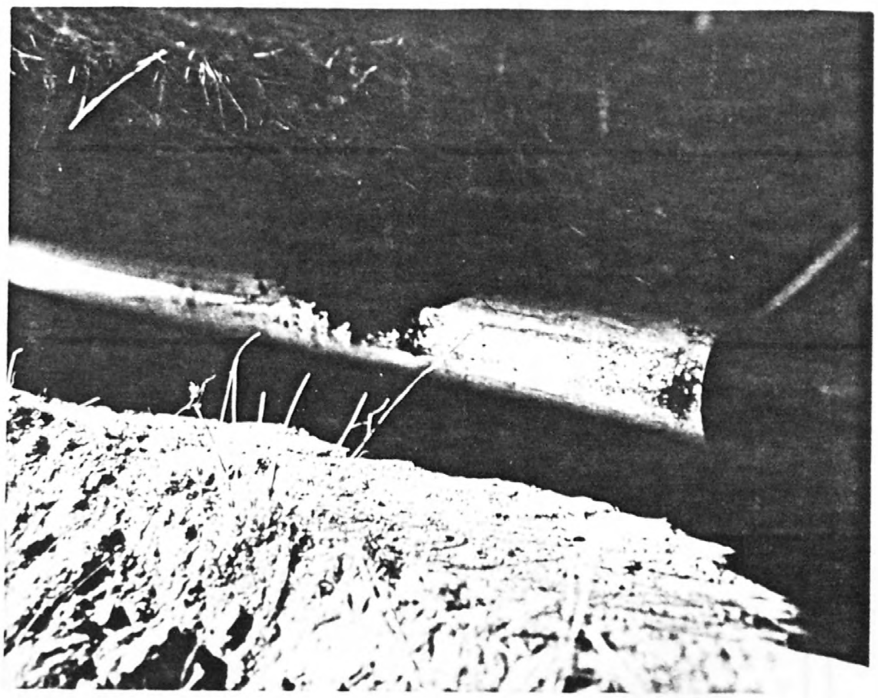


Figure 6

Joint Protection

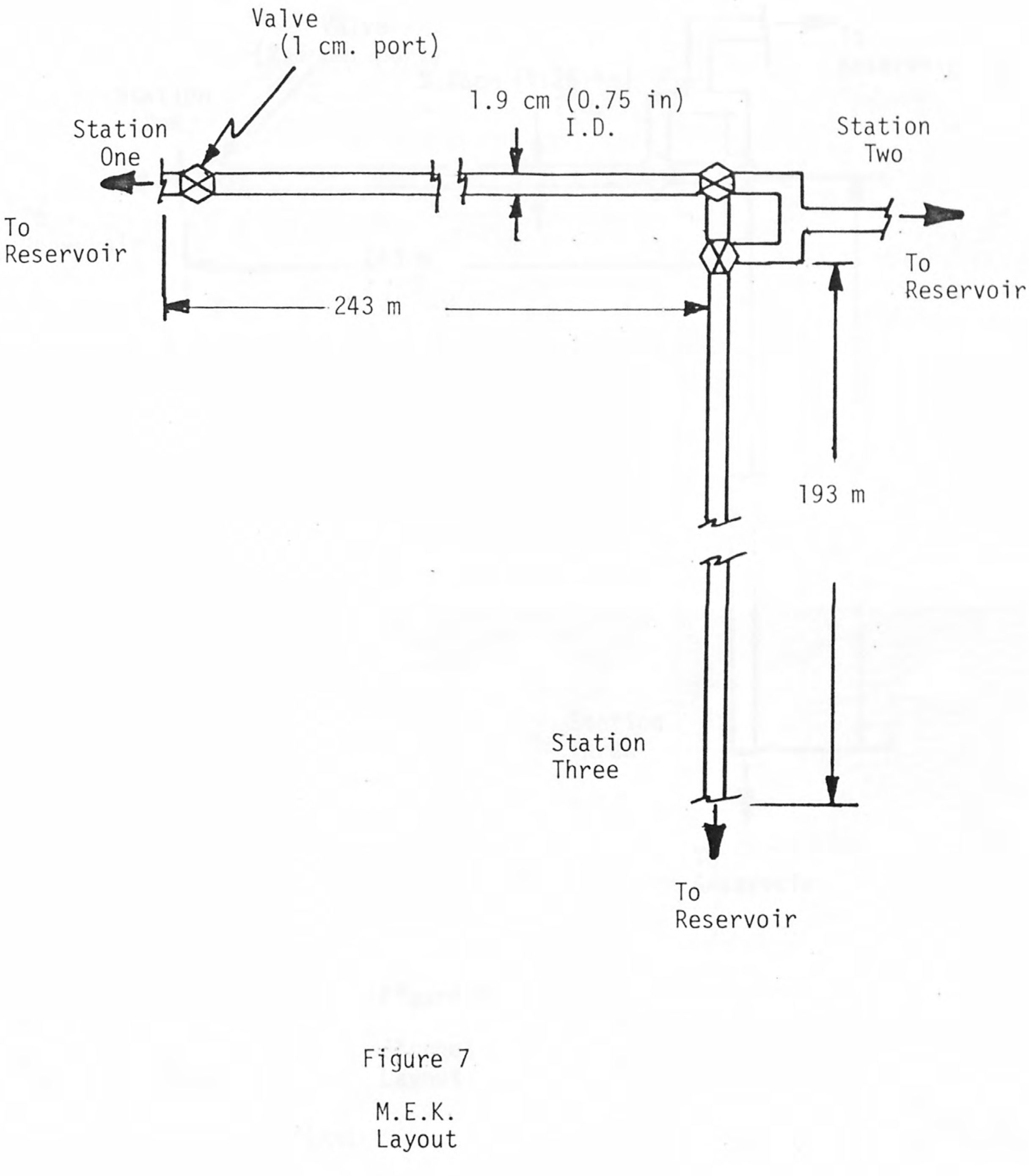


Figure 7

M.E.K.
Layout

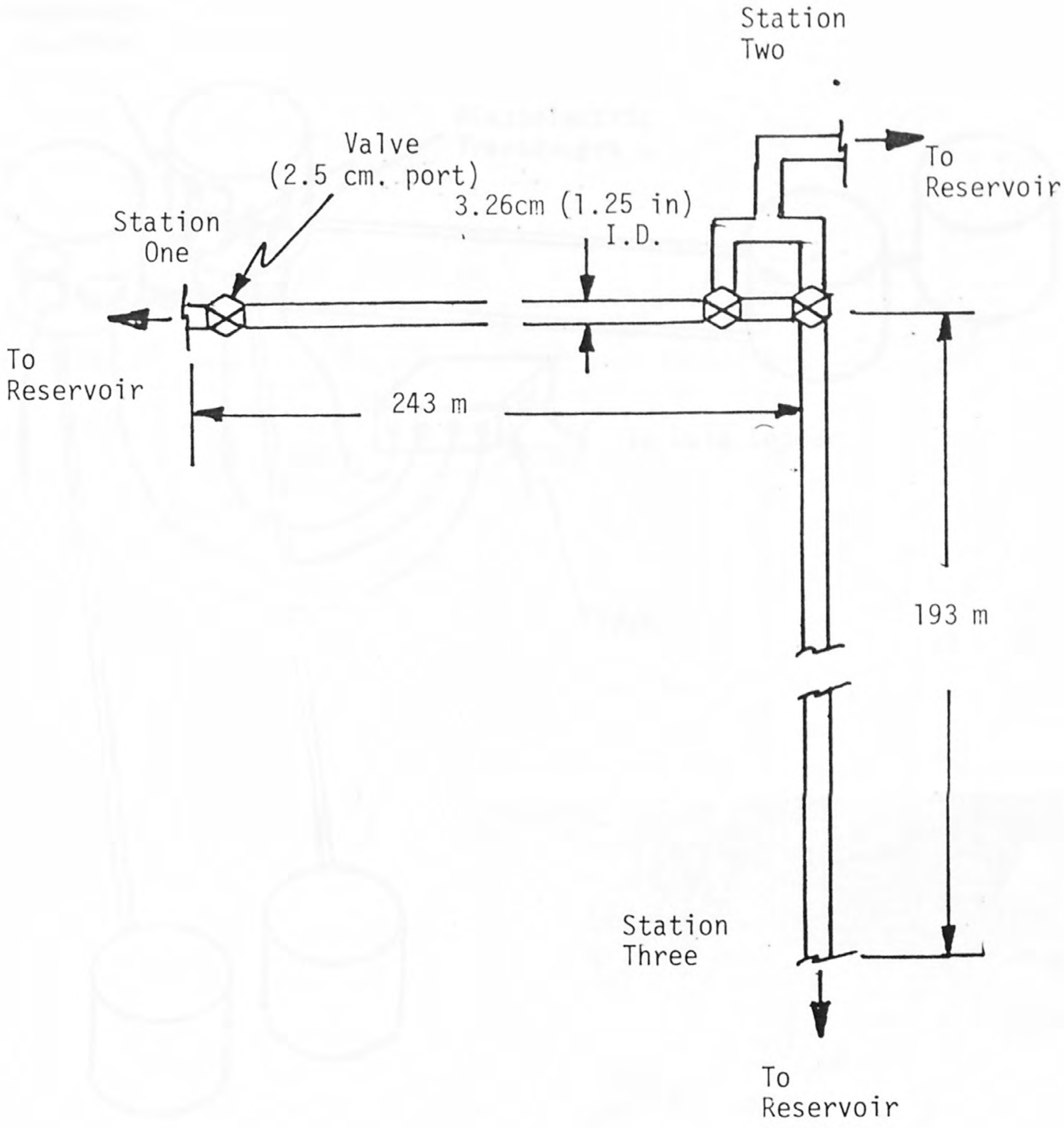


Figure 8

Alcohol
Layout

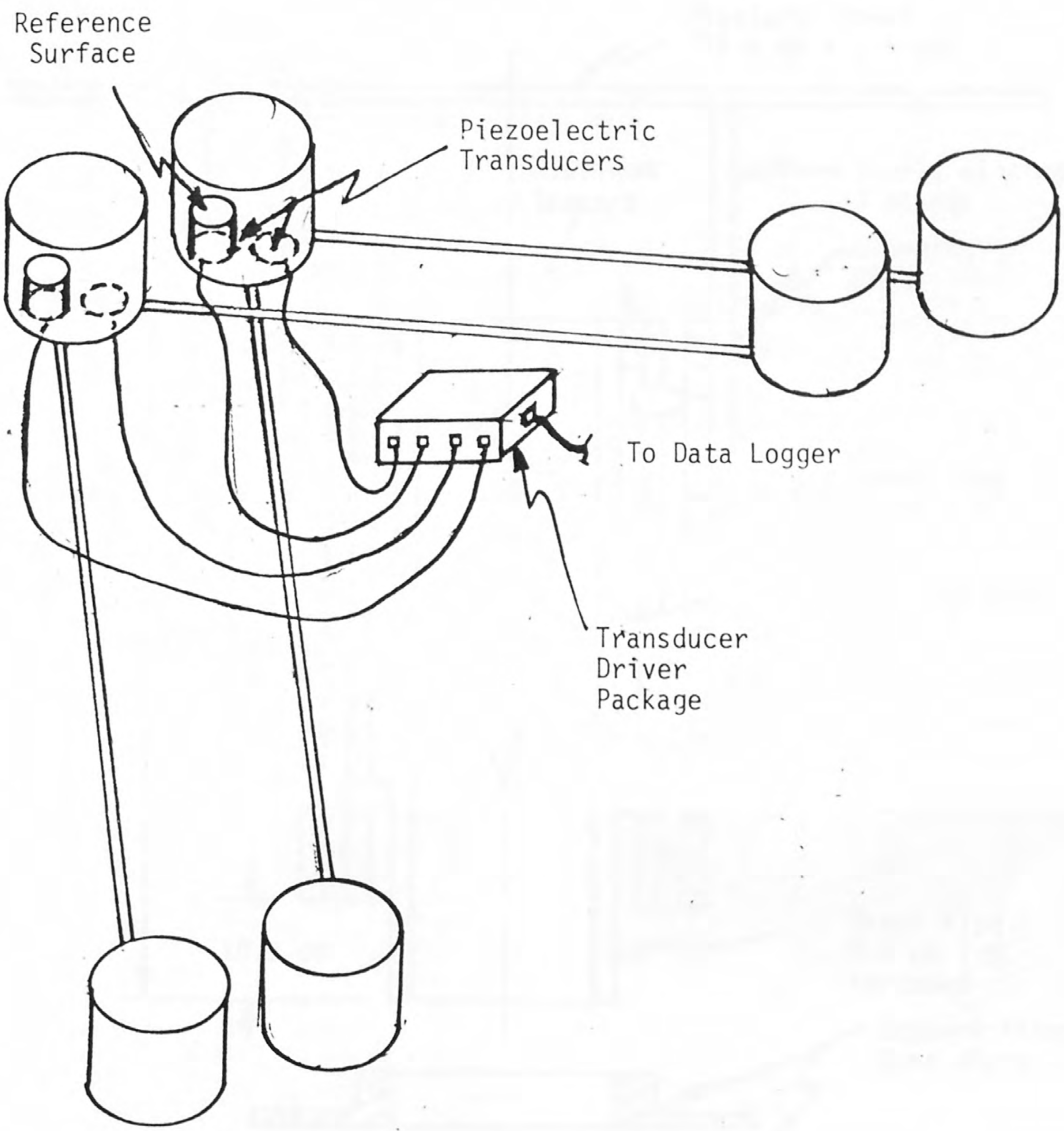


Figure 9

Transducer Locations

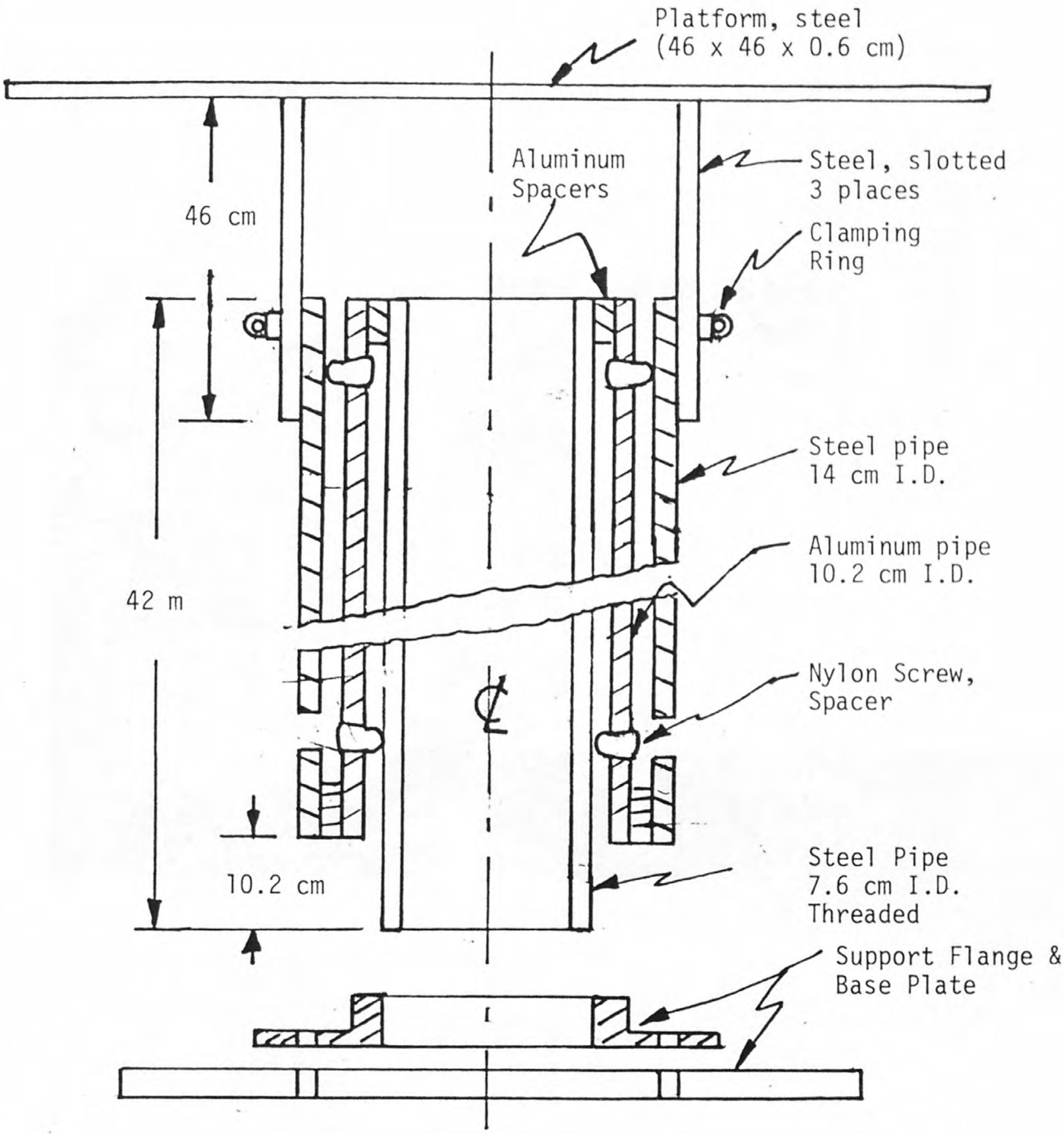


Figure 10

Compensated Pier

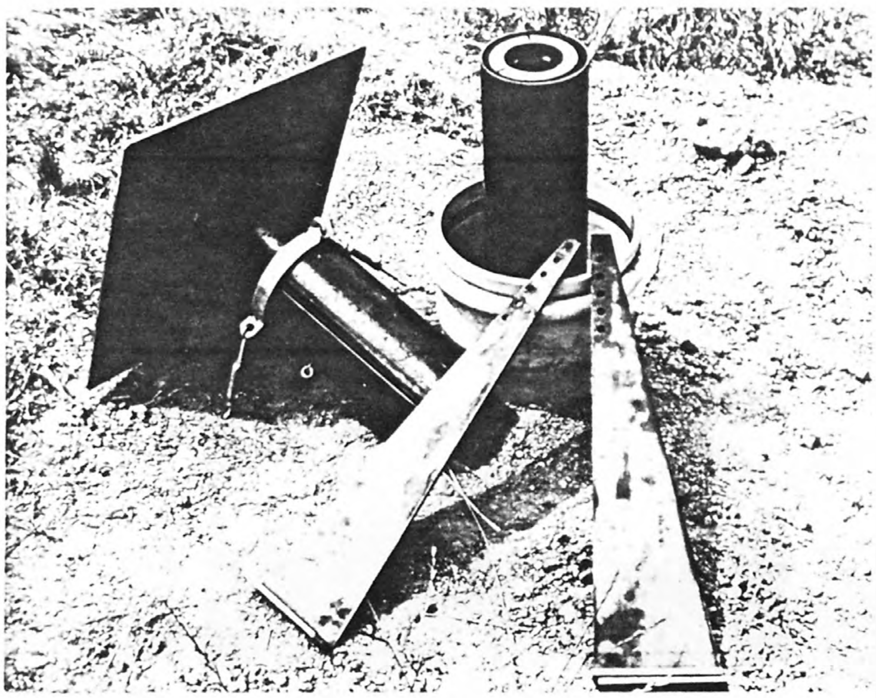


Figure 11

Pier Components

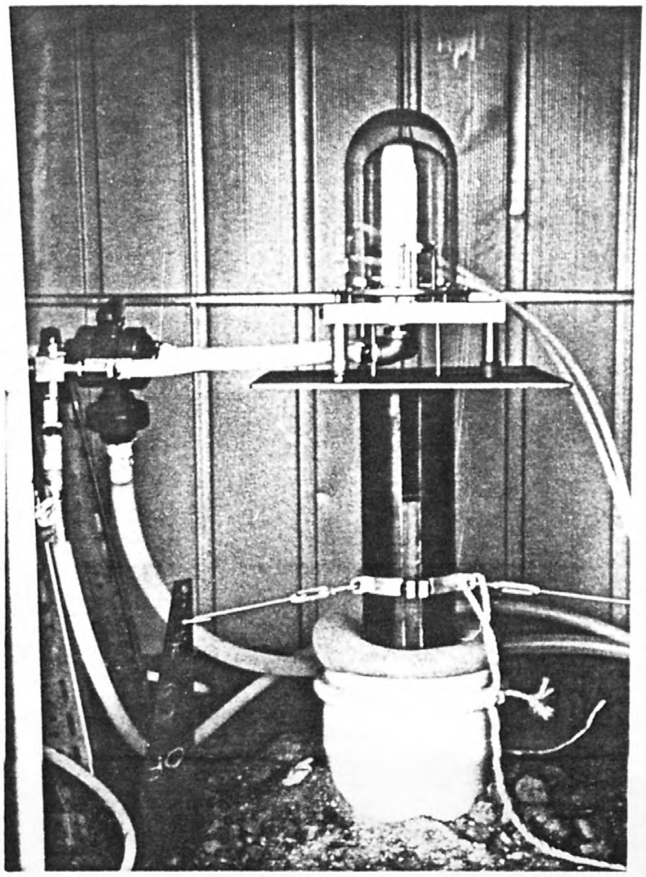


Figure 12

Station One, Complete

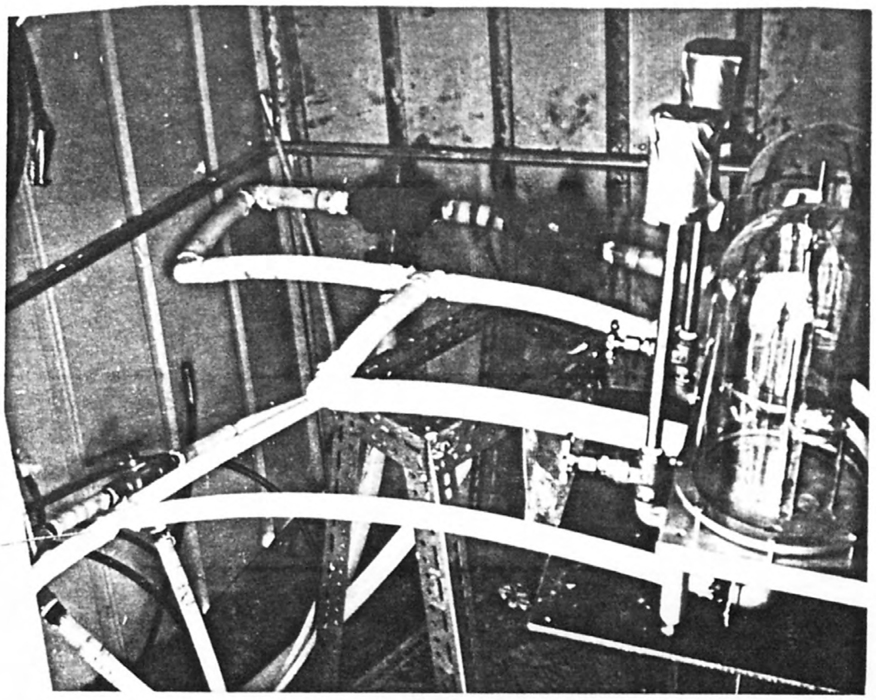


Figure 13

Station Two, Complete

APPENDICES

Appendix A

Fluid Properties Selection

1. Program FLUIDPH
2. Sample Output
3. Properties of Fluids Selected

1. FLUIDPH

UNIVERSITY OF MINNESOTA FORTRAN COMPILER (VERSION 5.4 - 02/22/79) ON 01/17/80 AT 19.35

```
                        MNF,T.
                        C * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
                        C * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
                        C                THIS PROGRAM IS TO AID IN THE SELECTION OF THE FLUIDS
                        C                     FOR THE TWO-FLUID TILTMETER
                        C                T=TEMPERATURE IN C.
                        C                DO(L)=DENSITY OF THE FLUID AT 0 C.
                        C                D(L)=DENSITY OF THE FLUID AT TEMPERATURE T .
                        C                A(L),B(L),C(L) ARE THE COEFFICIENTS IN THE EQUATION
                        C                D(L)=DO(L)+A*T+B*T**2+C*T**3+..........
                        C                MP=MELTING POINT OF THE FLUID
                        C                BP=BOILING POINT OF THE FLUID
                        C * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
                        C * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
                        C                     M A I N   P R O G R A M
                        C * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
   1.    000000B              PROGRAM FLUID(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)
                        C * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
                        C                     DIMENSION
                        C * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
   2.    002131B              DIMENSION NAME(80,2),D(80),A(80),B(80),C(80),ALPHA(80),
                             1BETA(80),GAMMA(80),RATIOA(80,80),RATIOB(80,80),RATIOC(80,80),
                             2ECOEF(80,80),MP(80),BP(80),RATIOD(80,80),RATIOE(80,80)
                        C * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
   3.    002131B              E=0.5
   4.    116711B              L=47
   5.    116713B              DO 10 J=1,L
   6.    116722B              READ(5,1000)NAME(J,1),NAME(J,2),D(J),A(J),B(J),C(J),MP(J),BP(J)
   7.    117001B        10    CONTINUE
                        C * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
   8.    117005B              WRITE(6,2000)
   9.    117013B              DO 15 J=1,L
  10.    117022B              ALPHA(J)=A(J)/D(J)
  11.    117027B              BETA(J)=B(J)/D(J)
  12.    117034B              GAMMA(J)=C(J)/D(J)
  13.    117041B        15    CONTINUE
  14.    117044B              J=1
  15.    117045B        20    DO 850 K=1,L
  16.    117056B              RATIOA(J,K)=ALPHA(J)/ALPHA(K)
  17.    117073B              IF(BETA(K))40,30,40
  18.    117101B        30    RATIOB(J,K)=0.0
```

```
 18.   117101B    30   RATIOB(J,K)=0.0
 19.   117112B         GO TO 50
 20.   117114B    40   RATIOB(J,K)=BETA(J)/BETA(K)
 21.   117134B    50   IF(GAMMA(K))70,60,70
 22.   117144B    60   RATIOC(J,K)=0.0
 23.   117154B         GO TO 80
 24.   117156B    70   RATIOC(J,K)=GAMMA(J)/GAMMA(K)
 25.   117176B    80   IF(RATIOA(J,K)-1.0)90,850,100
 26.   117212B    90   IF(RATIOA(J,K)-0.95)105,850,850
 27.   117226B   100   IF(RATIOA(J,K)-1.05)850,850,101
 28.   117242B   101   IF(ABS(RATIOA(J,K)-RATIOB(J,K))-E)110,110,850
 29.   117260B   105   RATIOD(J,K)=1/RATIOA(J,K)
 30.   117272B         IF(RATIOB(J,K))107,106,107
 31.   117302B   106   RATIOB(J,K)=0.0000001
 32.   117313B   107   RATIOE(J,K)=1/RATIOB(J,K)
 33.   117325B         IF(ABS(RATIOD(J,K)-RATIOE(J,K))-E)110,110,850
 34.   117340B   110   ECOEF(J,K)=(BETA(J)*ALPHA(K)-ALPHA(J)*BETA(K))/(ALPHA(J)-ALPHA(K))
 35.   117363B         WRITE(6,3000)NAME(J,1),NAME(J,2),MP(J),BP(J),NAME(K,1),NAME(K,2),
                      1MP(K),BP(K),RATIOA(J,K),RATIOB(J,K),RATIOC(J,K),ECOEF(J,K)
 36.   117502B   850   CONTINUE
 37.   117506B         J=J+1
 38.   117507B         IF(J-L)20,20,900
 39.   117507B   900   CONTINUE
                 C * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
                 C                    F O R M A T   S E C T I O N
                 C * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
 40.   117512B  1000   FORMAT(2A10,4F12.8,2A5)
 41.   117512B  2000   FORMAT(1H1,40X,↑FLUIDS SELECTION FOR THE TWO-FLUID TILTMETER↑,
                      120X,↑A-R. MANNAA↑,////,4X,↑NAME OF FLUID↑,10X,↑MP    BP↑,7X,
                      2↑NAME OF FLUID↑,8X,↑MP    BP↑,6X,,↑RATIO A↑,8X,↑RATIO  B↑,8X,
                      3↑RATIO  C↑,3X,↑ERROR COEFFICIENT↑,//)
 42.   117512B  3000   FORMAT(2X,2(A10),2X,A5,2X,A5,2X,2(A10),2X,A5,2X,A5,2X,4(E12.8,3X),
                      1//)
                 C * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
 43.   117512B         STOP
 44.   117513B         END
```

2. Sample Output

FLUIDS SELECTION FOR THE TWO-FLUID TILTMETER

NAME OF FLUID	MP	BP	NAME OF FLUID	MP	BP
ALPH-EPICHLOROHYDRIN	-25.6	117.0	BROMOBENZENE--C6H5BR	-30.6	156.2
ALPH-EPICHLOROHYDRIN	-25.6	117.0	CHLOROBENZENE-C6H5CL	-45.2	132.1
ALPH-EPICHLOROHYDRIN	-25.6	117.0	IODOBENZENE--C6H5I--	-31.4	188.6
ALPH-EPICHLOROHYDRIN	-25.6	117.0	BENZONITRITE---C7H5N	-13.1	190.7
ALPH-EPICHLOROHYDRIN	-25.6	117.0	METHYLANILINE--C7H9N	-57.0	195.7
ALPH-EPICHLOROHYDRIN	-25.6	117.0	QUINOLINE------C9H7N	-19.5	237.7
ALPH-EPICHLOROHYDRIN	-25.6	117.0	ETHYL-------BENZOATE	-34.6	213.2
ALPH-EPICHLOROHYDRIN	-25.6	117.0	CYMENE--------C10H14	-25.0	175.0
ALPH-EPICHLOROHYDRIN	-25.6	117.0	DIETHYLANILINE------	-34.4	216.3
METHYL-ETHYL-KETONE	-86.4	079.6	NBUTYL-ALCOHOLC4H10O	-89.8	117.7
METHYL-ETHYL-KETONE	-85.4	079.6	ACETYLACETONE-C5H8O2	-23.2	137.0
METHYL-ETHYL-KETONE	-86.4	079.6	DIETHYLKETONE-C5H10O	-42.0	101.7
METHYL-ETHYL-KETONE	-85.4	079.6	METHYL--N--BUTYRATE-	-95.0	103=3
METHYL-ETHYL-KETONE	-86.4	079.6	DIETHYL---OXALATE---	-40.6	185.1
METHYL-ETHYL-KETONE	-85.4	079.6	ETHYL--N--BUTYRATE--	-93.3	121.3
METHYL-ETHYL-KETONE	-86.4	079.6	BENZYL-ALCOHOL-C7H8O	-15.3	205.8

FLUIDS SELECTION FOR THE TWO-FLUID TILTMETER

BP	RATIO A	RATIO B	RATIO C	ERROR COEFFICIENT
156.2	1.14584633	1.31804470	0	-.00000019
132.1	1.07069363	.93742831	0	.00000042
188.6	1.27152207	.92053366	0	.00000029
190.7	1.18229838	1.51808720	0	-.00000025
195.7	1.26415705	.86815657	0	.00000036
237.7	1.48864307	1.77266421	0	-.00000007
213.2	1.19200853	.92218366	0	.00000032
175.0	1.12539079	.64817673	0	.00000121
216.3	1.22621063	.75989591	0	.00000056
117.7	1.45923717	1.43469643	0	.00000002
137.0	1.22829084	1.38903829	0	-.00000028
101.7	1.09802064	.70388443	0	.00000318
108=3	1.06413960	.72209327	0	.00000412
185.1	1.19120476	1.46167074	0	-.00000054
121.3	1.08035780	1.08987172	0	-.00000006
205.8	1.70951208	1.28514494	0	.00000026

3. Fluid Properties

N-BUTYL ALCOHOL

Density = 0.823 gm/cm^3 (0°C)

$\alpha = -8.49X10^{-4}/°C$

$\beta = -3.88X10^{-7}/°C^2$

Temp °C	Viscosity (poise)
0	0.07911
10	0.05735
20	0.03658
30	0.030658
40	0.022392

METHYL ETHYL KETONE

Density = 0.82251 gm/cm^3 (0°C)

$\alpha = -1.24X10^{-3}/°C$

$\beta = -5.59X10^{-7}/°C^2$

Temp °C	Viscosity (poise)
0	0.05361
10	0.04522
20	0.04170
30	0.03861
40	0.03342

Appendix B

Safety Considerations

1. Hygienic Guides for Fluids Selected
2. Respirator Specifications

1 - Hygenic Guides

AMERICAN
Industrial Hygiene
ASSOCIATION

Hygienic Guide Series

HYGIENIC GUIDE SERIES

METHYL ETHYL KETONE (Butanone)

I. Hygienic Standards

A. Recommended maximum atmospheric concentration (8 hours): 250 parts of vapor per million parts of air, by volume (ppm).[1]

(1) *Basis for Recommendation:* Human experience plus animal studies.

B. Severity of hazards:

(1) *Health:* Low, for both acute and chronic exposures. Capable of causing narcotic symptoms in man and animals, but irritant properties of vapor limit the possibility of voluntary exposure to high concentrations. No confirmed reports of serious chronic effects below irritating levels. It may cause drying and irritation of the skin.

(2) *Fire:* High. Flash point is –5.6°C (22°F) (open cup). Explosive limits are 1.8-11.5% by volume.[5]

C. Short exposure tolerance: Limited by irritant properties of vapor; 30,000 ppm is intolerable to man because of irritation of eyes and nasal passages; 3000 ppm is intolerable for more than just a short period of time.[4,6]

D. Atmospheric concentration immediately hazardous to life: Unknown, but probably 10,000 ppm or above.

II. Significant Properties

It is a colorless liquid with a characteristic ketonic odor. Although the product now available usually has a high degree of purity, the following properties will be somewhat modified for the commercial grade:

Chemical formula:	$CH_3COCH_2CH_3$
Molecular weight:	72.10
Specific gravity:	0.805 (20°/4°C)
Boiling point:	79.6°C
Relative vapor density:	2.49 (air = 1)
Vapor pressure:	90.7 mm Hg, at 25°C
At 25°C and 760 mm Hg,	
1 mg/liter of vapor:	340 ppm
1 ppm of vapor:	0.00294 mg/liter
Solubility:	Moderately, in water; forms azetropic mixture with water (boiling point 73.5°-C), at 89% by weight methyl ethyl ketone

III. Industrial Hygiene Practice

A. Recognition: It has been widely used as a solvent for resins and lacquers, in paint removers, and in miscellaneous organic syntheses. It can be recognized by its characteristic odor (somewhat similar to acetone, but slightly more irritating).

B. Evaluation of exposures: Can be determined by methods similar to those used for other ketones. It can also be determined by mass spectrometry and by suitably calibrated explosimeter type instruments.[2,3]

C. Recommended control procedures: Any operations involving spraying should be conducted in a properly designed spray booth. It should be used only in the presence of spark proof equipment and with due care, to avoid exposure to any other sources of ignition. Occasional short exposures to small quantities can usually be controlled by good general ventilation. If irritating levels are encountered, this can be controlled by the use of personal respiratory protective equipment.

IV. Specific Procedures

A. First aid: Remove any contaminated clothing promptly and flush skin with copi-

Reviewed—Second Printing
April, 1964

ous amounts of water. In case of eye burns, flush with water for 10 minutes.

B. PROPHYLACTIC PROCEDURES: Attempt to maintain workroom atmospheres below 250 ppm.

C. SPECIAL MEDICAL PROCEDURES: None generally necessary. If trapped in an area of high concentrations, causing narcotic symptoms, remove individual to fresh air and treat symtomatically.

V. Literature References

1. American Conference of Governmental Industrial Hygienists: *AMA Arch. Ind. Health,* 14:186, 1956.
2. ELKINS, H. B.: The Chemistry of Industrial Toxicology, p. 323. John B. Wiley and Sons, Inc., New York, 1950.
3. FAIRHALL, L. T.: Industrial Toxicology, p. 235. The Williams and Wilkins Co., Baltimore, 1949.
4. LA BALLE, M. S., and BRIEGER, H.: *AMA Arch. Ind. Health,* 12:623, 1955.
5. MARSDEN, C.: Solvents and Allied Substances Manual. Elsevier Press, Houston, Tex., 1954.
6. PATTY, F. A., SCHRENK, H. H., and YANT, W. P.: Public Health Reports, 50:1217-1228, 1935.

Because of space limitations, it is impossible to list all methods of exposure evaluation. The selections have been made on the basis of current usage, reliability, and applicability to the usual industrial type of exposure. Any specific evaluation and/or control problem will involve professional judgment. This can best be done by professional industrial hygiene personnel.

Respiratory protective devices are commercially available. Their use, however, should be confined to emergency or intermittent exposures and not relied upon as primary means of hazard control.

A relative scale is used for rating the severity of hazards: nil, low, moderate, high, and extra hazardous.

Hygienic Guide sheets may be obtained from the AMERICAN INDUSTRIAL HYGIENE ASSOCIATION, 14125 Prevost, Detroit 27, Michigan at 25 cents each. All orders for less than $2.00 must be prepaid. Discount of 20% on orders of five or more Guides; 40% discount on orders of 100 or more Guides. Special loose-leaf binders for the Guides may also be ordered from the Association office for $1.25 each.

AMERICAN Industrial Hygiene ASSOCIATION

Hygienic Guide Series

HYGIENIC GUIDE SERIES

BUTYL ALCOHOL (N-BUTANOL)

I. Hygienic Standards

A. RECOMMENDED MAXIMUM ATMOSPHERIC CONCENTRATION (8 hours): 100 parts of vapor per million parts of air (ppm).[1]

(1) *Basis for Recommendation:* Development of eye irritation upon prolonged exposure to levels over 100 ppm.[3,4]

B. SEVERITY OF HAZARDS:

(1) *Health:* Low. Volatility is low and odor response good.

(2) *Fire:* Moderate. The limits of inflammability are 1.5% and 11.3% by volume.[2] Because of the low volatility, however, explosive atmospheres are unlikely, except at elevated temperatures. Flash point is 84°F (closed cup).

C. SHORT EXPOSURE TOLERANCE: Occasional eye irritation at 200 ppm with several hours exposure.[3]

D. ATMOSPHERIC CONCENTRATION IMMEDIATELY HAZARDOUS TO LIFE: Unknown.

II. Significant Properties

Butanol is a flammable, colorless liquid, slightly soluble in water, miscible with most organic solvents. It has a pungent odor resembling fusel oil.

Chemical formula:	$C_2H_5CH_2CH_2OH$
Molecular weight:	74
Specific gravity:	0.810 (20°/4°C)
Boiling point:	117.7°C
Relative density:	2.56 (air = 1)
Vapor pressure:	6 mm of Hg at 25°C
Solubility:	In most organic solvents and in water to the extent of 8.9% at 25°C
1 ppm of vapor (25°C and 760 mm Hg):	0.00303 mg/l
1 mg/l (25°C and 760 mm Hg):	330 ppm
Odor threshold:	Ca. 25 ppm

III. Industrial Hygiene Practice

A. RECOGNITION:

(1) May be recognized by its odor. It is a lacquer solvent, as well as an ingredient of some rubber and plastic cements. It is also used in the plastic fabrication and chemical manufacturing industries.

(2) By its irritant action on the conjunctiva and mucous membranes, and by its minor skin irritant effects.

B. EVALUATION OF EXPOSURES: Because it is frequently used in association with other alcohols, a specific analytical method is difficult to achieve. In the absence of other alcohols an iodometric estimation of the amount of chromate necessary to oxidize it to butyric acid has been used by Tabershaw.[4] A DAVIS M-6 VAPO-TESTER, properly calibrated, has also been used. The vapors may also be determined by either a gas interferometer or a mass spectrometer.

C. RECOMMENDED CONTROL PROCEDURES: Enclosure of the processes using butanol should be practiced. Adequate ventilation of the surfaces of the benches at which the cementing operations are conducted is recommended.

IV. Specific Procedures

A. FIRST AID: Usual procedures, such as removal from exposure, washing of affected skin areas, and irrigation of the eyes with water should be practiced.

B. PROPHYLACTIC PROCEDURES: Maintain

Reviewed—Second Printing
April, 1964

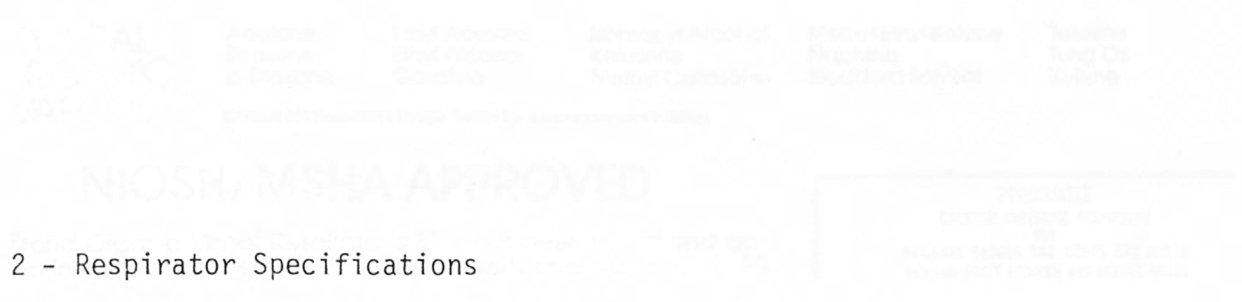
workroom atmospheres below 100 ppm by means of process enclosure and/or ventilation. This can best be done by personnel specifically trained in industrial hygiene procedures.

C. Special medical procedures (including preplacement): None.

V. Literature References

1. American Conference of Governmental Industrial Hygienists: *AMA Arch. of Ind. Health.*, 11:521, 1955.
2. Coward, H. F., and Jones, G. W.: U. S. Bureau of Mines, Bulletin 503, 1952.
3. Sterner, J. H., Crouch, H. C., Brockmyre, H. F., and Cusack, M.: *AIHA Quarterly* 10:53, 1949.
4. Tabershaw, I. R., Fahy, J. P., and Skinner, J. B.: *J. Ind. Hyg. and Tox.*, 26:328, 1944.

Hygienic Guide sheets may be obtained from the American Industrial Hygiene Association, 14125 Prevost, Detroit 27, Michigan at 25 cents each. All orders for less than $2.00 must be prepaid.



2 - Respirator Specifications

TYPICAL ORGANIC VAPORS

Acetone	Ethyl Acetate	Isopropyl Alcohol	Methyl Ethyl Ketone	Toluene
Benzene	Ethyl Alcohol	Kerosene	Naphtha	Tung Oil
p-Dioxane	Gasoline	Methyl Cellosolve	Stoddard Solvent	Xylene

Consult 3M Respirator Usage Guide for a more complete listing.

NIOSH/MSHA APPROVED

3M Brand Organic Vapor Respirator #8712 has been tested and approved in accordance with NIOSH/MSHA specifications detailed in 30 CFR Part 11 Subpart L: §11.162-1 (breathing resistance), §11.162-2 (valve leakage), §11.162-3 (face fit), and §11.162-8 (cartridge performance). The 8712 meets or exceeds these requirements for an organic vapor respirator.

Respirator life depends upon the activity of the wearer and specific type and concentrations of the organic vapors present. The 8712 can be worn until the wearer begins to smell or taste the organic vapor or an irritation occurs.

IMPORTANT: The 8712 should only be used for respiratory protection against organic vapors with good warning properties (e.g. smell, taste). It is to be used only for protection against not more than 1000 ppm organic vapors by volume. Maximum use concentrations will be lower than 1000 ppm where that concentration produces atmospheres immediately dangerous to life or health. Areas of use should be adequately ventilated (containing at least 19.5 percent oxygen). Respirator must not be worn when atmospheric concentrations of contaminants are unknown or immediately dangerous to life or health. **IF YOU HAVE ANY DOUBTS ABOUT THE APPLICABILITY OF THE 3M BRAND ORGANIC VAPOR RESPIRATOR #8712 TO YOUR JOB SITUATION, IT IS RECOMMENDED YOU CONSULT AN INDUSTRIAL HYGIENIST OR CALL 3M CO. TOLL FREE 1-800-328-1300 AND ASK FOR OH&SP TECH SERVICE DEPARTMENT.**

For information on any other 3M Brand respiratory products, call OH&SP Customer Service department at the toll free number listed above.

PERMISSIBLE
CHEMICAL CARTRIDGE RESPIRATOR
FOR
ORGANIC VAPORS AND DUSTS AND MISTS
AND FOR PAINT, LACQUER AND ENAMEL MISTS

MSHA NIOSH

MINE SAFETY AND HEALTH ADMINISTRATION
NATIONAL INSTITUTE FOR OCCUPATIONAL SAFETY AND HEALTH

APPROVAL NO. TC-23C-123

ISSUED TO

MINNESOTA MINING AND MANUFACTURING COMPANY
St. Paul, Minnesota, U. S. A.

LIMITATIONS

Approved for respiratory protection against not more than 1,000 parts per million organic vapors by volume and dusts and mists having a time weighted average not less than 0.5 milligram per cubic meter or 2 million particles per cubic feet and for paint, lacquer, and enamel mists. Not for use in atmospheres containing less than 19.5 percent oxygen. Do not wear for protection against organic vapors with poor warning properties or those which generate high heats of reaction with sorbent material in the cartridge. Maximum use concentrations will be lower than 1,000 parts per million where that concentration produces atmospheres immediately dangerous to life or health.

CAUTION

This respirator shall be entirely discarded when taste or smell of the contaminant is detected or the recommended use period is reached. When applicable, replacement filters and filter retainers identical with those furnished by the manufacturer under this approval shall be maintained. This respirator shall be selected, fitted, and used in accordance with Mine Safety and Health Administration, Occupational Safety and Health Administration, and other applicable regulations.

T-002728-C

MSHA-NIOSH APPROVAL TC-23C-123
ISSUED TO MINNESOTA MINING AND MANUFACTURING COMPANY
APRIL 18, 1978

The approved 8712 assembly for organic vapors consists of the following 3M part number: 8712 (TC-23C-123) respirator.

The approved 8717 assembly for organic vapors and dusts and mists and paint, lacquer and enamel mists consists of the following 3M part numbers: 8712 (TC-23C-123) respirator, 8718 (TC-23C-123) filter, and 8719 filter retainer.

T-002948-C

Appendix C

Dynamic Response

1. Program DYNAM
2. Sample Output

1. Program DYNAM

UNIVERSITY OF MINNESOTA FORTRAN COMPILER (VERSION 5.4 - 80/10/30) ON 81/03/11 AT 14.59

MNF,T.

```
000000B          PROGRAM DYNAM(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)
002131B          DIMENSION VISC(50,50),B11(50,50),B12(50,50),B22(50,50),
                1DENS(50,50),NAME(50,2),ALPH(50),BETA(50),GAMA(50),DENSR(50),
                2DP(10),AP(10)
002131B          PI=3.14159
033155B          M=10
033157B          D=16.51
033160B          G=980.0
033161B          RL=25000.0
033163B          NDP=2
033164B          DO 10 N=1,NDP
033173B          READ(5,50)DP(N)
033207B    10    CONTINUE
033213B          DO 20 J=1,M
033222B          READ(5,100)NAME(J,1),NAME(J,2)
033243B    20    CONTINUE
033247B          READ(5,150)((VISC(J,K),K=1,5),J=1,M)
033305B          DO 40 J=1,M
033314B          DO 30 K=1,5
033317B          VISC(J,K)=VISC(J,K)/100.0
033317B    30    CONTINUE
033342B    40    CONTINUE
033347B          READ(5,155)(DENSR(J),ALPH(J),BETA(J),GAMA(J),J=1,M)
033413B          TEMP=0.0
033413B          T=0.0
033413B          AR=(PI*D**2)/4.0
033416B          DO 450 N=1,NDP
033426B          AP(N)=(PI*DP(N)**2)/4.0
033434B          W011=SQRT((2.0*G*AP(N))/(RL*AR))
033452B          W012=SQRT((G*AP(N))/(RL*AR))
033467B          W022=SQRT((3.0*G*AP(N))/(RL*AR))
033506B          WRITE(6,500)DP(N),W011,W012,W022
033525B          DO 400 J=1,M
033534B          WRITE(6,550)NAME(J,1),NAME(J,2)
033555B          DO 350 K=1,5
033557B          IF(VISC(J,K))320,320,140
033570B    140   DENS(J,K)=DENSR(J)+ALPH(J)*TEMP+BETA(J)*TEMP**2+GAMA(J)*TEMP**3
```

```
      033605B          WRITE(6,580)TEMP,VISC(J,K),DENS(J,K)
      033622B          B11(J,K)=(4.0*PI*VISC(J,K))/(W011*DENS(J,K)*AP(N))
      033634B          B12(J,K)=(4.0*PI*VISC(J,K))/(W012*DENS(J,K)*AP(N))
      033644B          B22(J,K)=(4.0*PI*VISC(J,K))/(W022*DENS(J,K)*AP(N))
      033655B          WRITE(6,600)B11(J,K),B12(J,K),B22(J,K)
      033672B          WRITE(6,650)
      033700B          IF(B11(J,K)-1.0)296,160,200
      033703B     160  HRATIO=(1.0+W011*T)*(EXP(-W011*T))
      033715B          IF(T-800.0)190,190,195
      033720B     190  WRITE(6,700)HRATIO,T
      033731B          T=T+300.0
      033732B          GO TO 160
      033734B     195  IF(T-3600.0)196,196,290
      033740B     196  WRITE(6,700)HRATIO,T
      033751B          T=T+600.0
      033752B          GO TO 160
      033752B     200  CONTINUE
      033755B          IF(B11(J,K)-1.0)296,270,250
      033760B     250  C=SQRT(B11(J,K)**2-1.0)
      033770B          F=B11(J,K)*W011
      033772B          HRATIO=((B11(J,K)+C)/(2.0*C))*EXP((-F+W011*C)*T)
                      1    +((C-B11(J,K))/(2.0*C))*EXP((-F-W011*C)*T)

      034021B          IF(T-900.0)260,260,265
      034025B     260  WRITE(6,700)HRATIO,T
      034036B          T=T+300.0
      034037B          GO TO 250
      034041B     265  IF(T-3600.0)266,266,290
      034045B     266  WRITE(6,700)HRATIO,T
      034056B          T=T+600.0
      034057B          GO TO 250
      034057B     270  CONTINUE
      034062B     290  IF(TEMP-40.0)295,360,360
      034066B     295  TEMP=TEMP+10.0
      034072B          T=0.0
      034072B          GO TO 350
      034074B     296  C=SQRT(1.0-B11(J,K)**2)
      034103B          F=B11(J,K)*W011
      034105B          S=ATAN(C/B11(J,K))
      034112B     297  HRATIO=((EXP(-F*T))/C)*SIN((C*W011*T)+S)
      034134B          IF(T-900.0)298,298,299
      034137B     298  WRITE(6,700)HRATIO,T
      034151B          T=T+300.0
      034152B          GO TO 297
```

```
 79.   034160B   301   WRITE(6,700)HRATIO,T
 80.   034171B         T=T+600.0
 81.   034172B         GO TO 297
 82.   034174B   305   IF(TEMP-40.0)306,360,360
 83.   034177B   306   TEMP=TEMP+10.0
 84.   034203B         T=0.0
 85.   034203B         GO TO 350
 86.   034205B   320   IVNT=(K-1)*10
 87.   034210B         WRITE(6,540)NAME(J,1),NAME(J,2),IVNT
 88.   034232B         TEMP=TEMP+10.0
 89.   034233B         T=0.0
 90.   034234B   350   CONTINUE
 91.   034240B   360   TEMP=0.0
 92.   034242B         T=0.0
 93.   034243B   400   CONTINUE
 94.   034250B         IF(N-NDP)440,900,900
 95.   034250B   440   CONTINUE
 96.   034254B         TEMP=0.0
 97.   034254B         T=0.0
 98.   034255B   450   CONTINUE
                 C* * * * * * * * * * * F O R M A T   S E C T I O N   * * * * * * * * * * * *
 99.   034262B   50    FORMAT(F10.5)
100.   034262B   100   FORMAT(2A10)
101.   034262B   150   FORMAT(5F10.5)
102.   034262B   155   FORMAT(4F12.8)
103.   034262B   500   FORMAT(1H1,20(/),30X,
                      1↑THIS PROGRAM IS TO ESTIMATE THE SETTLING TIME FOR ↑,
                      2↑THE OSCILLATING FLUIDS↑,20X,↑A-R  MANNAA↑,///,40X,↑PIPE DIAMETER
                      3 :DP =↑,F10.5,///,20X,↑FREQUENCY OF THE SINGLE LEG SYSTEM:W011=↑,
                      4F10.5,//,20X,↑FIRST FREQUENCY OF THE DOUBLE LEG SYSTEM:W012=↑,
                      5F10.5,//,20X,↑SECOND FREQUENCY OF THE DOUBLE LEG SYSTEM W022=↑,
                      6F10.5,///)
104.   034262B   540   FORMAT(20X,↑DATA FOR VISCOSITY OF ↑,2A10,↑ AT A TEMP. OF ↑,
                      1I5,↑ IS NOT AVAILABLE ↑,///)
105.   034262B   550   FORMAT(1H1,40X,2A10,///)
106.   034262B   580   FORMAT(40X,↑CALCULATION IS CARRIED OUT AT TEMP. =↑,F10.3,2(5X,
                      1F10.5),///)
107.   034262B   600   FORMAT(20X,↑DAMP. COEF. OF SINGLE LEG SYST. : B11=↑,F10.5,//,20X,
                      1↑FIRST DAMP. COEF. OF DOUBLE LEG SYST. : B12=↑,F10.5,//,20X,
                      2↑SECOND DAMP. COEF. OF DOUBLE LEG SYST. : B22=↑,F10.5,///)
108.   034262B   650   FORMAT(30X,↑HRATIO=(H/HO)↑,10X,↑SETTLING TIME↑,//)
109.   034262B   700   FORMAT(30X,F10.8,15X,F10.2,//)
110.   034262B   900   STOP
111.   034264B         END
```

2 - Sample Output

```
THIS PROGRAM IS TO ESTIMATE THE SETTLING TIME FOR THE OSCILLATING FLUIDS

PIPE DIAMETER   :DP =    1.90500

FREQUENCY OF THE SINGLE LEG SYSTEM:W011=      .03436
FIRST FREQUENCY OF THE DOUBLE LEG SYSTEM:W012=      .02430
SECOND FREQUENCY OF THE DOUBLE LEG SYSTEM W022=      .04208
```

METHYL-ETHYL-KETONE

CALCULATION IS CARRIED OUT AT TEMP. = 0 .00536 .82251

DAMP. COEF. OF SINGLE LEG SYST. : B11= .83629

FIRST DAMP. COEF. OF DOUBLE LEG SYST. : B12= 1.18269

SECOND DAMP. COEF. OF DOUBLE LEG SYST. : B22= .68282

HRATIO=(H/HO)	SETTLING TIME
1.00000000	0
-.00001667	300.00
-.00000004	600.00
-.00000000	900.00
-.00000000	1200.00
.00000000	1800.00
.00000000	2400.00
.00000000	3000.00
-.00000000	3600.00

```
THIS PROGRAM IS TO ESTIMATE THE SETTLING TIME FOR THE OSCILLATING FLUIDS

PIPE DIAMETER  :DP =   3.17500

FREQUENCY OF THE SINGLE LEG SYSTEM:W011=      .06530

FIRST FREQUENCY OF THE DOUBLE LEG SYSTEM:W012=      .04617

SECOND FREQUENCY OF THE DOUBLE LEG SYSTEM W022=      .07997
```

CALCULATION IS CARRIED OUT AT TEMP. = 0 .07911 .82300

DAMP. COEF. OF SINGLE LEG SYST. : B11= 2.33652

FIRST DAMP. COEF. OF DOUBLE LEG SYST. : B12= 3.30434

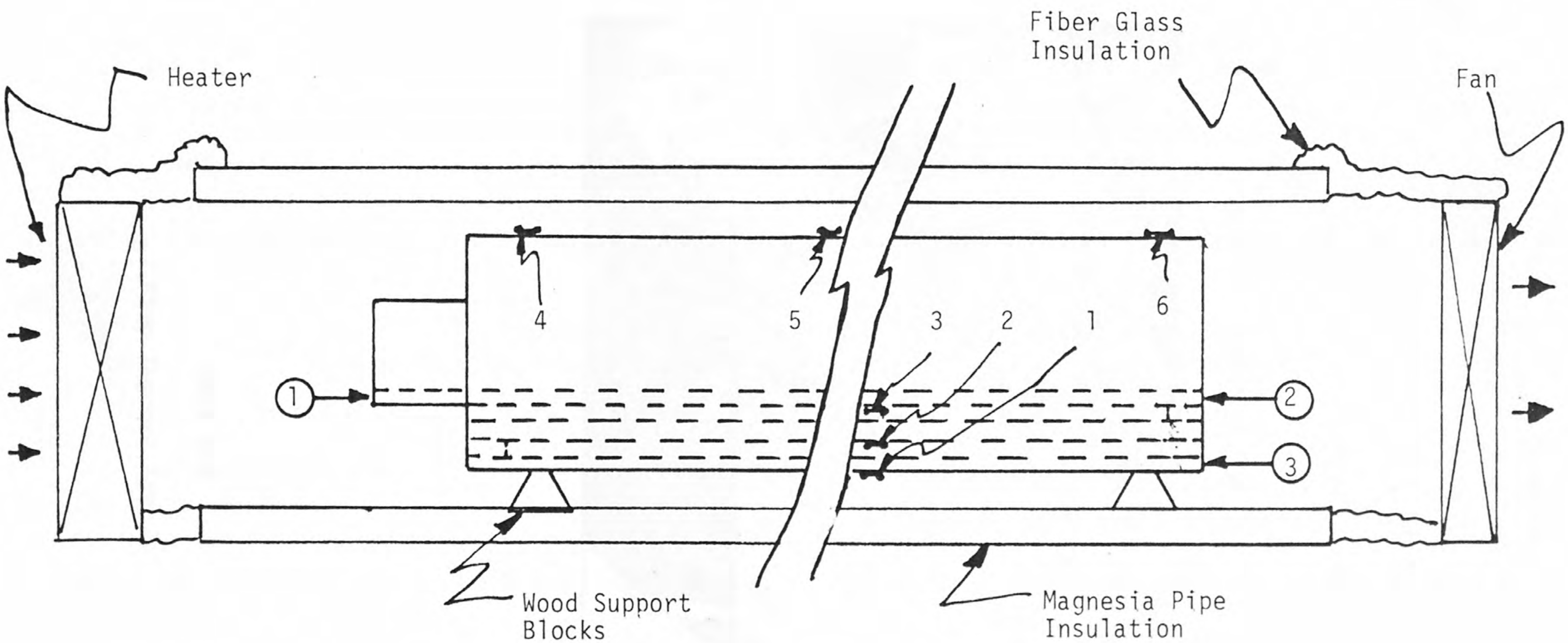
SECOND DAMP. COEF. OF DOUBLE LEG SYST. : B22= 1.90776

HRATIO=(H/HO)	SETTLING TIME
1.00000000	0
.01288093	300.00
.00015753	600.00
.00000193	900.00
.00000002	1200.00
.00000000	1800.00
.00000000	2400.00
.00000000	3000.00
.00000000	3600.00

APPENDIX D

Thermally Compensated Pier Test

1. Schematic and Photograph of Test Set Up (D-1,D-2)
2. Cooling Data (D-3)
3. Heating Data (D-4)



1 - 6 Thermocouples

(1)-(3) Dial Indicators

Figure D - 1

Pier Thermal Expansion Test

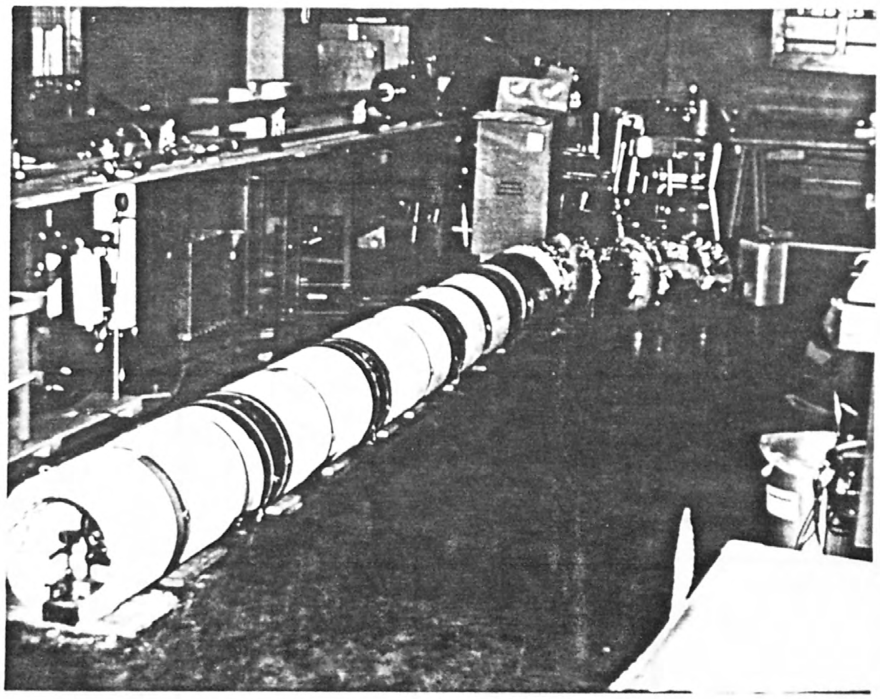


Figure D-2

Pier Thermal Test

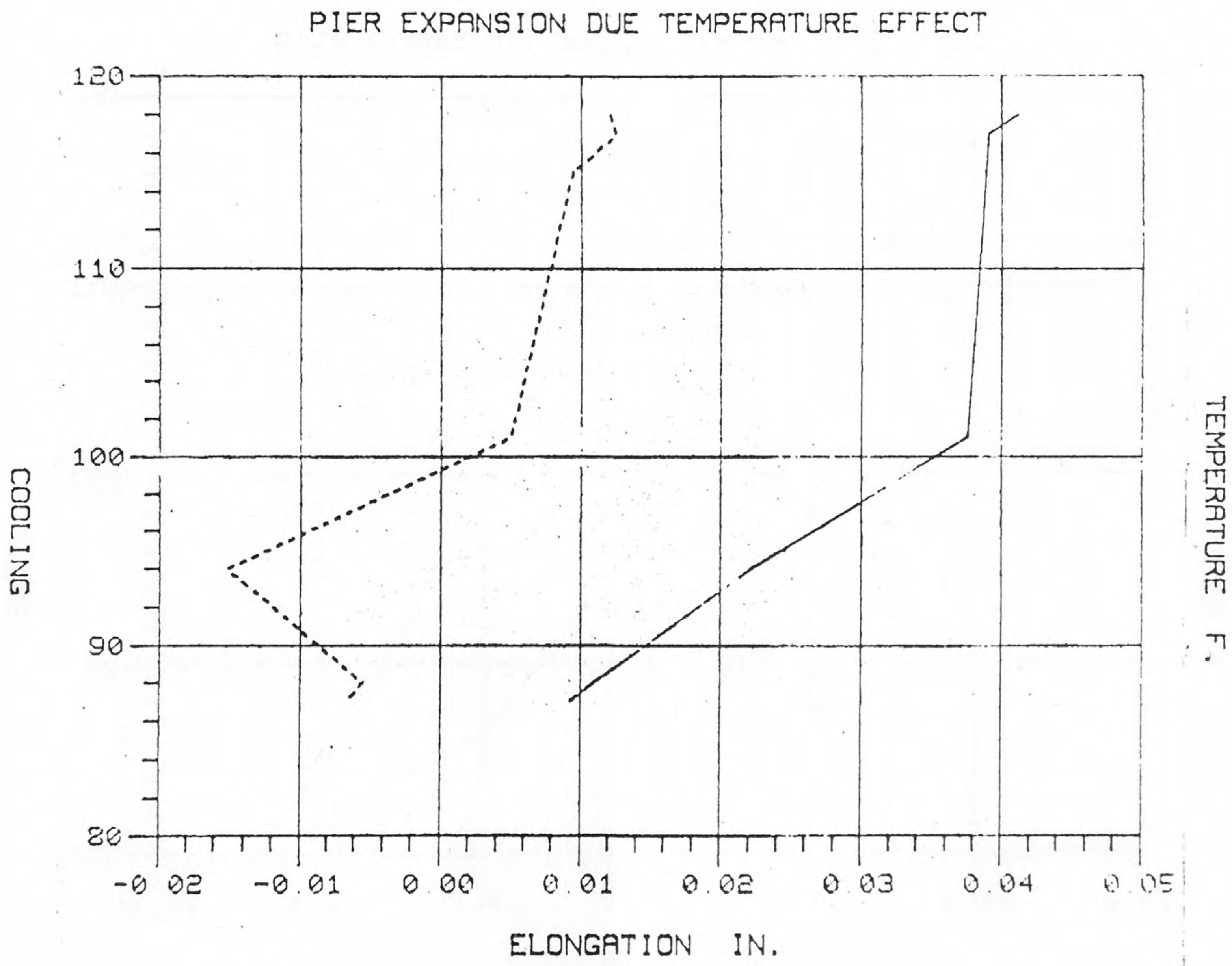


Figure D-3
Cooling Data

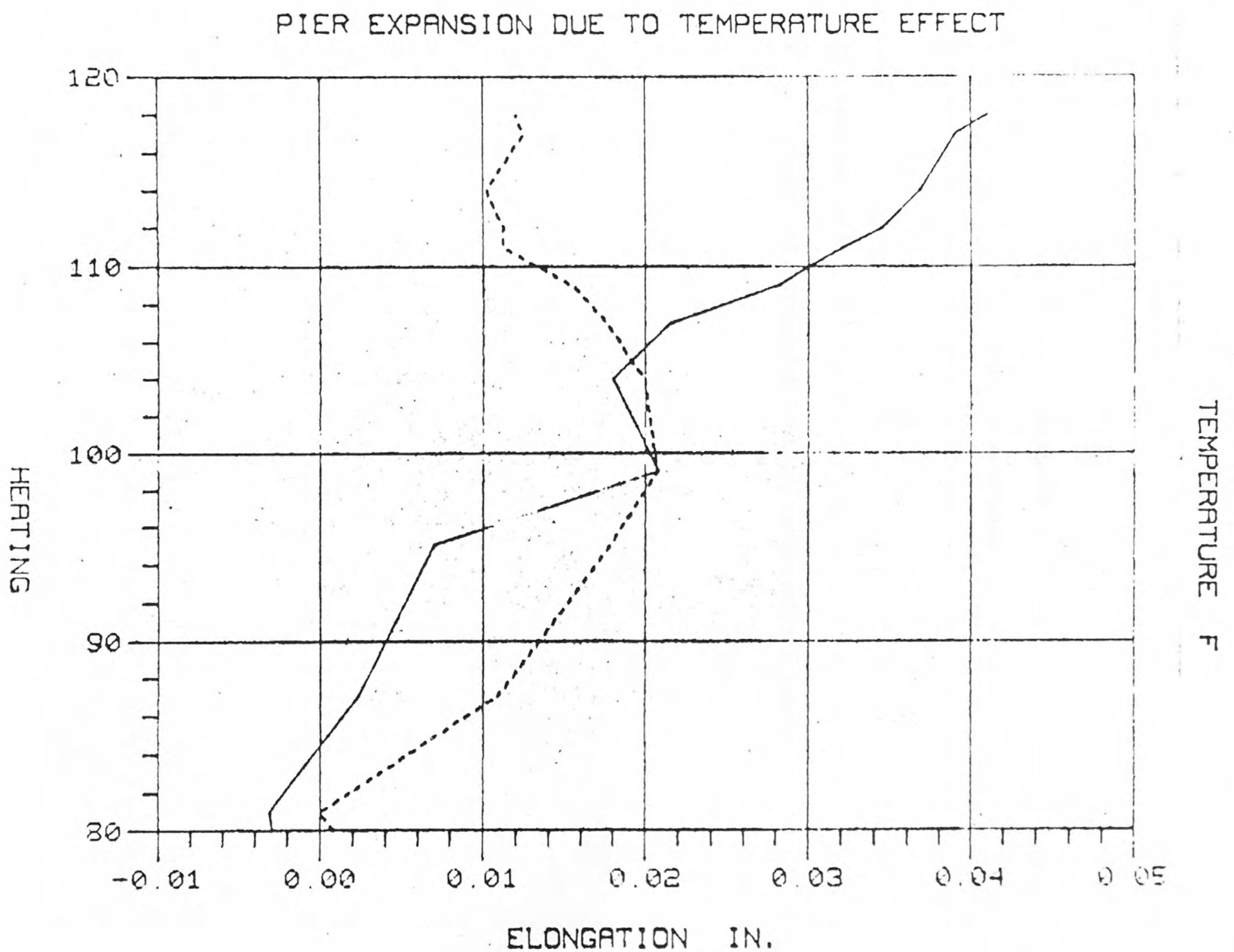


Figure D-4
Heating Data

Appendix E

Tilt Computations

1. Program TILT
2. Frequency data received from tiltmeter data logger.

1. Program Tilt

```
      PROGRAM TILT
      REAL ID,IH,IM,NRA3,NRM2,NSA2,NSM2,NSM1,NRM1,NRA4,NSA3,NSA4
C*******************************************************************************
C       NRA3=OSCILLATION COUNT BETWEEN REFERENCE AND ALCOHOL SURFACE
C            IN RESERVOIR NO. THREE
C       NRA4=OSCILLATION COUNT BETWEEN REFERENCE AND ALCOHOL SURFACE
C            IN RESERVOIR NO. FOUR
C       NRM1=OSCILLATION COUNT BETWEEN REFERENCE AND M.E.K. SURFACE
C            IN RESERVOIR NO. ONE
C       NRM2=OSCILLATION COUNT BETWEEN REFERENCE AND M. E.K. SURFACE
C            IN RESERVOIR NO. TWO
C       BH=LENGTH OF BASE LINE
C       N=NO. OF DATA LINES
C       ALPHA=THERMAL EXPANSION COEFFICIENT OF ALCOHOL
C       ALPHM=THERMAL EXPANSION COEFFICIENT OF M.E.K.
C       HR1=REFERENCE HEIGHT IN RESERVOIR NO. ONE
C       HR2=REFERENCE HEIGHT OF RESERVOIR NO. TWO
C       HR3=REFERENCE HEIGHT IN RESERVOIR NO. THREE
C       HR4=REFERENCE HEIGHT OF RESERVOIR NO. FOUR
C       LL=LOWER LIMIT OF FREQUENCY COUNT
C       UL=UPPER LIMIT OF FREQUENCY COUNT
C       HSA3=MEASURED ALCOHOL HEIGHT IN RESERVOIR NO. THREE
C       HSA4=MEASURED ALCOHOL HEIGHT IN RESERVOIR NO. FOUR
C       HSM1=MEASURED M. E. K. HEIGHT IN RESERVOIR NO. ONE
C       HSM2=MEASURED M. E.K. HEIGHT IN RESERVOIR NO.TWO
C       DELTA=THE DIFFERENCE IN ALCOHOL HEIGHTS IN THE TWO STATIONS
C       DELTM=THE DIFFERENCE IN M.E.K. HEIGHTS IN THE TWO STATIONS
C       TILT1=THE VALUE OF THE TILT CALCULATED BY CONSIDERING ALCOHOL
C           AS FLUID A AND M.E.K. AS FLUID B
C       TILT2=THE VALUE OF THE TILT CALCULATED BY CONSIDERING M.E.K.
C           AS FLUID A AND ALCOHOL AS FLUID B
C* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
C                  DIMENSION
      DIMENSION ID(100),NRA4(100),NRA3(100),NSA3(100),NSA4(100),
     1NRM1(100),NRM2(100),NSM1(100),NSM2(100),HSA3(100),HSA4(100),
     2HSM1(100),HSM2(100),DELTA(100),DELTM(100),EC1(100),EC2(100),
     3TILT1(100),TILT2(100),RA3(100),RA4(100),SA3(100),
     4SA4(100),SM1(100),SM2(100),RM1(100),IM(100),RM2(100),IH(100),
     5Y1(100),Y2(100),Y3(100),X(100)
C          I N P U T   O F   B A S I C   P A R A M E T E R S
C*******************************************************************************
      BL=1000.0
      N=4
      ALPHA=-0.000699
      ALPHM=-0.00122
      HR1=8.890
      HR2=8.890
      HR3=8.890
      HR4=8.890
      LL=30000.
      UL=90000.0
C*******************************************************************************
C         R E A D I N G   T H E   D A T A   F R O M   T H E   L O G G E R
C*******************************************************************************
      CALL ASSIGN(2,'COUNTS.DAT')
      READ(2,1000)(ID(K),IH(K),IM(K),NRM1(K),NRA4(K),NSM1(K),
     1NSA4(K),NSA3(K),NSM2(K),NRA3(K),NRM2(K),K=1,N)
 1000 FORMAT(F6.1,2X,F5.1,2X,F5.1,2X,F9.1,2X,F9.1,2X,F9.1,2X,
     1F9.1,2X,F9.1,2X,F9.1,2X,F9.1,2X,F9.1)
C*******************************************************************************
C          W R I T I N G   T H E   H E A D I N G
C*******************************************************************************
```

```
      WRITE(6,2000)
 2000 FORMAT(1H1,10X,'THIS PROGRAM IS TO CALCULATE THE VALUE OF TILT ',
     1'FROM FREQUENCY COUNTS',30X,'A-R  MANNAA',///)
      WRITE(6,2100)
 2100 FORMAT(10X,'LIST BELOW SHOWS THE DATA AS READ FROM THE DATA ',
     1'LOGGER',///,10X,'DAY',4X,'HOUR',1X,'MINUTE',4X,'NRM1',4X,'NRA4',
     26X,'NSM1',5X,'NSA4',5X,'NSA3',5X,'NSM2',7X,'NRA3',5X,'NRM2',//)
C* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
C      WRITING THE RAW DATA
C**********************************************************************
      WRITE(6,2500)(ID(K),IH(K),IM(K),NRM1(K),NRA4(K),NSM1(K),
     1NSA4(K),NSA3(K),NSM2(K),NRA3(K),NRM2(K),K=1,N)
 2500 FORMAT(10X,F5.1,2X,F4.1,2X,F4.1,2X,F9.1,F9.1,F9.1,F9.1,
     1F9.1,F9.1,F9.1,F9.1,/)
      WRITE(6,2550)
 2550 FORMAT(1H1,10X,'LIST BELOW SHOWS THE COUNTS REARRANGED.',
     11X,'THE COUNTS OF EACH FLUID ARE LISTED NEXT TO',
     2' EACH OTHER.',///,10X,'DAY',4X,'HOUR',1X,'MINUTE',4X,
     3'NRA3',4X,'NSA3',6X,'NRA4',5X,'NSA4',5X,'NRM1',5X,
     4'NSM1',5X,'NRM2',5X,'NSM2',//)
      WRITE(6,2500)(ID(K),IH(K),IM(K),NRA3(K),NSA3(K),NRA4(K),
     1NSA4(K)-NRM1(K),NSM1(K),NRM2(K),NSM2(K),K=1,N)
      WRITE(6,2600)
 2600 FORMAT(1H1,10X,'LIST BELOW SHOWS THE VALUES OF FLUID HEIGHTS IN CM
     1 INCLUDING ERRORS DUE TO THE TEMPERATURE EFFECT ON DENSITY ',///,10
     2X,'DAY',7X,'HOUR',4X,'MINUTE',9X,'HSA3',10X,'HSA4',10X,'HSM1',10X,
     3'HSM2',/)
C * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
C           TESTING LOWER AND UPPER BOUNDS OF THE COUNTS
C**********************************************************************
      DO 800 K=1,N
      RA3(K)=NRA3(K)
      RA4(K)=NRA4(K)
      SA3(K)=NSA3(K)
      SA4(K)=NSA4(K)
      SM1(K)=NSM1(K)
      SM2(K)=NSM2(K)
      RM1(K)=NRM1(K)
      RM2(K)=NRM2(K)
      IF(NSA3(K)-LL)800,200,200
 200  IF(NSA4(K)-LL)800,250,250
 250  IF(NSM1(K)-LL)800,300,300
 300  IF(NSM2(K)-LL)800,350,350
 350  IF(SA3(K)-UL)400,400,800
 400  IF(SA4(K)-UL)450,450,800
 450  IF(SM1(K)-UL)500,500,800
 500  IF(SM2(K)-UL)550,550,800
C**********************************************************************
C           CORRECTING THE VALUES OF THE COUNTS
C**********************************************************************
 550  RA3(K)=RA3(K)*(3.996/4.0)
      RA4(K)=RA4(K)*(3.996/4.0)
      SA3(K)=SA3(K)*(3.996/4.0)
      SA4(K)=SA4(K)*(3.996/4.0)
      RM1(K)=RM1(K)*(3.996/4.0)
      RM2(K)=RM2(K)*(3.996/4.0)
      SM1(K)=SM1(K)*(3.996/4.0)
      SM2(K)=SM2(K)*(3.996/4.0)
```

```
C*********************************************************************
C                    CALCULATING FLUIDS HEIGHTS
C*********************************************************************
        HSA3(K)=(RA3(K)/SA3(K))*HR3
        HSA4(K)=(RA4(K)/SA4(K))*HR4
        HSM1(K)=(RM1(K)/SM1(K))*HR1
        HSM2(K)=(RM2(K)/SM2(K))*HR2


C*********************************************************************
C            WRITING THE HEIGHTS OF THE FLUIDS
C*********************************************************************
        WRITE(6,3000)ID(K),IH(K),IM(K),HSA3(K),HSA4(K),HSM1(K),HSM2(K)
 3000   FORMAT(10X,3(F6.1,2X),2X,4(F12.8,10X),/)
 800    CONTINUE
        WRITE(6,3500)
 3500   FORMAT(1H1,10X,'LIST BELOW SHOWS THE VALUES OF THE DIFFERENCES IN
       1THE FLUIDS HEIGHTS IN THE TWO STATIONS IN CM AND THE VALUE OF THE
       2 TILT',//,11X,'DAY',7X,'HOUR',3X,'MINUTE',4X,'DELTA',10X,
       3'DELTM',10X,'EC1',12X,'EC2',12X,'TILT1',11X,'TILT2',//)
C*********************************************************************
C             CALCULATING THE TILT
C*********************************************************************
        DO 900 K=1,N
        DELTA(K)=HSA4(K)-HSA3(K)
        DELTM(K)=HSM2(K)-HSM1(K)
        EC2(K)=(DELTM(K)-(ALPHM/(ALPHA-ALPHM))*(DELTA(K)-DELTM(K)))
        EC1(K)=(DELTA(K)-(ALPHA/(ALPHM-ALPHA))*(DELTM(K)-DELTA(K)))
        TILT2(K)=ABS(EC2(K))/BL
        TILT1(K)=ABS(EC1(K))/BL
        X(K)=FLOAT(K)
        Y1(K)=EC1(K)
        Y2(K)=DELTA(K)
        Y3(K)=DELTM(K)
C*********************************************************************
C           WRITING THE VALUE OF THE TILT
C*********************************************************************
        WRITE(6,5000)ID(K),IH(K),IM(K),DELTA(K),DELTM(K),EC1(K),EC2(K),
     1TILT1(K),TILT2(K)
 5000   FORMAT(10X,3(F6.1,2X),6(F11.8,4X),//)
 900    CONTINUE
        CLOSE(UNIT=6,DISPOSE='PRINT')
        STOP
        END
```

2 - Data From the Logger

THIS PROGRAM IS TO CALCULATE THE VALUE OF TILT FROM FREQUENCY COUNTS

LIST BELOW SHOWS THE DATA AS READ FROM THE DATA LOGGER

DAY	HOUR	MINUTE	NRM1	NRA4	NSM1	NSA4	NSA3	NSM2	NRA3	NRM2
30.0	12.0	47.0	81794.0	82692.0	55551.0	59332.0	54552.0	61319.0	84589.0	79845.0
30.0	12.0	48.0	82103.0	82688.0	55983.0	59354.0	54594.0	61301.0	84579.0	79841.0
30.0	12.0	50.0	82091.0	82683.0	60286.0	59349.0	54031.0	61293.0	84566.0	79834.0
30.0	12.0	52.0	82024.0	82676.0	56099.0	59345.0	54609.0	61288.0	84543.0	79826.0