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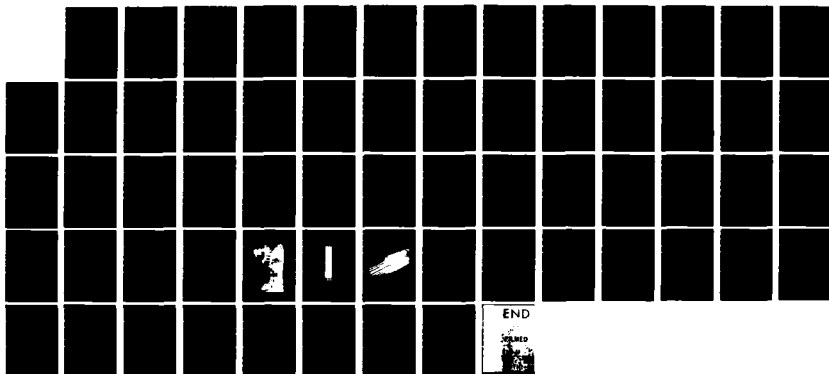
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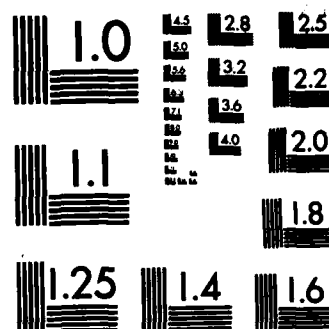
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PERFORMANCE OF A VARIABLE CONDUCTANCE
HEAT PIPE HEAT EXCHANGER

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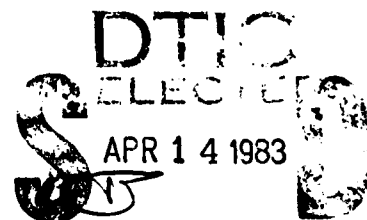
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This report has been reviewed by the EOARD Information Office and is releasable to the National Technical Information Service (NTIS). At NTIS it will be releasable to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

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1. INTRODUCTION

1.1 Background

The work begun in 1980-81 by Steve Drouilhet is currently being extended by the writer.¹ The primary objective of the work is to evaluate the performance of an air to air variable conductance heat pipe heat exchanger (VCHPHX). This type of heat exchanger is of particular interest to the commercial aircraft industry because of its unique control system. The results from this research will help to provide the engineer with experimental data necessary to design a full scale prototype heat exchanger to be tested insitu.

1.2 Scope of Work

Two heat exchangers of the type mentioned above have been supplied by the contractor. The heat exchangers are to be mounted in a test stand and instrumented for performance analysis. These tests should document not only the absolute performance in terms of effectiveness, but they should also be sufficient to evaluate the dependant variables in both a qualitative and a quantitative way. At present, little is known about the VCHPHX. Because of this, the question of why something happens often arises during the analysis. Answering this question may be the most important contribution of this work. Explanations which can be made using conventional heat pipe theory or a modified version of it will be provided with the hope of future usefulness to the engineer.

2. THE VARIABLE CONDUCTANCE HEAT EXCHANGER

The prototype heat exchanger which is the subject of this work is an air to air heat exchanger. The novelty of the design is that heat transfer is not the typical stream to stream heat transfer across a plate or a tube wall. Instead, heat is transferred to a finned evaporator and from a finned condenser via a heat pipe. A simple arrangement for this type of heat exchanger is shown in figure 1. The variable conductance heat pipe is to the condenser fins a heat source and to the evaporator fins a heat sink. Since heat transferred from the evaporator to the condenser must be conducted via the heat pipe, a variable conductance heat pipe means a variable conductance heat exchanger. This is the principal advantage of the variable conductance heat pipe heat exchanger, the ability to modulate power transfer independent of stream inlet conditions. The two types of heat exchangers may be modeled using the electrical circuit analogy as shown in figure 2. Note that for the conventional heat exchanger the various resistances are essentially fixed, preventing current (heat flow) modulation for a fixed voltage (temperature difference). However, the VCHPHX analog has one variable resistance, that of the heat pipe; consequently, power modulation is possible for a fixed voltage.

The VCHPHX relies on mainly two technologies; finned tube heat exchanger technology and variable conductance heat pipe technology. While the former is well understood and characterized from years of use, the latter is relatively new. Indeed the VCHP based on liquid reservoir temperature control is at this stage purely experimental.

While the principal objective of this work is performance evaluation, the opportunity to add to what is known about the VCHP is obvious. The data gathered for performance analysis is useful for exploring VCHP operation as will be shown later in Chapter 6.

3. EXPERIMENTAL FACILITY

3.1 The Test Stand

The prototype heat exchanger is mounted in a stand which furnishes 2 streams of air at varying temperatures and mass flow rates. Figures 3A and 3B illustrate the arrangement of the components. Power from the heated evaporator stream is transferred to the cooler condenser stream. The power transferred is variable, depending on the inlet stream conditions and the reservoir temperatures. The stream inlet conditions may be varied as follows:

Condenser

Temperature 29-35 C
Mass Flow Rate 0-.1 KG/sec

Evaporator

Temperature 45-150 C
Mass Flow Rate 0-.1 KG/sec

The reservoir temperature may be adjusted within the following range:

Reservoir

Temperature 16.7-90 C

3.2 The VCHPHX

The heat exchanger consists of 16 vertical heat pipes arranged into 4 rows of 4 heat pipes each. The condenser region and the evaporator region of the heat exchanger is fitted with aluminum fins to provide an extended surface for heat transfer. Each row of 4 heat pipes is gathered to a common liquid reservoir. There are 4 reservoirs. Each of the liquid reservoirs is fitted with a Peltier cell to either heat or cool the liquid within the reservoir. A simple aluminum channel with aluminum honeycomb within serves as either heat sink or heat source for the Peltier cells. The condenser air stream is induced through the channel. Refer to figures 4 and 5 for details.

Heat exchanger dimensions are given in Appendix B. Properties of the heat pipe working fluid are also included in this appendix.

3.3 Measurements and Consequent Instrumentation

Evaluating the performance of the heat exchanger system is a task which requires the information gained from a first law analysis of the system. The system may be divided into the following 4 subsystems:

1. Condenser
2. Evaporator
3. Reservoirs
4. Peltier Cooler

Evaluating these individual subsystem performances requires a first law energy balance for each. The measurements taken by the writer provide sufficient data to make a first law analysis of the system as a whole; direct measurement of the subsystem performances is not practical and so these performances are obtained indirectly when required.

The measurements recorded to obtain a first law analysis on the system are listed in Table 1 below. An annotated sketch of the system with state points is also provided, figure 6. It is now possible to write the first law energy balance for the entire system:

$$P_{\text{cond}} + P_{\text{evap}} + P_{\text{cooler}} + P_{\text{elect}} + P_{\text{convection}} = 0 \quad (1)$$

Note that a fifth term appears in equation (1) above which is not obtained by direct measurement.

Table 1 List of Measurements

State Point	Measurement	Transducer
1	Temperature	Single T/C
2	"	15 T/C Grid
3	"	Single T/C
4	"	15 T/C Grid
5	"	Single T/C
6	"	Single T/C
7	Pressure	Setra Tdx. (350 mm)
8	"	Setra Tdx. (350 mm)
9	Elect. Power	Voltmeter/Ampmeter

Note this term, $P_{\text{convection}}$, is the power exchange between the system and the surroundings due to convection.

In addition to the measurements listed thus far, several additional measurements were taken in order to relate the system performance to the operating conditions. These are given in table 2 below.

Table 2 Parametric Measurements

Measurement	Transducer
Reservoir Temperature	
Row 1	Single T/C
Row 2	" "
Row 3	" "
Row 4	" "
Ambient Temperature	" "

Having described the various measurements which were recorded, the instrumentation will now be detailed. Please see figures 7 and 8. The two fundamental quantities measured are temperature and pressure. The measurement chains for each are

deficted in figures 7 and 8. A typical first law analysis is made by the computer once the heat exchanger system has reached steady state. The sequence of operations, transducer scan/calculations/printout, is completed in about 90 seconds.

Appendix A contains a listing of the BASIC program which was written to accomplish the data acquisition and to perform the first law calculations. A sample printout is also included in this appendix.

4 TESTING PROCEDURE

Since the primary emphasis of this work is to evaluate heat exchanger performances, the testing program must document the behavior of the heat exchanger over a wide range of operating conditions. While one might propose a large number of tests (ie. operating conditions), it is clear that limiting cases will be of utmost importance. Once these limits are established, the work of filling in the "holes" in the data can be carried out in a logical way.

Remembering that two VCHPHX are to be tested, the difference between the two is now discussed. The first configuration is as shown thus far, with the reservoirs located at the bottom. The second configuration has reservoirs located at the top. The reason for this design variation is easily understood. Reservoirs located at the bottom are physically nearest the hot evaporator; this configuration favors the case of heated reservoirs. Reservoirs located at the top favors the case of cooled reservoirs. In each case, heat flows via conduction in the heat pipe wall to either help or to hinder the reservoir temperature control system. From this point on the writer will refer to the two configurations as the L prototype for lower reservoirs and the U prototype for upper reservoirs.

The parameters which may be varied during the tests are:

- | | | |
|----------|-------------------------------------|---------------------------|
| MR | Mass Ratio | $(\dot{m}_c / \dot{m}_e)$ |
| MRT | Mean Reservoir Temperature | (C) |
| T_{ei} | Temperature at the evaporator inlet | (C) |
| T_{ci} | Temperature at the condenser inlet | (C) |

Since documenting the limiting cases is the first goal for the performance tests, the writers' idea of a limiting case is defined:

A limiting mode of operation has been reached when the effects of the control system cease to modify the behavior of the heat exchanger.

A limiting case is thus a loss of controllability. This loss of control will be reached at either extreme of heat exchanger operation. Operating points exist at which for given air inlet conditions, a maximum power transfer is achieved and at which a minimum power transfer is achieved. The range between these two operating points constitutes the range of controllability. There is, however, a catch to this line of reasoning. Note that the limits of controllability depend on the air inlet conditions and perhaps the mass flow ratio. Bearing this in mind, a salient point comes to light. Understanding the reasons for the existence of the limits can lead to better heat exchanger design and therefore they should be evaluated. With this information the experimenter can provide the designer with an important tool, that of prediction.

Determination of the limiting cases establishes the range of testing possible. Data gathered over this interval must be sufficient to describe the response of the heat exchanger when the control parameters are varied. The following chapters will propose reasons for controllability, so at the present the writer admits only that modulation of the mentioned parameters does control power transfer within limits. In the proposed application the single control parameter will be the reservoir temperature.

Mass flow ratio and inlet temperatures will not in general be modulated.

For a given set of operating conditions,

MR set

T_{ei} set

T_{ci} set,

power transfer from the evaporator to the condenser may be modulated by varying the mean reservoir temperature. Two approaches are considered:

1. Cool or heat each reservoir equally. This amounts to providing equal power to each Peltier cell.
2. Cool or heat each reservoir independantly.

The merits of each approach have been evaluated for the L prototype.

Only the former approach has been evaluated for the U prototype.

5 TEST RESULTS

5.1 Control Via Variable Peltier Cell Power

Both the U and The L prototypes were tested using this mode of control. For a given set of stream inlet conditions, the range of controlability was determined. Operation within this band provided ample data to characterize a broad linear range of control for each of the heat exchangers.

Figures 9 and 10 depict the controlability of the L and U prototypes. The graphs were produced using the following method:

1. The heat exchanger was allowed to come to equilibrium for the given set of stream inlet conditions with no Peltier cell power (the reservoirs being well insulated from the surroundings)
2. This equilibrium, zero Peltier cell power, average reservoir temperature is plotted as a vertical line
3. The system was forced from equilibrium by providing Peltier cell power.

The abscissa can be thought of as a figure of merit. The units, degrees C per watt reflect the mean reservoir temperature change from 2) above per watt of control power. Since the power transferred from the evaporator to the condenser is a function of mean reservoir temperature, the larger the figure of merit, the better. Note the broad linear range of evaporator power versus mean reservoir temperature. This linear control range is a desirable feature from the standpoint of automated control. The condenser power curves for each heat exchanger exhibit different behaviors at the limits of controlability. The U prototype has clear asymptotic values at either extreme while the L prototype is essentially linear throughout the achievable range

of reservoir temperatures. For the Uprototype, operating points are reached after which increasing or decreasing mean reservoir temperature has no discernable effect. Clearly, limits have been reached which are unalterable by the control system. These limits must have arisen due to heat exchanger failure of some sort. The L prototype does not reach these limits for the stated operating conditions. One might argue why this occurs, but figure 11 points out an identical behavior to the U prototype at the upper limit. Note that the inlet stream conditions have been changed in order to obtain this graph. It was not possible to illustrate the lower asymptotic extreme for the L prototype, but its existence is well indicated.

5.2 Control By Selective Reservoir Heating

The U prototype heat exchanger performance was evaluated while selectively heating the reservoirs. If, for instance, reservoir 1 was heated, then reservoirs 2,3, and 4 were cooled. Peltier cell power was held constant at 12 watts total for the 4 cells. Figure 3 explains the reservoir numbering scheme while Table 3 contains the data from 9 of the possible 16 combinations.

From the data, it is clear that each of the 4 reservoirs has a unique effect on performance when heated. Heating reservoir 4 achieves the greatest evaporator power while heating reservoir 1 achieves the lowest. This can be explained by the placement of the reservoirs. Reservoir 4 communicates with the 4 heat pipes in row 4. This row of heat pipes is located at the evaporator inlet and is therefore exposed to the maximum stream temperature. Thus for a given Peltier cell power, row 4 has the potential to reach the highest temperature (the data confirms this line of reasoning).

RESERVOIRS ACTIVE 1 2 3 4	QUANTITY OF INTEREST	MASS FLOW RATE			
		1.0	0.8	0.6	0.4
	Mean Reservoir Temp	29	30	30	27
	ρ_{COND}	19	17	15	11
	ρ_{EVAP}	20	18	16	12
	ρ_{EVAP}/ρ_{COND}	859/792	786/744	682/632	431/413
		30	39	29	29
		21	19	17	14
		23	20	18	15
		979/898	880/829	712/698	590/542
		27	29	29	30
		21	20	18	14
		24	22	20	16
		996/879	934/846	785/716	611/544
		30	30	29	30
		24	21	18	14
		26	23	20	16
		1176/1048	992/874	837/725	632/553
		31	34	34	34
		23	21	20	17
		23	22	20	17
		995/971	970/938	817/827	683/656
		35	37	38	39
		27	26	23	19
		29	28	24	20
		1238/1144	1186/1097	1017/961	765/731
		35	34	34	35
		29	25	21	16
		32	28	24	19
		1393/1254	1214/1092	974/864	745/641
		32	33	34	
		25	22	20	
		26	24	21	
		1123/1046	1014/952	901/829	
		32	33	33	33
		24	22	19	15
		27	24	21	16
		1125/1026	989/916	850/775	634/580

TABLE 3 Data For Individually Heated Reservoirs

Increasing the reservoir temperature forces more working fluid to enter the heat pipe; an increase of the average thickness of the liquid profile within the wick results. Pumping losses within the liquid are reduced and more power is transferred.

Is this mode of control sufficient. The writer thinks not. While the heat exchanger does admit to control by selective reservoir heating, the discrimination is poor. Note that while the range of controllability is as good as for the alternate mode of control, the ability to provide smooth evaporator power modulation is lacking. Indeed, the maximum number of power increments is limited to 16. Were these 16 increments evenly distributed this mode of control might be feasible. Since they are not, the hope for control solely by reservoir selection is remote. This mode of control may, however, be important in order to augment the alternate mode.

5.3 Practical Considerations

The most outstanding difference between the two prototypes is the turn down ratio which the writer defines as follows:

$$\text{TDR} = \text{Max Condenser Power} / \text{Min Condenser Power} \quad (2)$$

From a practical standpoint, this quantity is very important; indeed, maximizing this ratio was the motivation behind testing both the L and the U prototypes. From figures 9 and 10, the U prototype has a TDR of about 10 while the L prototype has a TDR of about 3.

A second practical consideration is identified by the following ratio:

$$\text{CPR} = \text{Condenser Power} / \text{Peltier Cell Power} \quad (3)$$

This control power ratio (CPR) relates the "cost of control". Clearly, one would like to effect control with the smallest

possible control power. That is to say that the CPR should be maximized. Since the condenser power is controlled largely by the mean reservoir temperature, the plot of reservoir temperature versus Peltier cell power indicates the ease of control (see figures 12 and 13). Ideally both prototypes should have equal condenser powers for equal mean reservoir temperatures at a given set of operating conditions. This is not true in the present case; the reasons for this may include different quantities of working fluid in the pipes. Reference to figure 14 allows one to evaluate the cost of control for each of the prototypes. Noting the heated reservoir case, the CPR is noticeably better for the upper reservoir configuration. Indeed, the U prototype minimum condenser power is the equilibrium temperature; hence no U prototype curve is plotted for the case of cooled reservoirs. This point is a valuable one to note since a simplification of the control system results.

5.4 Transient Response

The transient response of both prototypes was evaluated by making a step change in Peltier power and then recording the following variables versus time:

1. Mean reservoir temperature
2. Evaporator power
3. Evaporator effectiveness.

This data is presented on figures 17,18, and 19. Noting figures 17 and 18, it is clear that the response of the U prototype is superior to the response of the L prototype. The explanation for this seems to be simply the details of each liquid reservoir

design (see figure 20). Transfer of heat with the reservoir is across the two resistances shown. In the case of the U prototype $R_{c \text{ fluid}}$ is smaller than for the L prototype. This is because the thickness of the fluid layer is less for the U prototype than for the L prototype. The end result is that reservoir temperature can be changed more quickly for the U prototype than for the L prototype (note that swings in evaporator power and evaporator effectiveness "follow" swings in the mean reservoir temperature).

6 ANALYSIS OF TEST RESULTS

6.1 Objectives of Analysis

The objective of this section is to attempt to answer the following question:

Why does the VCHPHX admit to control via varying the liquid reservoir temperature?

There is no apriori reason for this experimentally observed fact. Indeed, when one considers the governing equation for power transfer in conventional heat pipes,²

$$\dot{Q}_{max} = \frac{K A L}{\mu_l} \cdot \frac{1}{l_{eff}} \cdot \left\{ \frac{2 \sigma \cos \theta}{r_c} + \rho_l g l_{eff} \sin \phi \right\} \quad (4)$$

it can be shown that $\dot{Q}_{max}$ decreases with increasing temperature of the heat pipe working fluid. At this point it becomes obvious that special circumstances must account for what the experimenter observes.

6.2 Heat Pipe Theory

Heat pipe operation depends on the flow of working fluid within a capillary structure to the evaporator and a subsequent return of the vapor to the condenser. The equation given above is derived from the following pressure balance:

$$\begin{aligned} \text{Net Capillary Head} = & \text{Liquid Pressure Drop} \\ & + \text{Vapour Pressure Drop} \\ & + \text{Body Force Head} \end{aligned} \quad (5)$$

The vapor pressure drop is usually negligible and the equation becomes:

$$\begin{aligned} \text{Net Capillary Head} = & \text{Liquid Pressure Drop} \\ & + \text{Body Force Head} \end{aligned} \quad (6)$$

The capillary head is generated by the wick through which the liquid flows. It is a surface tension effect and for single layer screen mesh wicks is equal to:

$$\Delta P_{\text{capillary max}} = \frac{2 \gamma \cos \theta}{r_c} \quad (7)$$

The liquid pressure drop in the wick is given by Darcy's Law, essentially a definition for porosity, K:

$$\frac{dP_l}{dz} = \frac{\mu_l \dot{m}_l z}{K A l_l} \quad (8)$$

The body force head is given by:

$$\frac{dP_{\text{body}}}{dz} = \pm l_l g \sin \phi \quad (9)$$

From equations 7, 8, and 9 we can begin to examine the question posed in the light of conventional heat pipe theory.

6.3 The Linear Range of Control

The data presented in Chapter 5 showed that a large linear range of control existed for the VCHPHX. How can this be explained in the light of the governing equations? If one assumes a saturated wick, this fact cannot be explained by the theory. Therefore, the wick must not be saturated. There are several liquid profile models which one might propose.

These include:

- a) Reeceded linear liquid profile within the wick
- b) Reeceded sloped liquid profile within the wick
- c) The step wick model⁴
- d) Reeceded curved liquid profile within the wick

Any one of these possibilities could explain the behavior which is observed. The net effect of any of these mechanisms for liquid profile variation would be to reduce the effective cross sectional area of the wick. Equation (8) shows that dP of the liquid increases with decreasing A_{eff} . For fixed $dP_{capillary}$ and dP_{body} , this means that m must decrease and hence Q must decrease.

6.4 The Question of Limits

The asymptotes which are observed on the plot of condenser power versus mean reservoir temperature are not so easily explained in terms of the conventional heat pipe equations. Let us consider first the asymptote at the upper limit. A maximum condenser power is reached after which elevating the reservoir temperature serves no purpose. If the previous mode of control relied on variation of the wick thickness, it is clear that a maximum wick thickness must be reached at some point. This limit to wick thickness may result from one of the following conditions:

- a) The wick is fully saturated
- b) All the liquid in the reservoir has been expended.

Either of these conditions could explain the upper limit on condenser power transfer. Based on the expected overflow of the reservoirs, the former condition seems most likely.

The lower condenser power asymptote must result from a heat pipe wick which is starved for liquid. An important question to answer here is the following:

Does dryout occur along any portion of the evaporator? A quantitative answer to this question can be seen on figure 15. The temperature profile of the air leaving the evaporator is a good indication of the onset of evaporator dryout. Note that the reduced temperature profile is plotted versus percent evaporator length. As the reservoir temperature is reduced, the curve indicates a reduced temperature profile which "climbs" the evaporator wall toward the condenser. Since a reduced temperature of unity indicates no heat transfer from the heat pipe in that region, it seems safe to assume that the evaporator has dried out in this region. This mode of heat pipe failure has also been observed by Chun⁵. Granted now that partial dryout of the evaporator has occurred, does this explain the much reduced condenser power? Not to be overlooked is the effect of dryout on the heat exchanger fin performance. As the liquid layer in the evaporator dries out, the ability of a "dry fin" to transport heat is much reduced. This is because heat which was transported by the condensing vapor must now be transported by the heat pipe wall, a path of much greater resistance. Consider the case of the heat pipe wick and liquid as shown in figure 16. The liquid layer has dropped below the first fin. The evaporator's first fin is no longer "wet". Current flow in loop A is thus mainly via conduction along the heat pipe wall; through resistance $R_{c,current}$ i2.

The liquid layer has not dried out at the second evaporator fin. Therefore, heat transfer along this path is mainly through resistor R_{HP} , current i3. R_{HP} is a film and conduction resistance combined; convection to the surface of the liquid layer and conduction across the liquid thickness. Heat transfer along the former path is much less than heat transfer along the alternate path due to R_{HP} being much less than R_C . This mode of power transfer modulation wet fin / dry fin, seems to play a major role in VCHPHX control.

Figure 15 also indicates another mode of control in operation. Note that once the entire evaporator wall is wetted, the liquid profile seems to thicken in an effort to saturate the wick. About 60% of the heat exchangers maximum power transfer is realized once the wick is saturated. How can the proposed model account for the last 40%? If the various resistances R_{HP} are independant variable resistors, then the proposed model can accomodate this experimental observation. R_{HP} would ideally be a function of only the liquid layer thickness at the fin in question.

7 CONCLUSIONS

The VCHPHX is clearly a viable approach to the problem of power transfer modulation in an air to air heat exchanger. The controlability which results from the use of temperature controlled liquid reservoirs is good when the U-prototype is considered. A further strong point of the U prototype is its ability to traverse the entire range of controlability without the need for reservoir cooling. The broad linear control range is ideal for automated control.

The question of the VCHPHX admission to control by variable reservoir temperature is largely answered. The 2 major modes of heat pipe-exchanger failure which are in operation seem to be:

- a) wet fin / dry fin
- b) Liquid layer recession

The incorporation of these failure modes into a heat pipe simulation presumes an ability to predict the liquid profile which results from a given set of heat pipe operating conditions. This prediction is the frontier of heat pipe research^{4,5} and is the key to analytical design of the VCHPHX.

8 DEFINITION OF VARIABLES

A	Area (m^2)
C	Centigrade
K	Porosity
L	Latent Heat (Joules/Kilogram)
P	Power (Watts)
Q	Heat Rate (Watts)
R	Resistance (m^2 C/Watt)
T	Temperature (C)
r_c	Capillary Radius (m)
g	Gravity (m/sec^2)
h	Heat Transfer Coefficient ($Watts/m^2$ C)
l_{eff}	Effective Length (m)
m	Mass Flow Rate (Kilograms/sec)
z	Coordinate Length (m)
ϕ	Angle of Heat Pipe With Horizontal (degrees)
θ	Contact Angle of Working Fluid (degrees)
ρ	Density (Kilograms/ m^3)
σ	Surface Tension (Nt/m)
μ	Viscosity (poise)

Subscripts

c	Condenser
e	Evaporator
l	Liquid
v	Vapour

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2. Cotter, T.P. "Theory of Heat Pipes", LA3264 MS, Los Alamos Laboratories, Los Alamos, N. Mexico, March 1965.
3. "Boiling and Evaporation From Heat Pipe Wicks With Water and Acetone", A Abhat, R.A. Seban. ASME Transactions August 1974.
4. "Some Experiments on Screen Wick Dry Out Limits", K.R. Chun ASME Transactions, February 1972.

APPENDIX A - COMPUTER PROGRAM LISTING FOR DATA ACQUISITION

```

0000 DIM E(15),C(15)
0005 S=-2.224E-5
0010 Q1=41
0015 Q2=42
0020 REM GRID TEMP OUTPUT MODES
0025 GOTO A(43)
0030 DIM A(15)
0035 PRINT "REFERENCE TEMPERATURE"
0040 INPUT T1
0045 PRINT "PELIER POWER"
0050 INPUT P1
0055 T2=0
0060 T3=0
0065 POKE(45059,40): # OF RELAYS
0070 POKE(45061,4): # OF CHANNELS
0075 POKE(45058,1): # OF LOOPS
0080 POKE(41049,6)
0085 POKE(73,97): HIGH BYTE OF ASLGP ADDRESS
0090 POKE(74,213): LOW BYTE OF ASLGP ADDRESS
0095 S0=USER(S0)
0100 REM INITIATE SCAN
0105 POKE(73,98)
0110 POKE(74,66)
0115 S1=USER(S1)
0120 REF ADJUST LAST THREE VALUES
0125 X1=PEEK(45071)
0130 X2=PEEK(45072)
0135 A=((X1*256)+X2)-6
0140 FOR I=1 TO 3
0145 X1=PEEK(A)
0150 X2=PEEK(A+1)
0155 V=((X1*256)+X2)/40
0160 GOSUB 1000
0165 NEXT I
0170 REM PRINT OUT DATA
0175 FOR I=1 TO 43
0180 J=I-1
0185 K=2*J
0190 A=46064+K
0195 X1=PEEK(A)
0200 X2=PEEK(A+1)
0205 V=((X1*256)+X2)
0210 A(I)=V
0215 NEXT I
0220 A(41)=(A(41)-01)*.7335
0225 A(42)=(A(42)-02)*.1244E
0230 PRINT A(41),A(42)
0235 GOTO 1070
0240 REM SUBROUTINE 1000
1000 V1=V/32
1005 V2=INT(V1)
1010 Q=V1-V2
1015 POKE(A+V1)
1020 POKE(A+1,V)
1025 A=A+1
1030 RETURN
0245 PRINT "END OF DATA"
0250 GOTO 1070
0255 PRINT "END OF DATA"

```

```

1086 A(I)=X/100
1088 NEXT I
1089 FOR I=1 TO 7
1090 K=I+1
1092 L=I+9
1094 C(I)=A(L)
1096 T3=T3+C(I)
1100 E(I)=A(K)
1102 T2=T2+E(I)
1110 NEXT I
1120 FOR X=8 TO 15
1130 K=I+17
1140 E(I)=A(K)
1142 T2=T2+E(I)
1144 L=I+25
1146 C(I)=A(L)
1148 T3=T3+C(I)
1150 NEXT I
1151 GOSUB 1300
1152 PRINT
1153 PRINT
1154 PRINT "          EVAPORATOR TEMPERATURE MAP"
1155 PRINT "          DEGREES CENTIGRADE"
1157 PRINT
1159 FOR I=1 TO 5
1170 K=16-3*I
1180 PRINT E(K),E(K+1),E(K+2)
1182 NEXT I
1184 PRINT
1187 T2=T2/15
1188 T2=T2*100
1190 T2=INT(T2)
1192 T2=T2/100
1193 PRINT "TEIN= "; A(19)
1194 PRINT "TAVE="; T2
1195 D1=(356/(273.2+A(20)))
1196 D2=(350/(273.2+A(17)))
1197 C9=.005667*SQR(A(41)/D1)+.005
1198 E9=.009678*SQR(A(42)/D2)+.008
1200 E1=E9*1000*(A(19)-T2)
1201 IF C9>E9 GOTO 1204
1202 Z9=E9
1203 GOTO 1205
1204 Z9=C9
1205 Q=Z9*1000*(A(19)-A(20))
1207 E6=(E1/Q)*100
1210 C1=C9*1000*(A(20)-T3)
1211 C6=-(C1/Q)*100
1220 P1=C9*1000*(A(17)-A(18))
1221 C6=C6*100
1222 E6=E6*100
1223 C6=INT(C6)
1224 E6=INT(E6)
1225 C6=C6/100
1226 E6=E6/100
1240 L1=E1+C1+P1+E1
1241 L1=L1
1242 GOTO 1407
1243 A(20)=
1244 A(19)=
1245 PRINT "          Q=1.000000E+000"
1246 PRINT "          Q=1.000000E+000"
1247 PRINT
1248 PRINT
1249 PRINT
1250 PRINT

```

```
1460 NEXT I
1472 TS=T3/15
1474 TS=T3*100
1476 TS=INT(TS)
1478 TS=T3/100
1480 PRINT
1483 PRINT "TCIN= " ; A(20)
1484 PRINT "TCAVE= " ; TS
1486 RETURN
1497 PRINT
1498 PRINT
1520 PRINT "      RESERVOIR TEMPERATURES"
1540 PRINT "      DEGREES CENTIGRADE"
1560 PRINT
1570 M2=A(21)+A(22)+A(23)+A(24)
1571 M2=M2/4
1580 PRINT "ROW1 " ; A(21)
1600 PRINT "ROW2 " ; A(23)
1620 PRINT "ROW3 " ; A(22)
1640 PRINT "ROW4 " ; A(24)
1660 PRINT
1662 PRINT "MEAN " ; M2
1660 PRINT
1662 PRINT
1666 PRINT "      PELTIER COOLER TEMPERATURES"
1668 PRINT "      DEGREES CENTIGRADE"
1670 PRINT
1672 PRINT "INLET TEMP= " ; A(17)
1674 PRINT "EXIT TEMP= " ; A(18)
1680 PRINT
1689 PRINT C9/E9
1690 R7=C9/E9
1692 PRINT "MASS FLOW RATIO" ; R7
1694 L7=(T2-M2)/(P1+R1)
1695 L7=L7*(-1)
1696 PRINT "LOSS COEFFICIENT" ; L7
1700 PRINT
1720 PRINT "      FIRST LAW ANALYSIS"
1730 PRINT "      POWER IN WATTS"
1740 PRINT
1760 PRINT "CONDENSER POWER " ; C1
1780 PRINT "EVAPORATOR POWER " ; E1
1800 PRINT "PELT COOLER POWER " ; P1
1810 PRINT "PELT CELL POWER " ; R1
1820 PRINT "TRANSFER WITH AMS " ; L1
1840 PRINT
1860 PRINT
1880 PRINT "      HEAT EXCHANGER EFFECTIVENESS"
1890 PRINT "      PERCENT"
1900 PRINT
1920 PRINT "CONDENSER EFFECTIVENESS " ; C6
1940 PRINT "EVAPORATOR EFFECTIVENESS " ; E6
1960 PRINT
1961 GOTO 18
1980 END
```

READY

APPENDIX B - WORKING FLUID PROPERTIES

Property Data For Methyl Chloride

C	Liquid Density (K/m ³)	Vapour Density (K/m ³)
1	957.883868	6.3568821
2	955.787546	6.6371848
3	953.712342	6.9075327
4	951.656365	7.1690384
5	949.618525	7.4224625
6	947.597731	7.6686936
7	945.592893	7.9085883
8	943.602918	8.1438112
9	941.626718	8.3728269
10	939.6632	8.5989
11	937.711275	8.8228951
12	935.76985	9.0432768
13	933.837836	9.2633897
14	931.914141	9.48385841
15	929.997675	9.7033875
16	928.087347	9.92516161
17	926.182867	10.1492453
18	924.286742	10.3765032
19	922.382284	10.6077999
20	920.4856	10.844
21	918.5896	11.0853681
22	916.693194	11.3345688
23	914.795289	11.5906667
24	912.894797	11.8551264
25	910.990625	12.1288125
26	909.081683	12.4125896
27	907.166881	12.7073223
28	905.245127	13.0138752
29	903.31533	13.3331129
30	901.3764	13.6659
31	899.427246	14.0131011
32	897.466778	14.3753888
33	895.493983	14.7542037
34	893.507533	15.1498344
35	891.506575	15.5633375
36	889.489939	15.9955776
37	887.456535	16.4474193
38	885.405271	16.9197272
39	883.335056	17.4133659
40	881.2448	17.9292
41	879.133412	18.4685941
42	876.999882	19.0339128
43	874.842878	19.6185207
44	872.661549	20.2217824
45	870.454725	20.8715625
46	868.221315	21.5387216
47	865.960229	22.2241383
48	863.678375	22.9288332
49	861.369882	23.7131889
50	859	24.4965
51	856.617298	25.3155471
52	854.201466	26.1851848
53	851.751411	27.0989172

56	844.185011	29.9066336
57	841.587163	30.9320733
58	838.949633	31.9952712
59	836.271348	33.0970919
60	833.5512	34.2384
61	830.788104	35.4200602
62	827.98097	36.6429369
63	825.128705	37.9078948
64	822.230221	39.2157984
65	819.284425	40.5675126
66	816.290227	41.9639017
67	813.246537	43.4058304
68	810.152263	44.8941633
69	807.006314	46.4297649
70	803.8076	48.0135001
71	800.55503	49.6462332
72	797.247514	51.3288289
73	793.88396	53.0621518
74	790.463277	54.8470665
75	786.984375	56.6844376
76	783.446163	58.5751297
77	779.847551	60.5200074
78	776.187446	62.5199353
79	772.46476	64.575778
80	768.6784	66.6384001
81	764.827276	68.8586662
82	760.910298	71.0874409
83	756.926373	73.3755869
84	752.874413	75.7239746
85	748.753325	78.1334626
86	744.562019	80.6049173
87	740.299404	83.1392045
88	735.96439	85.7371874
89	731.555886	88.399731
90	727.0728	91.1277002
91	722.514042	93.9219593
92	717.878522	96.7833373
93	713.165148	99.7128059
94	708.372829	102.711123
95	703.500475	105.779188
96	698.546395	108.917866
97	693.511299	112.128021
98	688.392295	115.410519
99	683.198392	118.766224
100	677.9	122.196

stabilité

Le chlorométhane, stable à température ordinaire et en absence d'humidité, se décompose à des températures supérieures à 400°C avec émission de produits toxiques: chlorure d'hydrogène, chlore, et dans certaines conditions, oxyde de carbone et phosgène.

inflammabilité [9]

- Dans l'air:
- Limites d'inflammabilité à 20°C, 1 atm
inférieure: 8,1%
supérieure: 17,2%
 - Température minimale d'auto-inflammation à 1 atm: 632°C

propriétés biologiques [6, 7, 8, 9]

Le chlorométhane est un gaz toxique, narcotique, qui pénètre dans l'organisme par les voies respiratoires.

Le degré d'intoxication est variable et les principaux symptômes sont:

- pour les intoxications légères, état d'ébriété avec céphalées, vertiges, nausées ou vomissements, hoquets.
- pour les intoxications plus graves, troubles fonctionnels et certains cas, une perte de connaissance transitoire, puis des manifestations neurologiques cérébelleuses et stress.
- pour les intoxications sévères, des douleurs abdominales violentes avec vomissements, diarrhées, démarche chancelante, tremblements, nervosité extrême, confusion mentale précédant un coma parfois fébrile ou convulsif.

On a également noté des troubles rénaux et des hépatites toxiques.

Un absorption rétablissement de ce qui semble être une intoxication respiratoire anodine peut être suivie d'effets tardifs sérieux et prolongés après un délai de quelques jours à quelques semaines. Les séquelles neurologiques sont lourdes. Une attention se peut subsister au cours de la convalescence.

La concentration maximale admissible recommandée pour le chlorométhane dans les atmosphères des locaux industriels permettant des expositions de 8 heures par jour pendant 5 jours par semaine sans effets décelables pour la plupart des individus est de:

100 ppm-vol ou 210 mg m⁻³

Des expositions répétées sont dangereuses car le chlorométhane s'accumule lentement dans le corps, dans lequel il se transforme en acide chlorhydrique et alcool méthylique.

Le contact avec la peau et les yeux, de vapeurs concentrées de chlorométhane liquide, provoque des gelures, la formation d'ampoules et, éventuellement, de la gangrène.

stabilité

Méthyl chloride is stable at room temperature in the absence of moisture, but decomposes at temperatures above 400°C, generating toxic hydrogen chloride, chlorine and, in certain cases, carbon monoxide and phosgene.

flammability [9]

- In air:
- Flammability limits at 20°C, 1 atm
lower: 8,1%
upper: 17,2%
 - Minimum autoignition temperature at 1 atm: 632°C

biological properties [6-7-8-9]

Methyl chloride is a toxic, narcotic gas, which penetrates the organism through the respiratory system.

The degree of intoxication varies and the main symptoms are the following:

- For slight poisoning: state of drunkenness with headaches, vertigo, nausea, vomiting and hiccups.
- For more serious poisoning: mental confusion and, in some cases, temporary loss of consciousness, followed by cerebellar and striated neurological symptoms.
- For severe intoxication: violent abdominal pains with vomiting, diarrhea, staggering, trembling, extreme nervousness, mental confusion, followed by a coma sometimes accompanied by fever, convulsions and death.

Toxic kidney and liver affections have also been observed. Apparent recovery from what appears to be a harmless respiratory intoxication may be followed by serious, prolonged, delayed effects after a period lasting from a few days to a few weeks. The neurological consequences are very serious.

The following threshold limit value is recommended for methyl chloride, as the concentration in air to which nearly all workers may be exposed during an 8-hour workday and 40-hour workweek, without adverse effects:

recommandations

Veillez à ce que des sujets présentant des affections nerveuses et hépatorénales ne puissent être en contact de chlorométhane.

traitement des intoxications accidentelles

En cas d'intoxication, prévenir le service médical, retirer la victime de la zone polluée. Mettre en oeuvre si nécessaire les méthodes de réanimation.

précautions pour le stockage et la manipulation

ATTENTION: LE CHLOROMÉTHANE EST UN GAZ TOXIQUE, INFLAMMABLE, PLUS LOURD QUE L'AIR. NE JAMAIS UTILISER DE CHLOROMÉTHANE SANS AVOIR CONSULTÉ LE CHAPITRE III.

détection des fuites - analyse

Le chlorométhane est incolore et a une odeur éthérée. Avant utilisation d'un appareillage devant contenir du chlorométhane, tester le montage avec un détecteur de fuite.

On peut déceler les fuites:

- par formation de bulles avec un agent tensio-actif
- en injectant ce gaz dans une flamme en présence de cuivre; on obtient une coloration verte (lampe halogène).
- à l'aide d'un détecteur spécifique de gaz inflammable basé sur la mesure de la variation de résistance d'un fil de platine allié avec du palladium qui oxyde catalytiquement le chlorométhane.

Les atmosphères contenant du chlorométhane peuvent être dosées par:

- passage de l'air à analyser préalablement saturé de vapeur d'eau, dans un tube de silice porté au rouge. L'acide chlorhydrique libéré est ensuite dosé par absorption dans une solution de nitrate d'argent.
- adsorption des vapeurs sur du charbon actif ou du gel de silice et dosage par gravimétrie.
- combustion dans un microburner et dosage par titrimétrie ou conductimétrie.
- Les méthodes industrielles d'analyse sont les suivantes: chromatographie en phase gazeuse (en particulier avec détecteur à capture d'électrons)
- spectrométrie de masse
- spectrométrie d'absorption infra-rouge
- spectrométrie d'émission de plasma

compatibilité avec les matériaux

[9 10 11 12-15]

Le chlorométhane s'hydrolyse dans l'eau pour donner, sous l'action de la chaleur, de l'acide chlorhydrique et de l'alcool méthylique.

Par conséquent, toute installation devant contenir du chlorométhane, doit subir simultanément:

- un étuvage aux environs de 120°C pendant au moins 30 minutes.
- un pompage sous vide ($p \leq 10^{-2}$ mm Hg) plutôt qu'un balayage de gaz sec.

recommandations

Make sure that persons affected by nervous and kidney liver problems refrain from contact with methyl chloride.

first aid suggestions

In case of intoxication, summon medical aid immediately, and remove the victim from the contaminated zone. If necessary, practice resuscitation.

precautions in handling and storage

CAUTION: METHYL CHLORIDE IS A TOXIC, FLAMMABLE GAS WHICH IS HEAVIER THAN AIR. NEVER USE IT WITHOUT REFERRING TO CHAPTER III.

leak detection and analysis

Methyl chloride is colorless and has an odor of ether. Before using equipment containing methyl chloride test the assembly with a leak detector.

Leaks may be detected:

- by the application of a surface active substance at suspected points.
- by injecting the gas into a flame in the presence of copper, giving a green color (halide lamp)
- by means of a detection instrument for flammable gases, based on the measurement of variations in resistance of a platinum palladium alloy wire, which acts as a catalyst to oxidize the methyl chloride.

Atmospheres containing methyl chloride may be analyzed by the following means:

- Introduction of the air to be analyzed, previously saturated with moisture, into a silica tube heated to redness. The hydrochloric acid liberated is determined by absorption in a silver nitrate solution.
- adsorption of gases on activated charcoal or silica gel followed by gravimetric analysis.
- combustion in a microburner followed by titrimetric or conductimetric analysis.
- The following industrial analytical methods are used: gas phase chromatography (especially with an electron capture detector)
- mass spectrometry
- plasma emission spectrometry

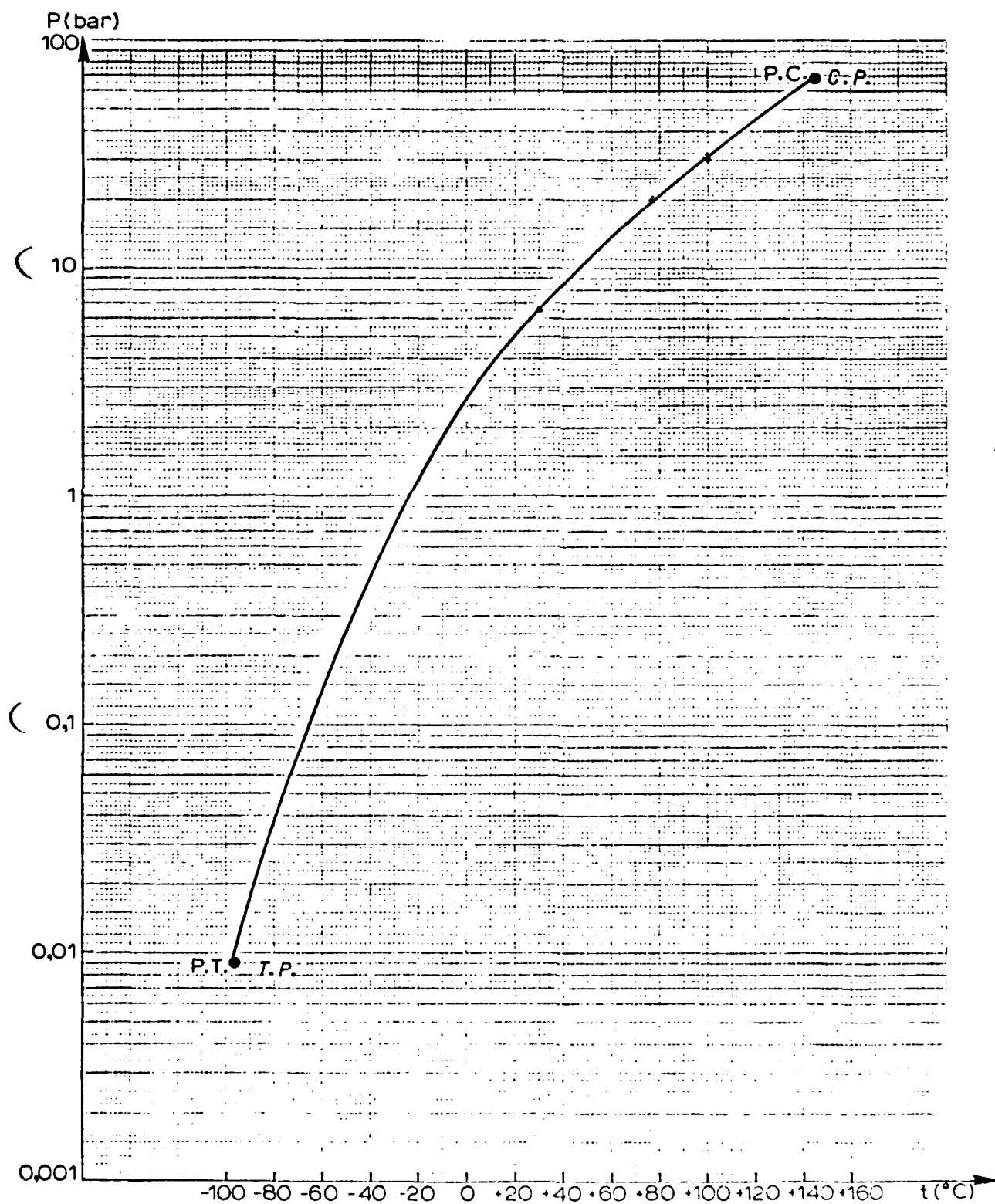
material of construction [9 10 11 12-15]

Methyl chloride is hydrolysed in water and under the action of heat, to form hydrochloric acid and methyl alcohol. Any installation designed to contain methyl chloride must be subjected simultaneously to the following:

- Stoving at about 120°C for at least 30 minutes
- Vacuum pumping ($p \leq 10^{-2}$ mm Hg) in preference to dry gas flushing.

pression de vapeur saturante [1]

vapor pressure [1]





facteur de compressibilité [2-3]

compressibility factor [2-3]

t(°C)	P(bar)	1	2	3	4	5	7	8	9	6
15		0,9858	0,9711	0,9560	0,9270					
50		0,9840	0,9726	0,9590	0,9450	0,9308	0,9030	0,8872	0,8712	

chaleur spécifique [4]

$c_p = 0,193 \text{ kcal.kg}^{-1} \cdot \text{K}^{-1}$ pour le gaz parfait à 25°C

heat capacity [4]

$c_p = 0,193 \text{ kcal.kg}^{-1} \cdot \text{K}^{-1}$ for the perfect gas at 25°C

viscosité

(1 atm)

(multiplier ces valeurs par 10^{-5} pour obtenir des poises)

viscosity

(1 atm)

(multiply these values by 10^{-5} to obtain poises)

Température (°C)	Viscosité (*)
Temperature	Viscosity
0	9,89
15	10,44
50	11,73
100	13,55

$$\mu_{\text{eau}} = 10^{-5} (T + 9,89)$$

(*) calcul L'AIR LIQUIDE

(*) L'AIR LIQUIDE calculation

conductivité thermique

(1 atm)

(multiplier ces valeurs par 10^{-5} pour obtenir des $\text{cal.cm}^{-1} \cdot \text{s}^{-1} \cdot \text{K}^{-1}$)

thermal conductivity

(1 atm)

(multiply these values by 10^{-5} to obtain $\text{cal.cm}^{-1} \cdot \text{s}^{-1} \cdot \text{K}^{-1}$)

Température (°C)	Conductivité (*)
Temperature	Conductivity
0	2,51
15	2,71
50	3,19
100	3,97

(*) calcul L'AIR LIQUIDE

(*) L'AIR LIQUIDE calculation

tension superficielle [13]

(interface liquide-vapeur)

$\gamma = 16,2 \text{ dynes.cm}^{-1}$ à 20°C

surface tension [13]

(liquid-gas interface)

$\gamma = 16,2 \text{ dynes.cm}^{-1}$ at 20°C

indice de réfraction [13]

(raie D du sodium)

$n = 1,3389$ pour le liquide à 20°C, $P \sim P_{\text{sat}}$

refractive index [13]

(sodium D line)

$n = 1,3389$ for the liquid at 20°C, $P \sim P_{\text{sat}}$

solubilité [13-14-16]

• Dans l'eau:

coefficient de Bunsen = 3,17 à 15°C

• Autres solvants:

Le chlorométhane est soluble dans l'alcool, l'éther, le chloroforme, l'acide acétique, l'acétone et le benzène.

solubility [13-14-16]

• In water:

Bunsen coefficient = 3,17 at 15°C

• Other solvents:

Methyl chloride is soluble in alcohol, ether, chloroform, acetic acid, acetone and benzene.

monochloromethane
 CH_3Cl

methyl chloride
 CH_3Cl



Freon 40

Le monochlorométhane ou chlorure de méthyle ou chlorométhane est un gaz dans les conditions ordinaires (15°C, 760 mm Hg).

C'est un gaz incolore, toxique et modérément inflammable. Il est livré liquéfié sous sa propre pression de vapeur. Les marques commerciales portent la référence R40.

propriétés physiques

Formule chimique: CH_3Cl

Masse molaire: 50,488 g.mole⁻¹

point triple [1]

Température (K) (°C)	Pression (bar)	Chaleur latente de fusion (kcal.kg ⁻¹)
Temperature Temperature	Pressure Pressure	Latent heat of fusion Latent heat of fusion
175,44 -97,71	0,0087	30,44

point d'ébullition [1]
(1 atm)

Methyl chloride, also known as chloromethane, is a gas in normal atmospheric conditions (15°C and 760 mm Hg). It is a colorless, toxic, slightly flammable gas. It is shipped as a liquefied gas under its own vapor pressure.

Commercial brands carry the designation R40.

physical properties

Formula: CH_3Cl

Molecular weight: 50,488 g.mole⁻¹

triple point [1]

Température (K) (°C)	Chaleur latente (kcal.kg ⁻¹)	Masse volumique liquide (kg.m ⁻³)	Masse volumique vapeur (kg.m ⁻³)
Temperature Temperature	Latent heat Latent heat	Liquid density Liquid density	Gas density Gas density
249,39 -23,76	102,3	1002,9	2,55

1 litre de liquide libère 469 litres de gaz (détendu à 15°C, 1 bar)

1 liter of liquid liberates 469 liters of gas (expanded to 15°C, 1 bar)

point critique [1]

critical point [1]

Température (K) (°C)	Pression (bar)	Masse volumique (kg.m ⁻³)
Temperature Temperature	Pressure Pressure	Density Density
416,25 143,1	66,8	353

masse volumique [1]

density [1]

Température (°C)	Pression (bar)	Liquide (kg.m ⁻³)	Vapeur (kg.m ⁻³)
Temperature Temperature	Pressure Pressure	Liquid Liquid	Gas Gas
0 (*)	2,56	960	6,066
15 (*)	4,20	930	9,704
50 (*)	10,92	859	24,51

(*) équilibre liquide-vapeur

(*) liquid-gas equilibrium

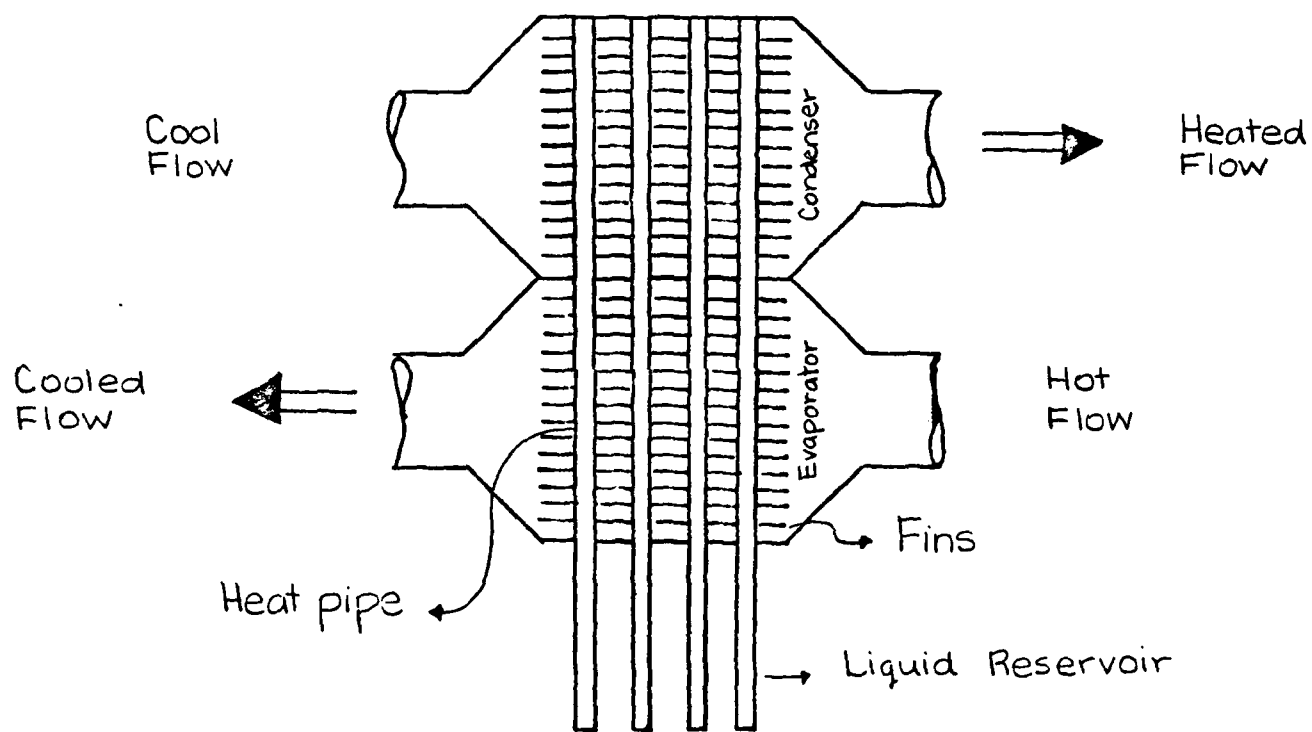


Figure 1 Variable Conductance Heat Pipe Heat Exchanger

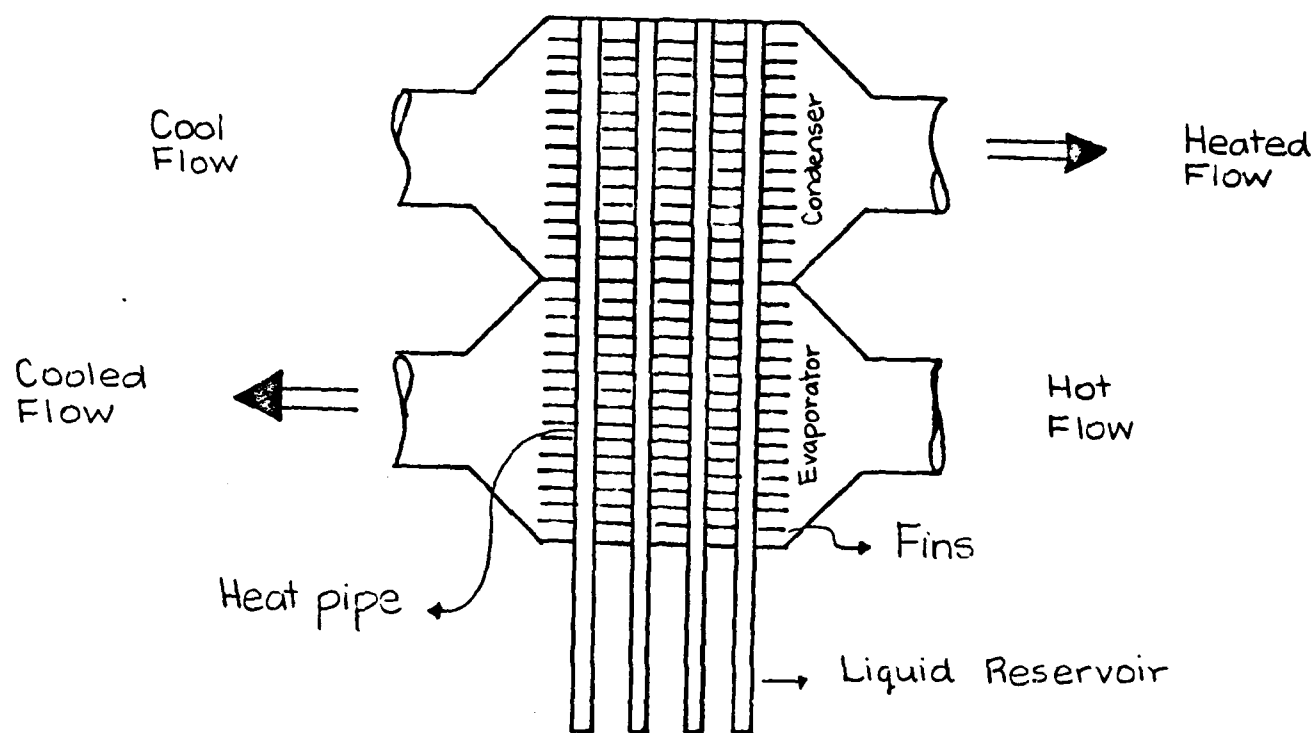
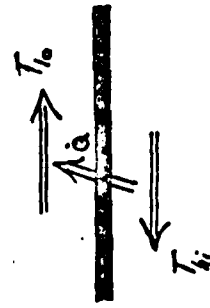
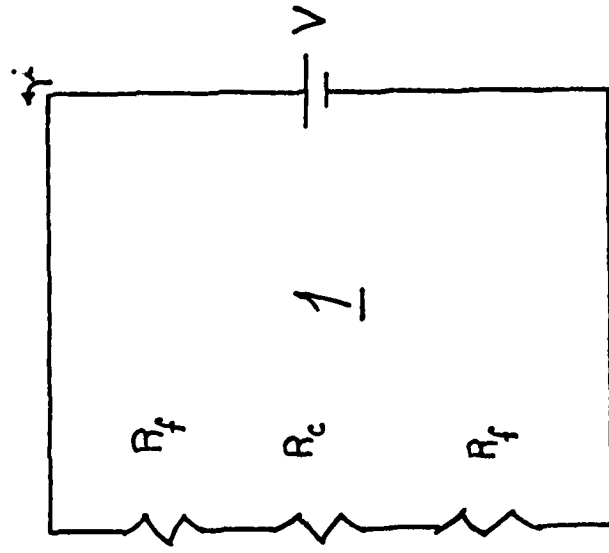


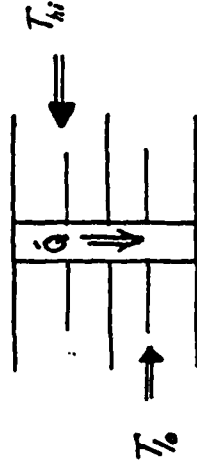
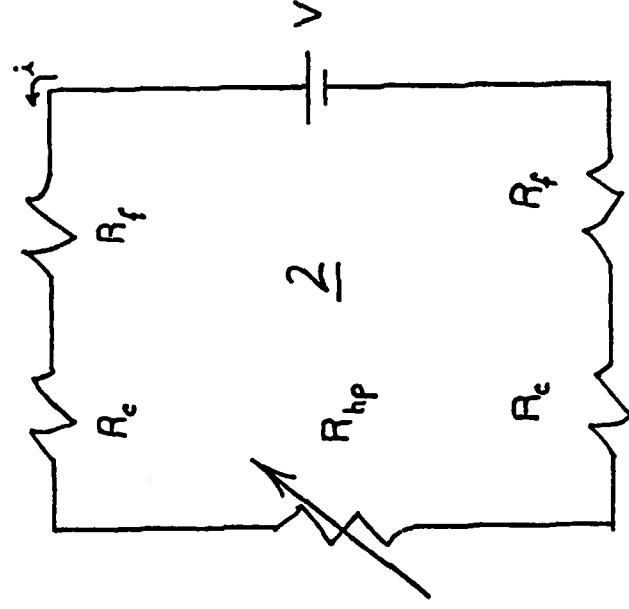
Figure 1 Variable Conductance Heat Pipe Heat Exchanger

Conventional
Heat Exchanger



$$\dot{Q} = k A \Delta T$$

Heat Pipe
Heat Exchanger



$$i = V/R$$

Figure 2 Electrical Circuit Equivalents Compared

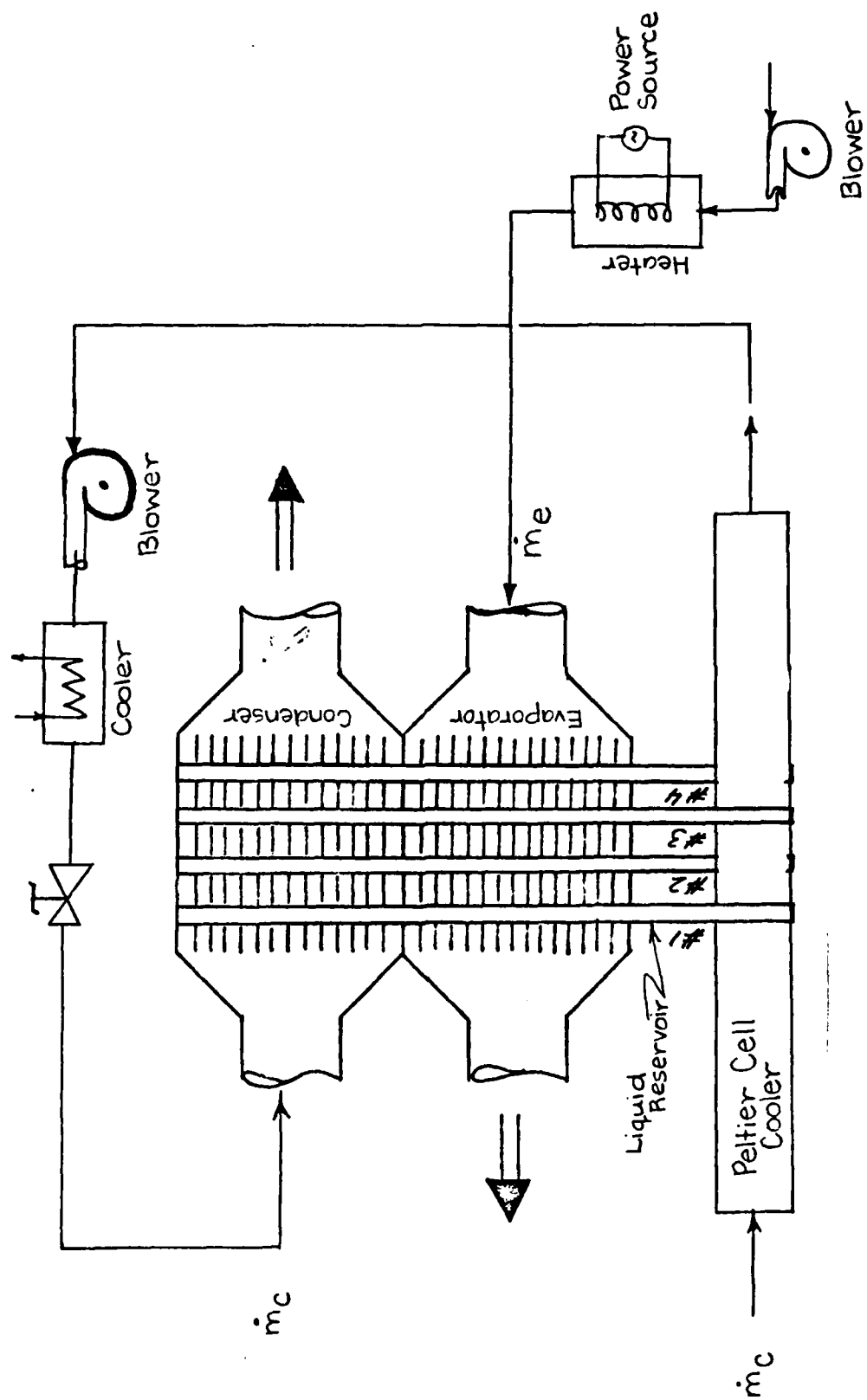


Figure 3A Arrangement of System Components

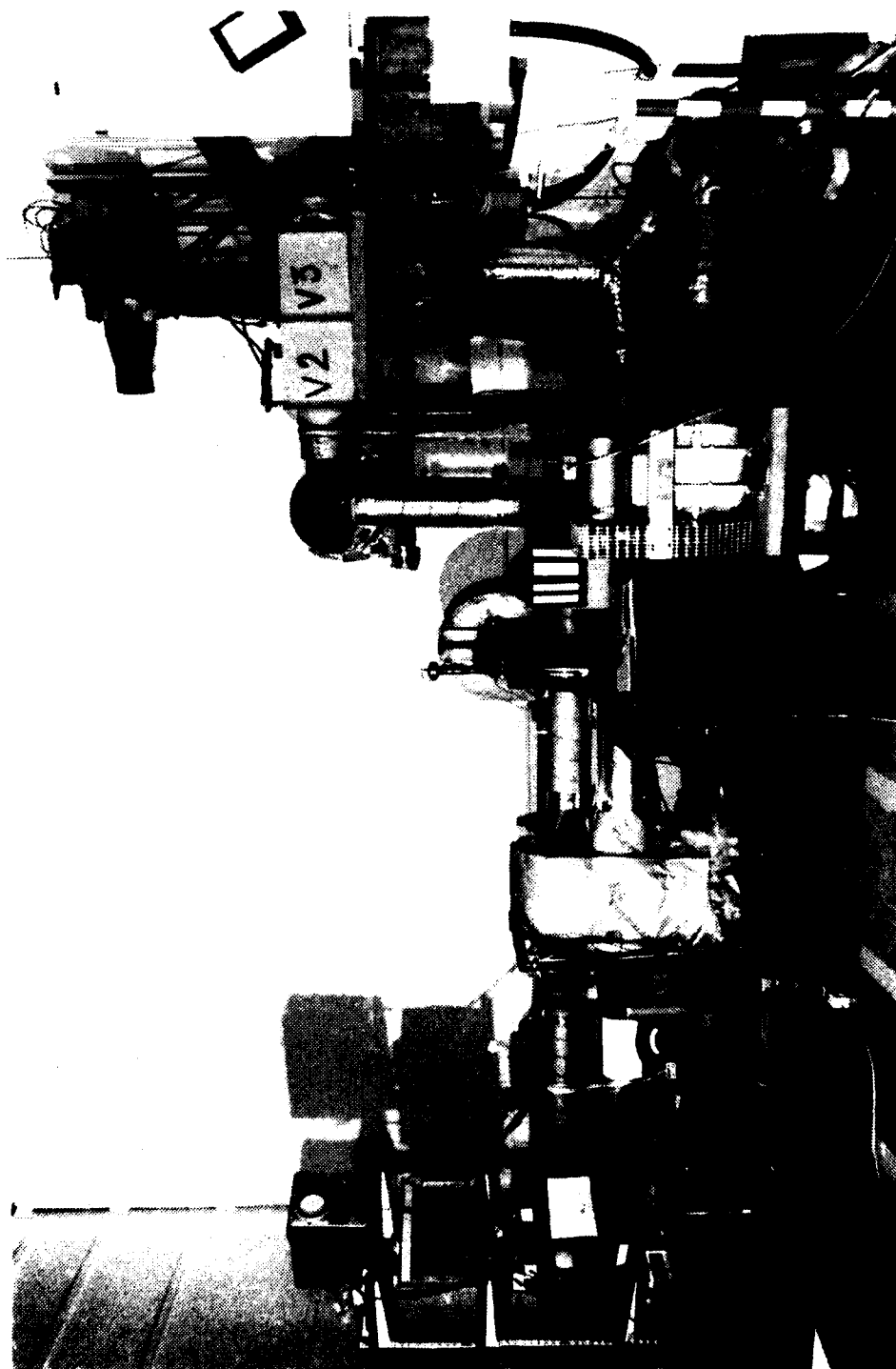


Figure 3B The Experimental Facility



Figure 4 The Heat Exchanger Element

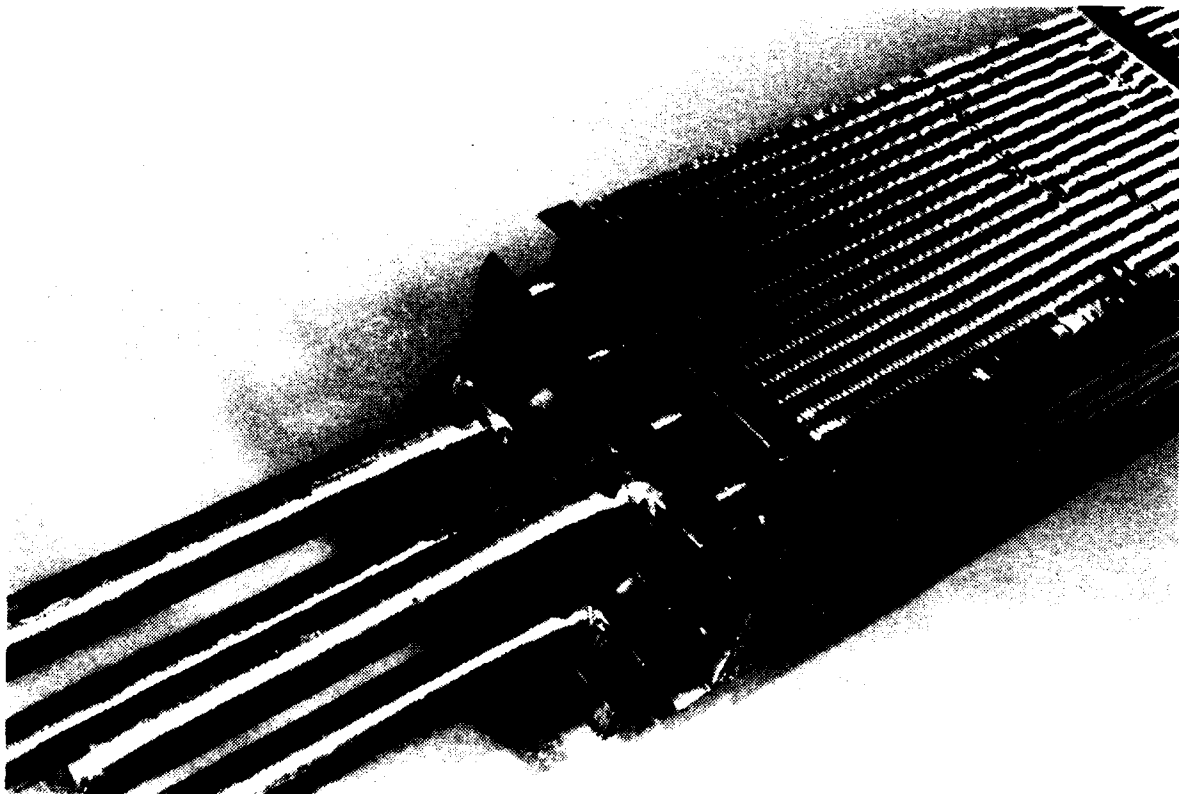


Figure 5 Detail of Reservoir Construction

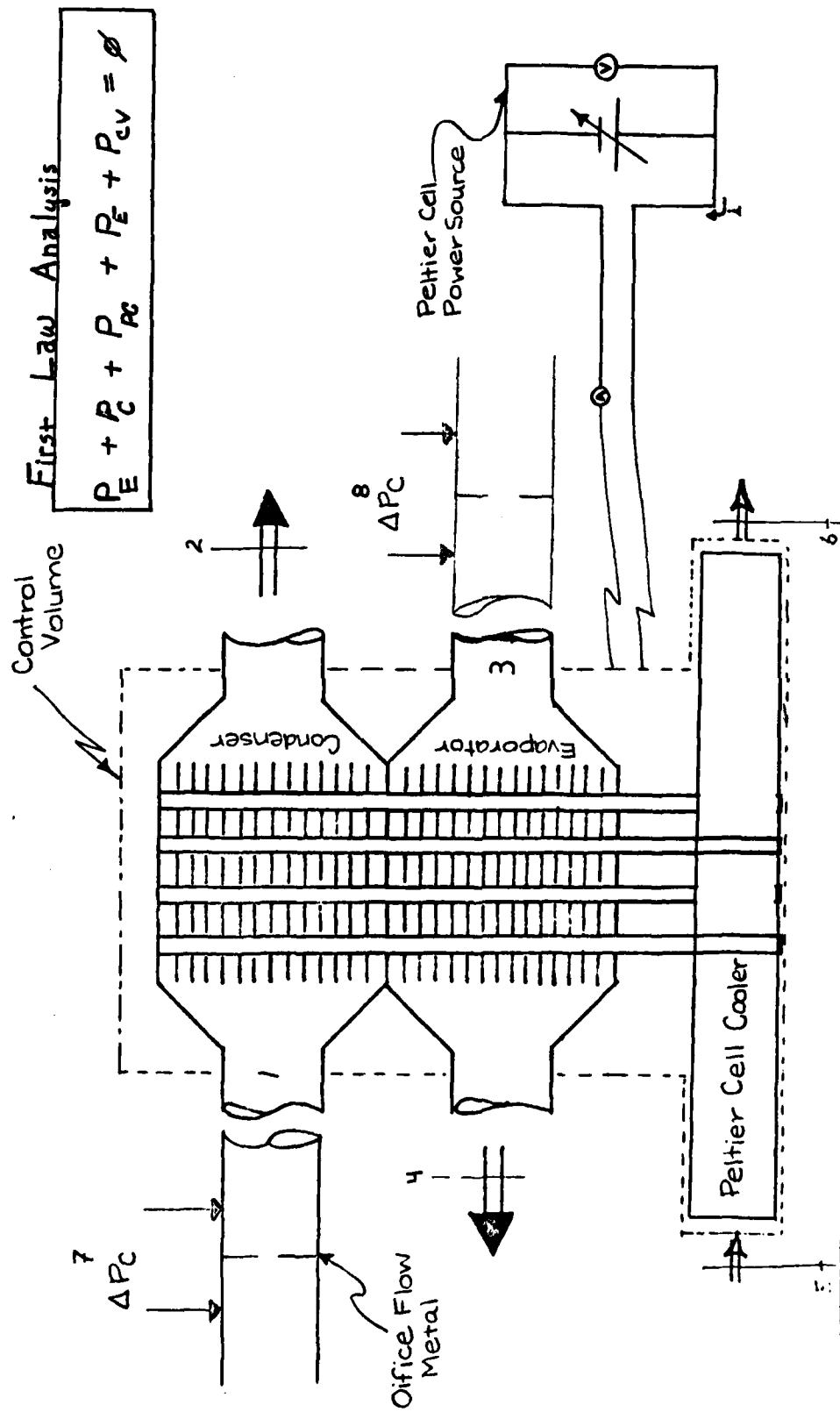


Figure 6 State Point Diagram

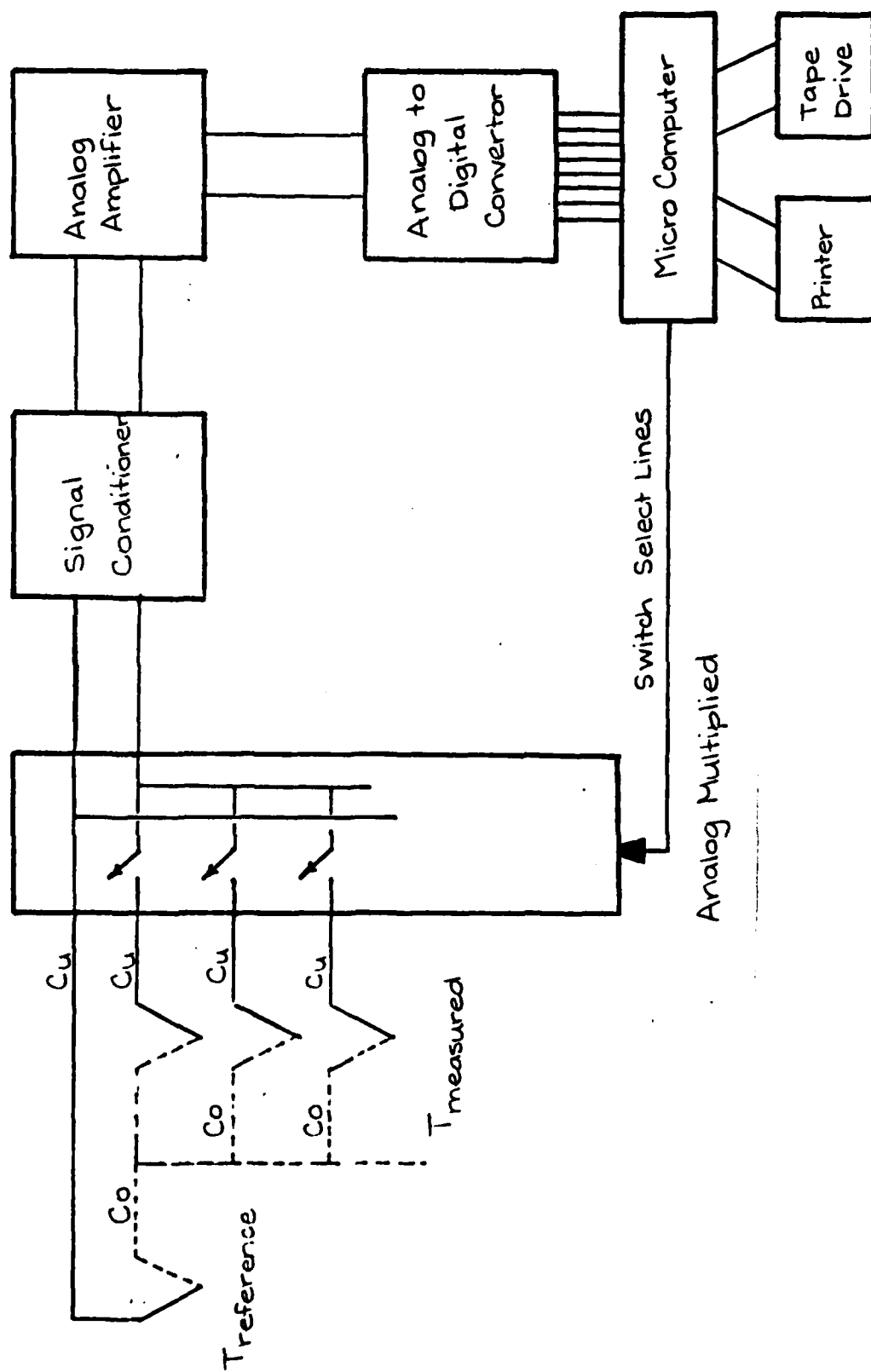


Figure 7 Schematic of Temperature Measurement System

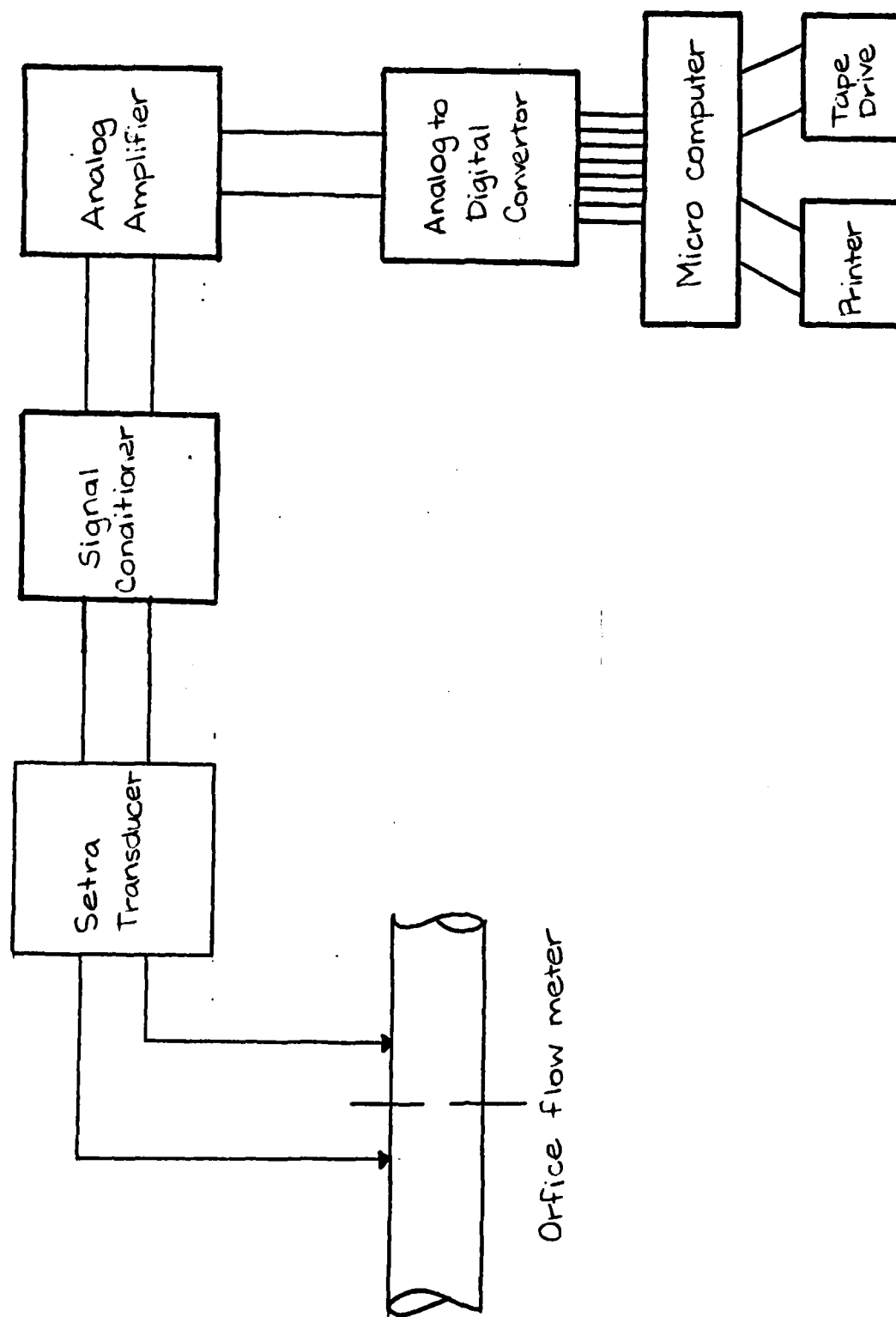


Figure 8 Schematic of Pressure Measurement System

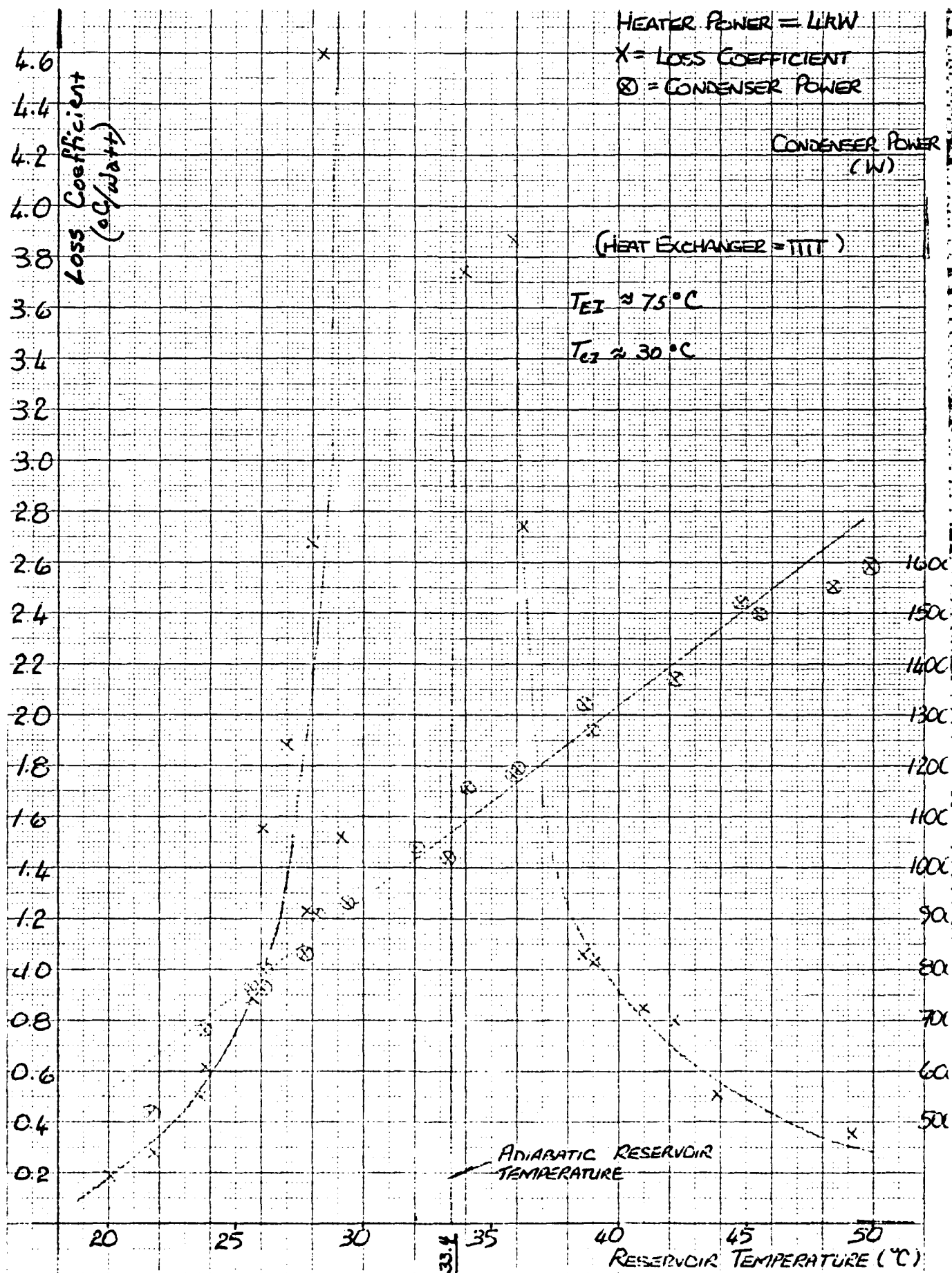


Figure 9 Performance Graph for The L-Prototype

PERFORMANCE GRAPH for PROTOTYPE III

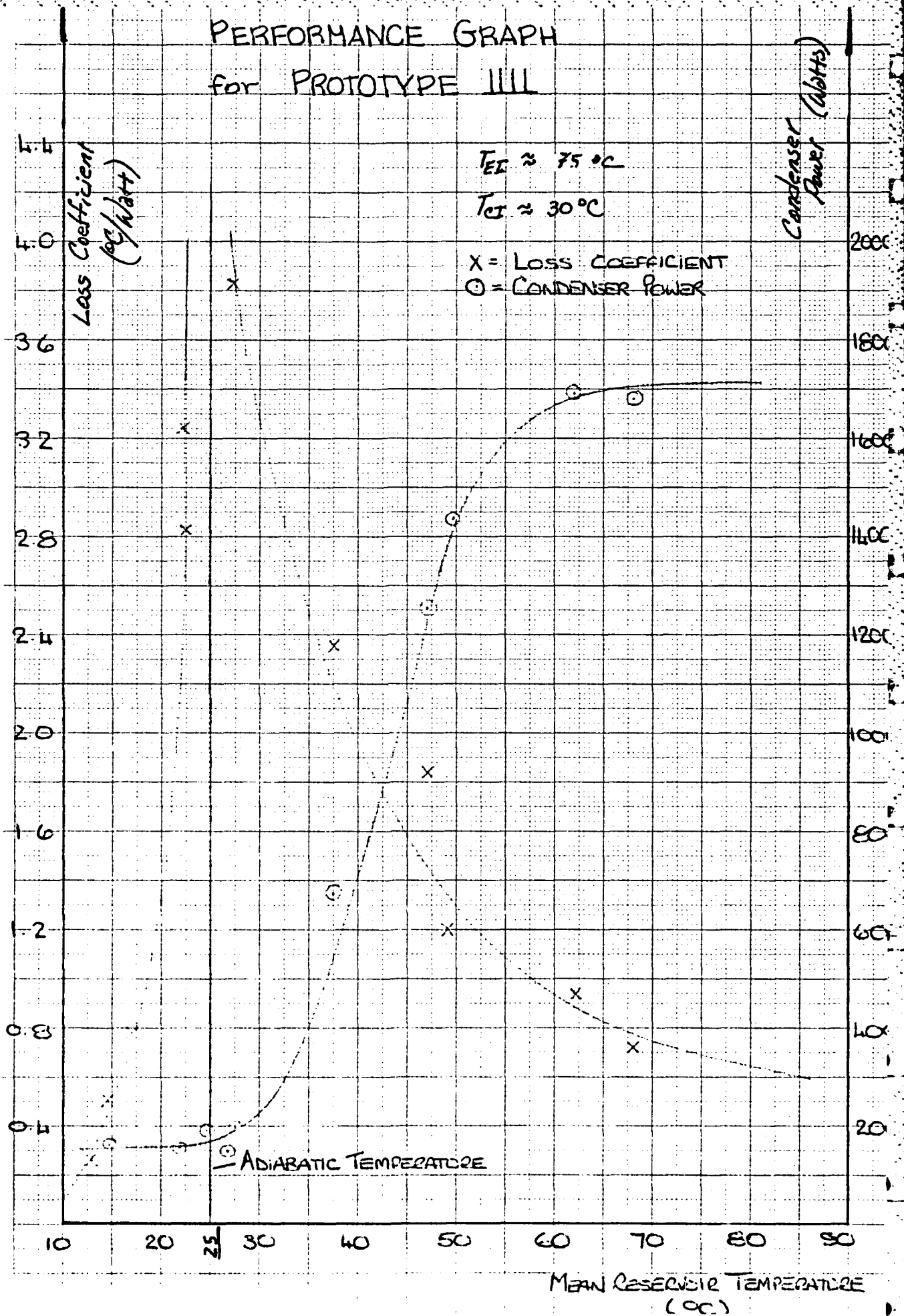


Figure 10 Performance Graph for The U-Prototype

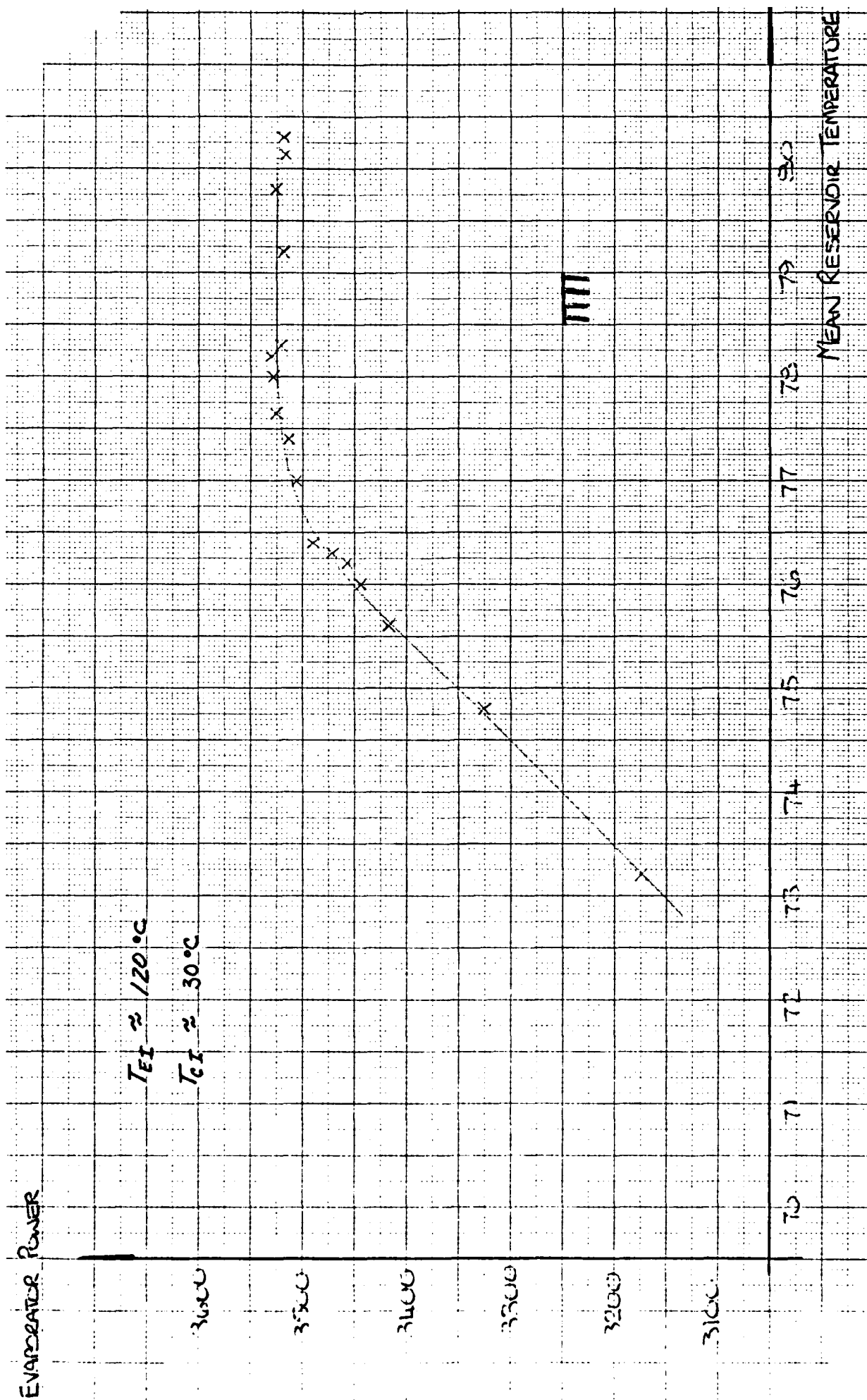


Figure 11 Upper Asymptote for The L-Prototype

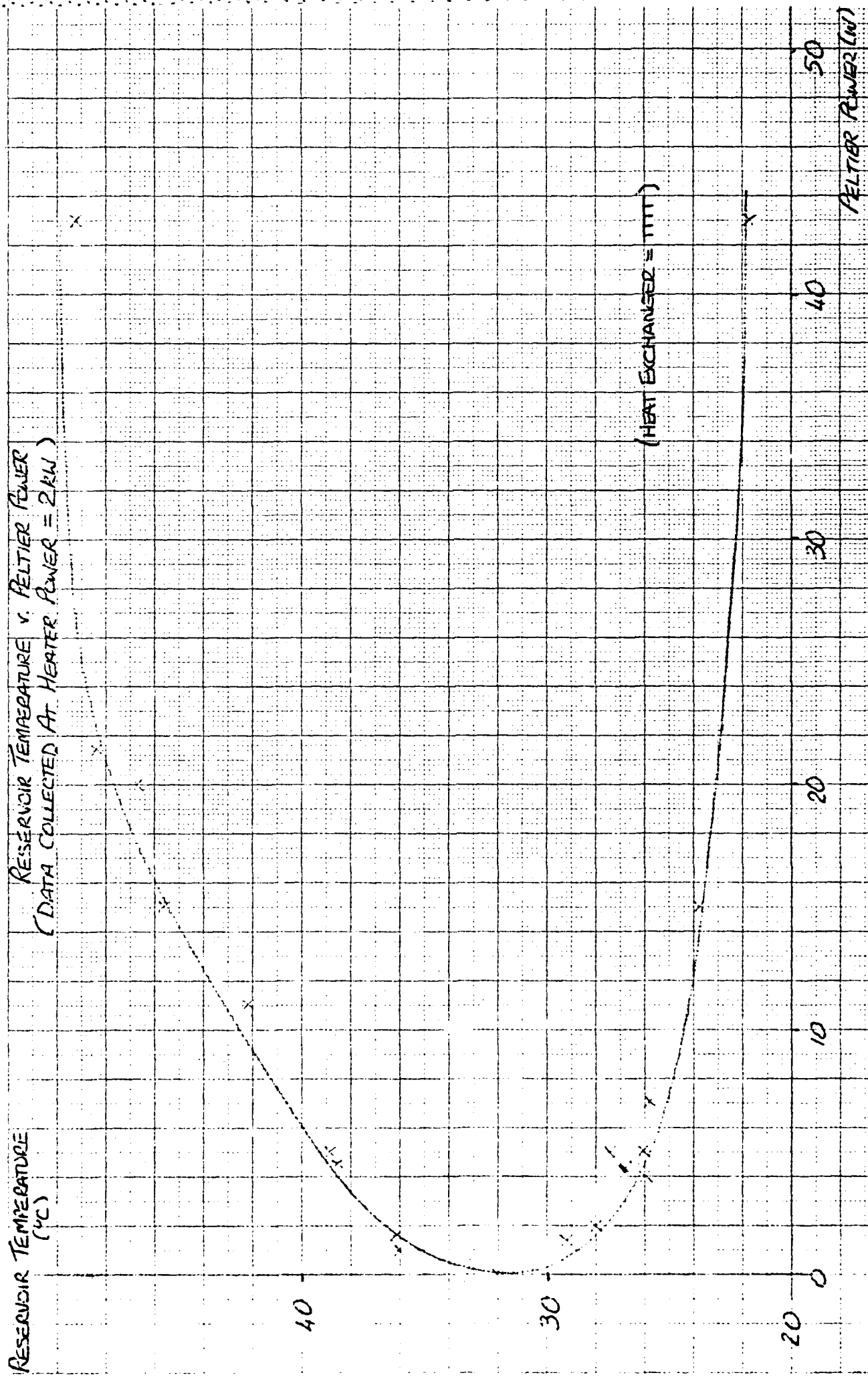


Figure 12 Reservoir Temperature vs Peltier Power For L-Prototype

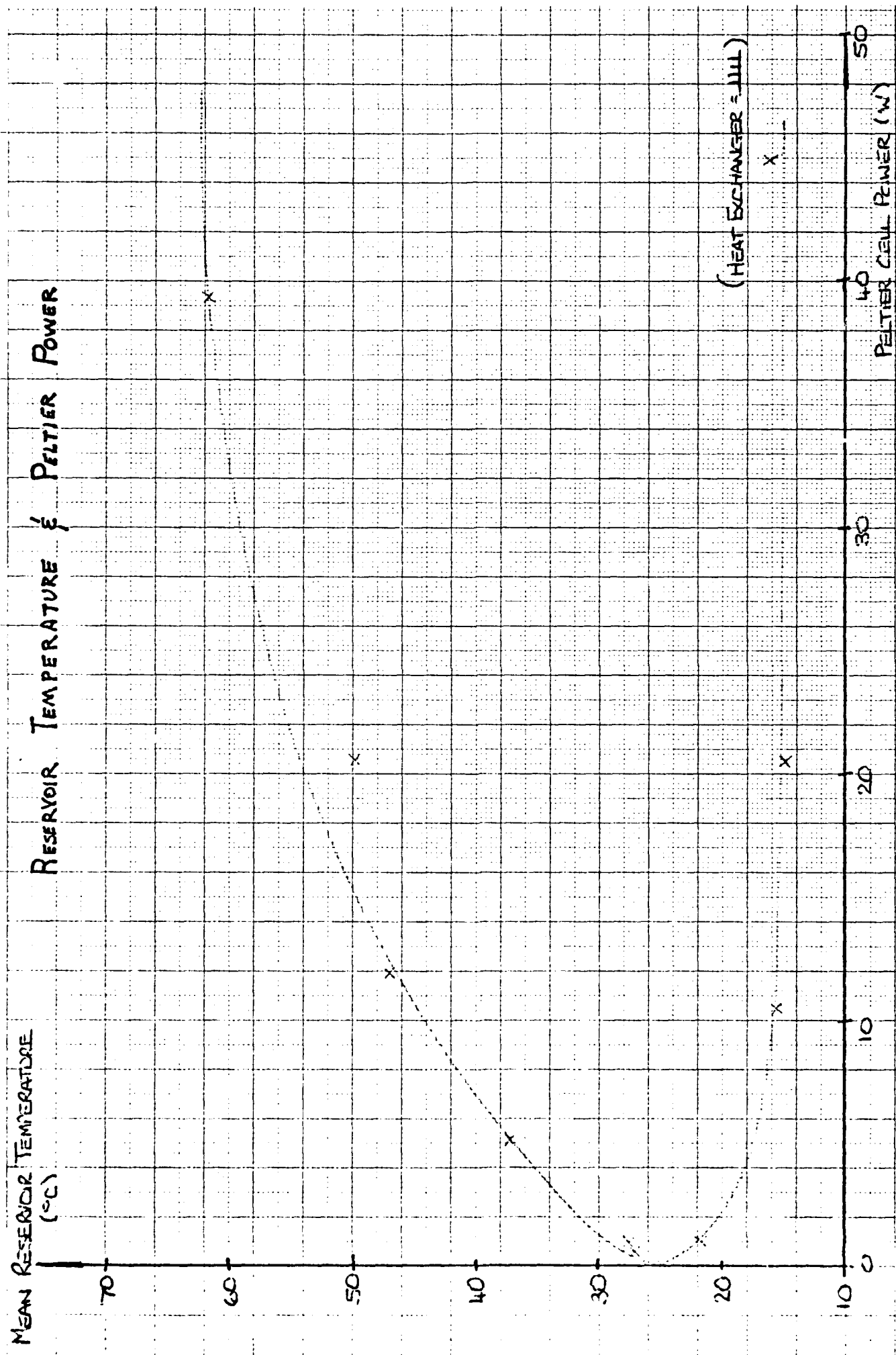


Figure 13 Reservoir Temperature vs Peltier Power For The U-Prototype

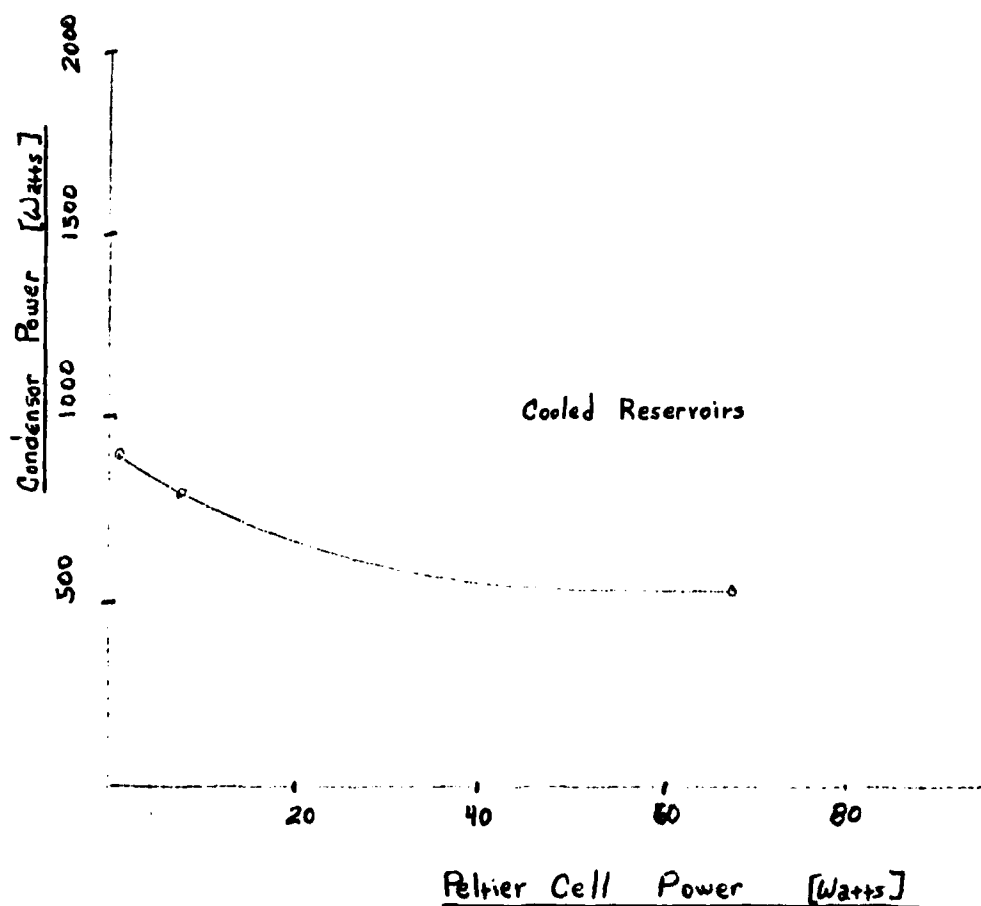
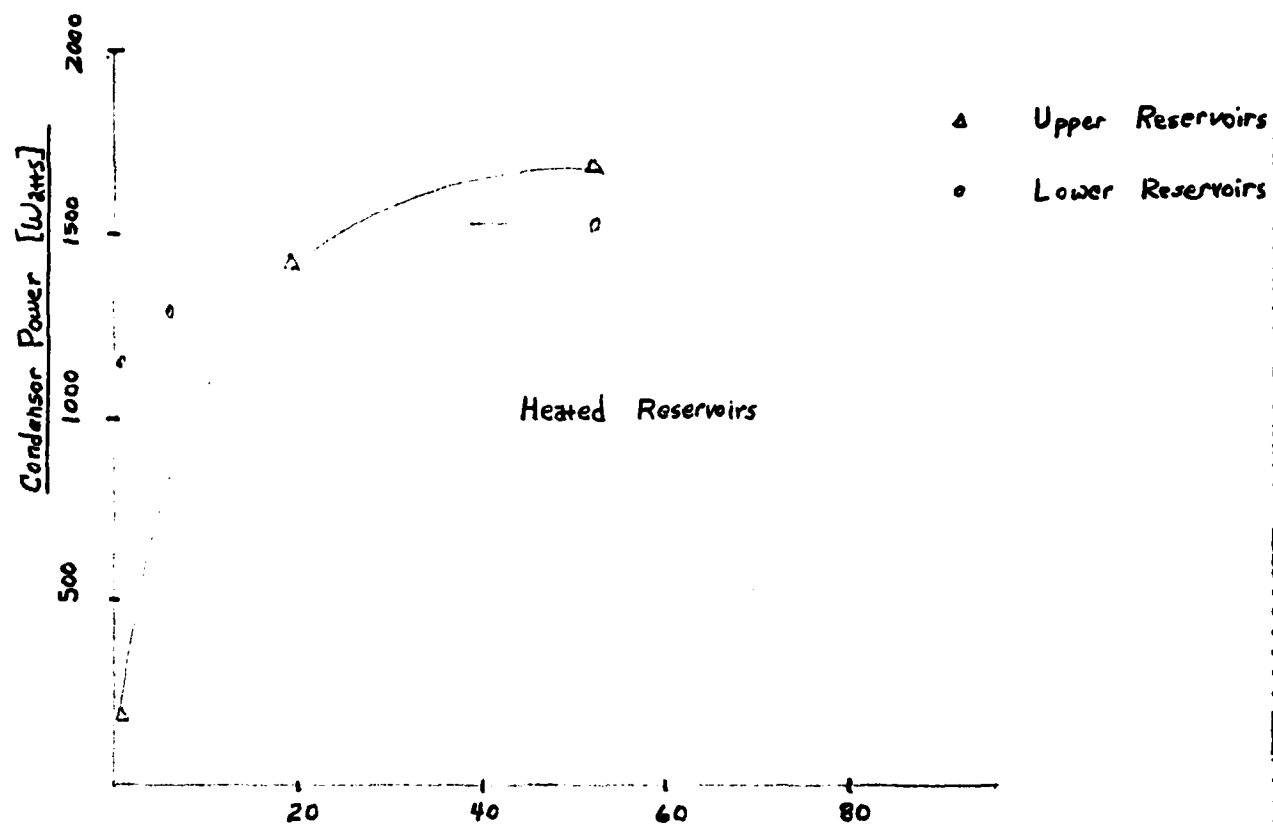


Figure 14 Condensor Power vs Peltier Power

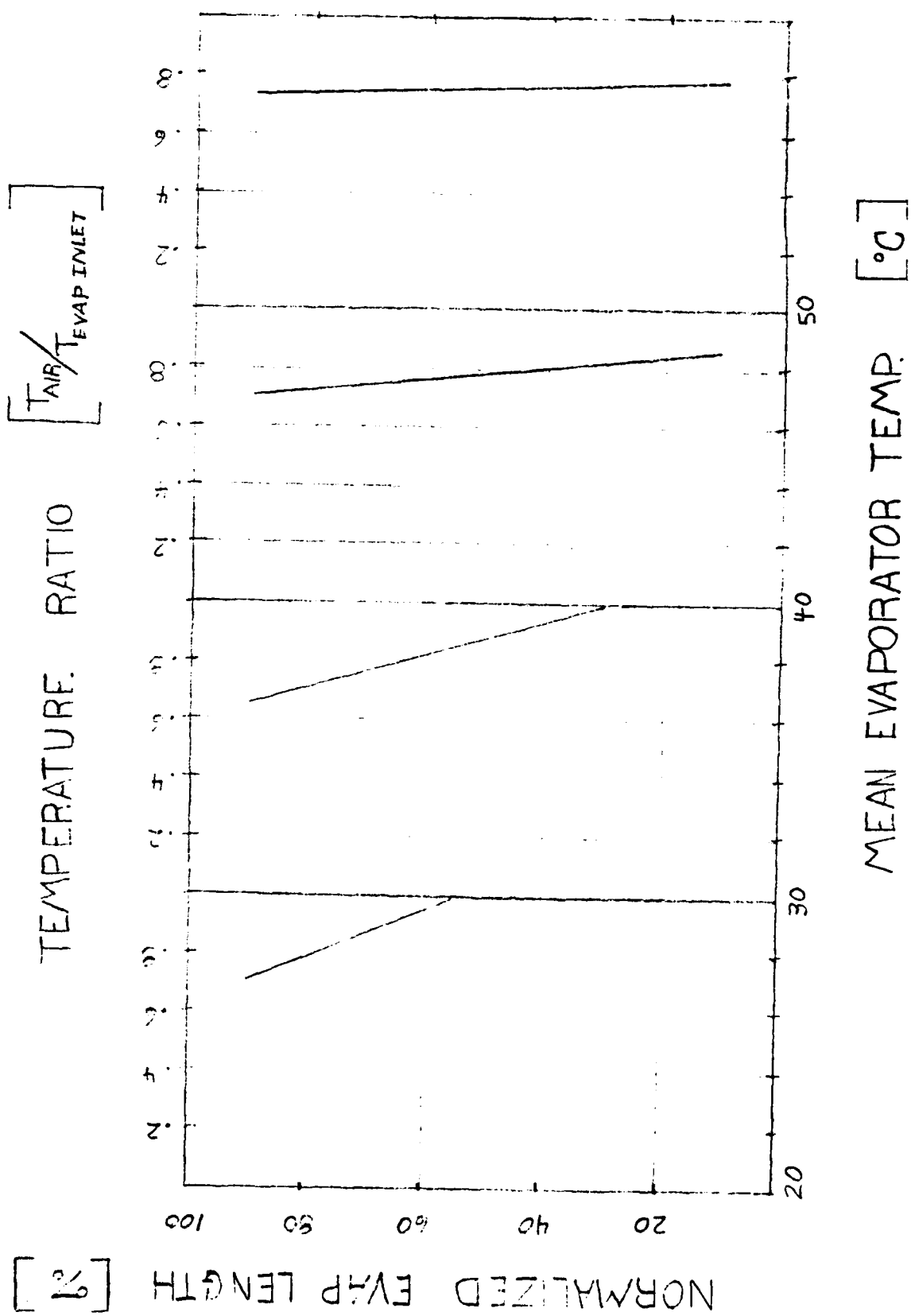


Figure 15 Reduced Evaporator Temperature

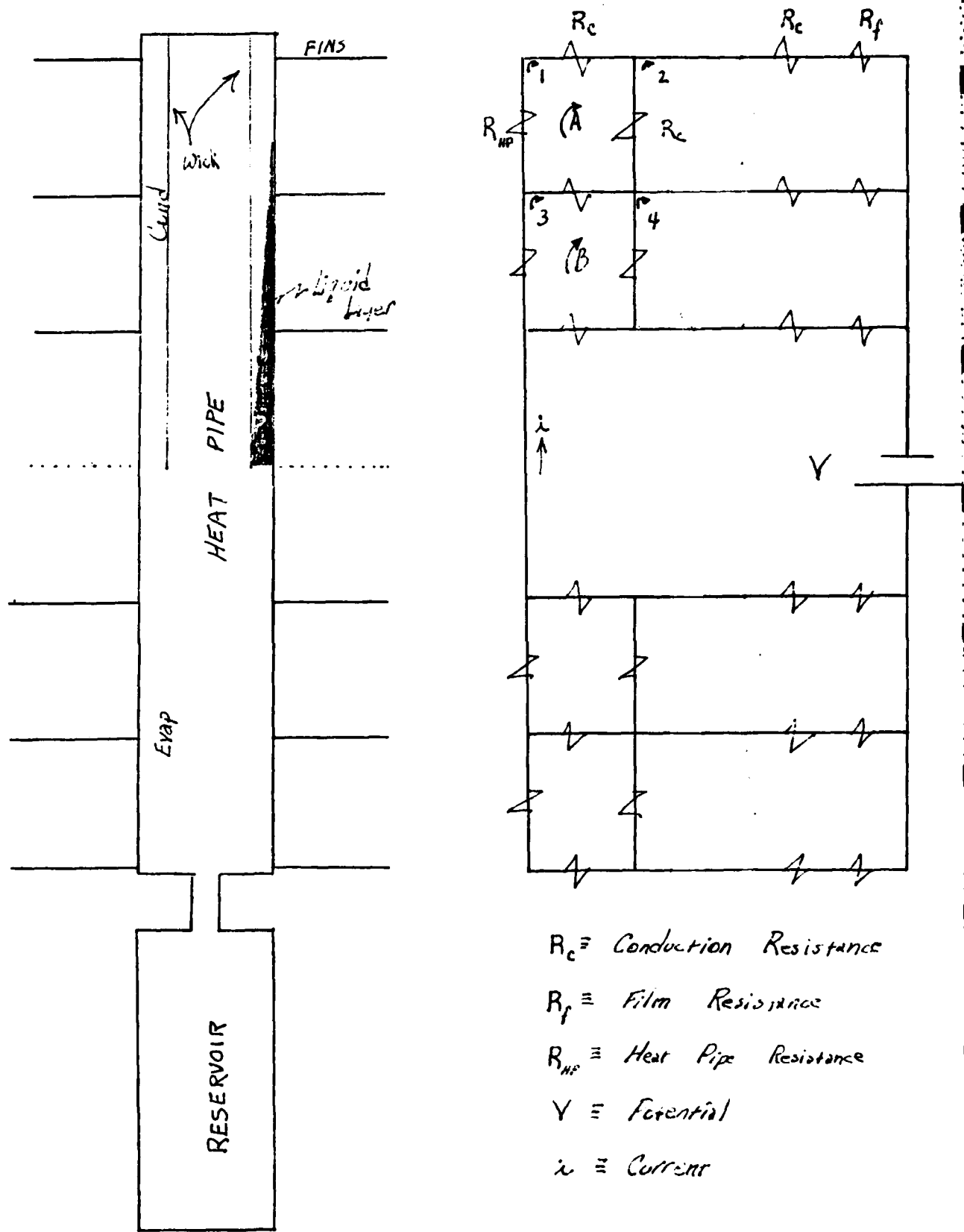
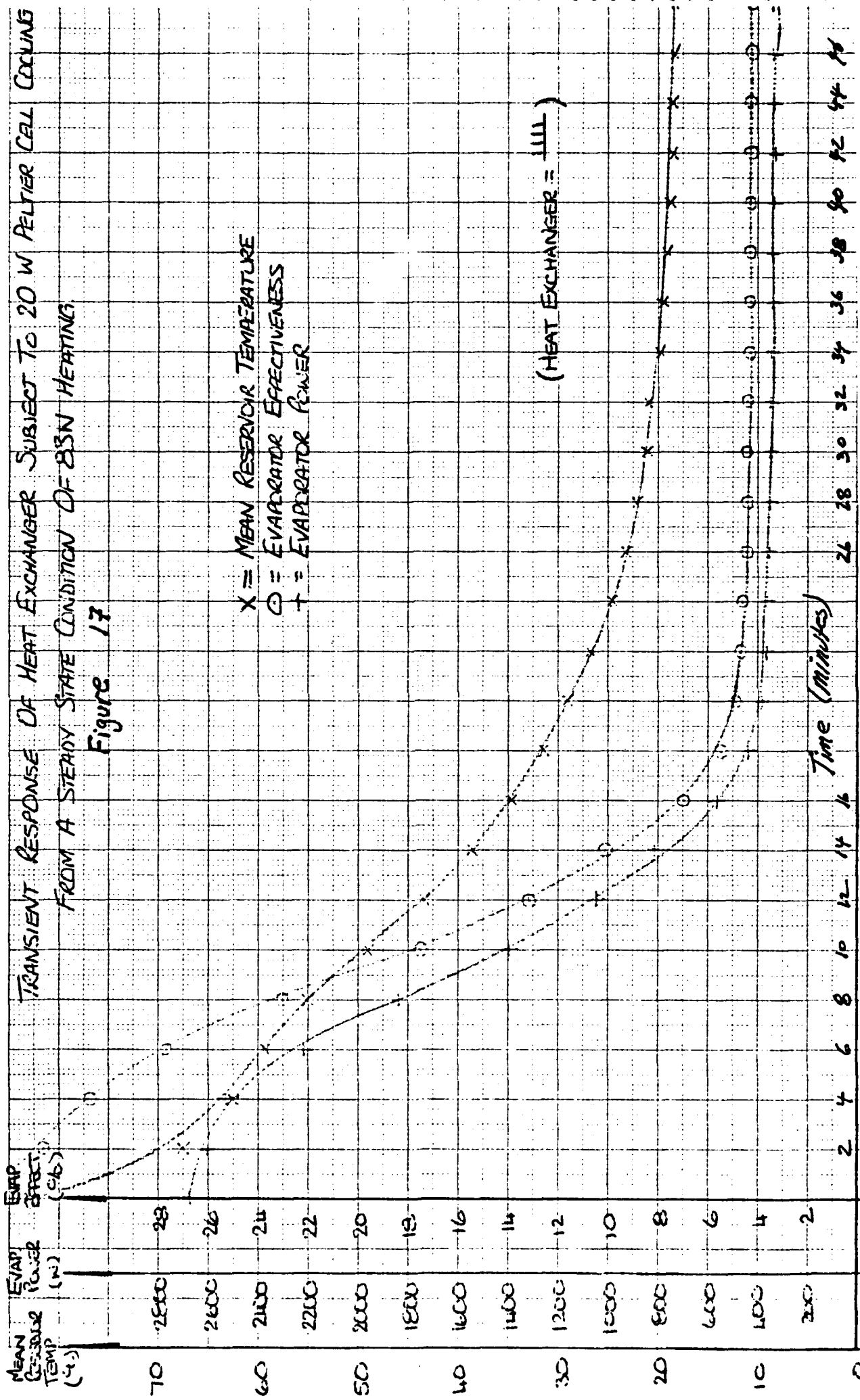
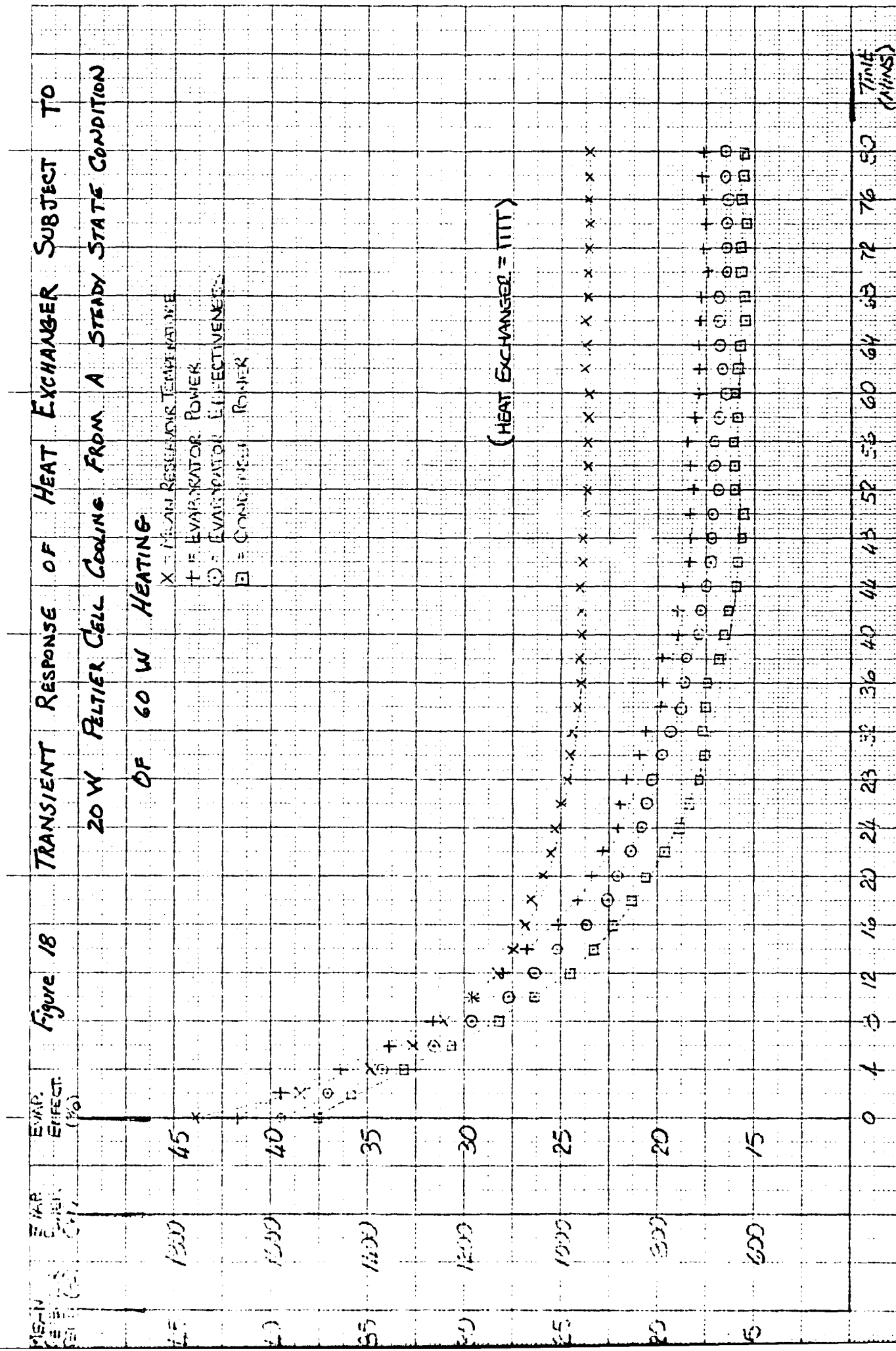


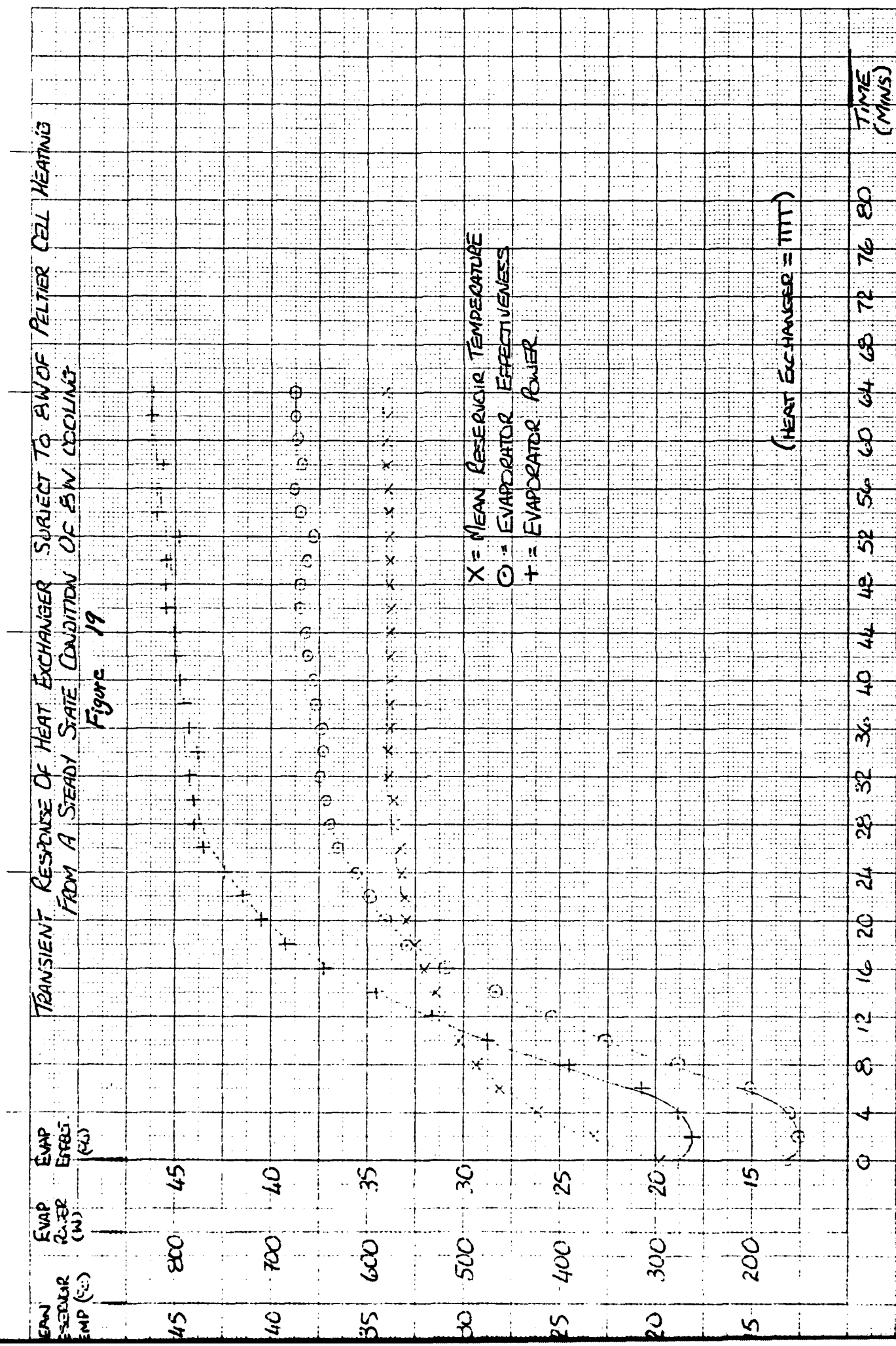
Figure 16 VCHPHX Equivalent Circuit Model

TRANSIENT RESPONSE OF HEAT EXCHANGER SUBJECT TO 20 W Peltier Cell COOLING
FROM A STEADY STATE CONDITION OF 83N HEATING.

Figure 17

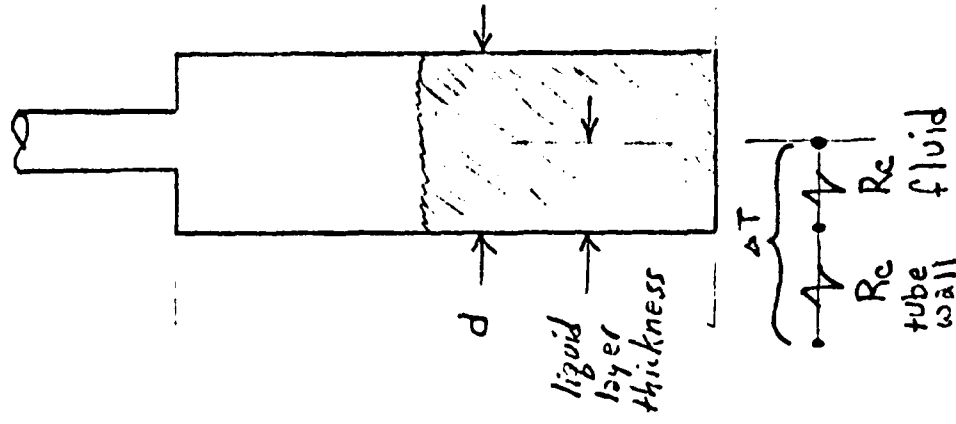






L Prototype

U Prototype



$$\dot{Q} = h A \Delta T$$

$$h \equiv [Watts/m^2 \cdot ^\circ C]$$

$$A \equiv [m^2]$$

$$\Delta T \equiv ^\circ C$$

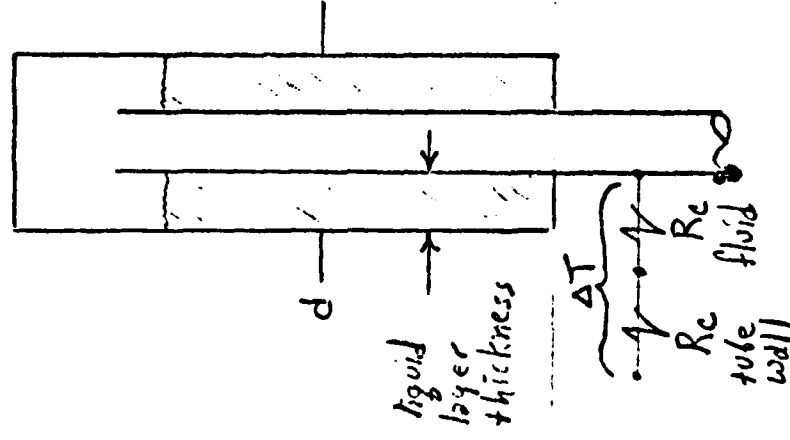


Figure 20 Construction of Liquid Reservoirs

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