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# Thermal Control of an Electronic Enclosure Utilizing a Vapor Chamber

Michael L. Dougherty
*University of Central Florida*

# THERMAL CONTROL OF AN ELECTRONIC ENCLOSURE UTILIZING A VAPOR CHAMBER

By

MICHAEL L. DOUGHERTY
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THESIS

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ABSTRACT

This thesis addresses the problem of extracting heat from sealed electronic enclosures. Typical industry practice is to use various air-to-air and air-to-liquid heat exchangers. These techniques are known to require costly custom designs.

This thesis points out how one can apply heat pipe technology in the form of a vapor chamber to solve this type of problem. The details on the design and testing of two prototype vapor chambers are cited.

Included in the text are typical industrial applications that require sealed enclosures to protect their associated electronic control hardware. Also mentioned is some historical background on heat pipes.

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TABLE

## LIST OF SYMBOLS

$A$ = Area ($ft^2$).

$a$ = Accomodation Or Sticking Coefficient, Dimensionless.

$b$ = Geometrical Form Factor, Dimensionless.

$b$ = Grid Spacing (inch).

CFM = Air Flow ($ft^3$/min).

$C_r$ = Capillary Conductance. ( /b), Dimensionless.

$E_{tot}$ = Total System Energy (btu/hr).

$E$ = Modulus Of Elasticity ($lb/in^2$).

$h$ = U-Tube Manometer Height Differential (mm,inch).

$h_i$ = Internal Film Coefficient (btu/hr-$ft^2$ °F).

$h_o$ = External Film Coefficient (btu/hr-$ft^2$ °F).

$L$ = Latent Heat Of Vaporization (btu/lb).

$l_d$ = Distance Between Hot Spots (inch).

$l_w$ = Width Of Hot Spots (inch).

$p$ = Vapor Pressure (psia).

$P$ = Unknown Pressure (psia).

$P_a$ = Atmospheric Pressure (psia).

$Q$ = Energy In The Form Of Heat (btu/hr).

$Q_i$ = Input Energy (btu/hr).

$R$ = Universal Gas Constant (ft-lbf/lb-mole °R).

$r_c$ = Condensation Rate Per Unit Area (lbm/hr-$ft^2$).

$r_c$ = Pore Size (inch).

$r_e$ = Evaporation Rate Per Unit Area (lbṁ/hr-ft$^2$).

S.P = Standard Pressure (1 atm, psia).

T = Absolute Temperature (°R).

$T_i$ = Inside Enclosure Temperature (°F).

$T_a$ = Room Ambient Temperature (°F).

$T_o$ = Room Ambient Temprtature (°F).

t = Plate Thickness (inch).

t = Time In Minutes.

$t_w$ = Screen Thickness (inch).

U = Internal Energy (btu/hr).

U = Overall Heat Transfer Coefficient ( btu/hr-ft$^2$°F).

w = Load (lbf/in$^2$).

W = Energy In The Form Of Work (btu/hr).

y = Maximum Deflection (inch).

$\alpha$ = Shape Factor, Dimensionless.

$\gamma$ = Surface Tension (dunes/cm, lbs/hr$^2$).

$\epsilon$ = Wick Porosity, Dimensionless.

$\nu$ = Kinematic Viscosity (ft$^2$/hr).

$\rho_a$ = Density Of Air (lb/ft$^3$).

$\rho_{hg}$ = Density Of Mercury (lb/ft$^3$).

CHAPTER I

# INTRODUCTION

## TODAY'S INDUSTRIAL MARKET

In today's industrial market place there is a continual demand to produce cost effective products. One way in which the electronics producers have endeavored to satisfy this need is by more sophisticated control packages at competitive prices. Competition has forced the electronics manufacturer to invest hugh sums of money in research and development to provide more and more capability at lower prices. This increased capability at lower prices has manifested itself in shrinking package sizes as is witness the hand held calculator and larger digital and analog computer systems.

## TECHNOLOGICAL RESULTS

Although technology has resulted in super sophisticated computer systems to be contained in high density packages, it has also resulted in creating very sensitive products. For example, many integrated circuits begin failing exponentially above 70$^{0}$C (158$^{0}$F). Although at first glance this seems like a relatively high temperature compared to ambient room temperature, one must not lose sight of the fact that these integrated circuits are buried inside a high density electronic package. These high density packages are often accompanied by other similar packages in a system and these systems in today's applications are being subjected to more and more hostile environments. The reason for this subjection can best be understood by the following example.

ENVIRONMENTAL APPLICATIONS

A typical computer system to control a hot ingot rolling mill in a steel mill cost approximately $150.000. This control system because of its heat sensitivity is installed in a specially designed environmental control room. It will cost upwards of $1,000.000 to wire up the rolling mill to the computer control. The major reason for the high installation costs are due to extremely long signal wire runs and the special room to house the system control. The room, of course, insures proper temperature controls but, it also protects the various electronic circuits from conductive dirt that will cause failure. Similar examples can be cited for the control systems required in the petro-chemical industry where corrosive vapors and potential explosions result in high installation costs. Some process control manufacturers have attempted to solve the high installation costs in hostile environments by placing their electronic controls in various MEMA-rated sealed enclosure[1]. These sealed enclosures are then placed closer to the actual process they are controlling.

## TYPICAL HEAT TRANSFER TECHNIQUES

Some of the ways that process control manufacturers have attempted to maintain safe operating temperatures for their electronic packages in sealed enclosures are by installing various air-to-air and air-to-liquid heat exchangers. These heat exchanging techniques often require custom designs for each enclosure. These devices often require as much as 30% of the available enclosure space. The prime movers required to move the various working fluids often add to the heat load that they were intended to remove. The heat exchangers employing a liquid working fluid require the end user of the system to install costly remote supply lines or if the system is closed a more costly self-contained circulating system results. The various mechanical elements in these heat exchangers are subject to wear and must have continual maintenance to insure they do not cause a catastrophic failure in the system under control.

## PROPOSED HEAT EXCHANGER CRITERIA

There is a definite need for a heat exchanging device that will effectively insure safe operating temperatures for high density computer control systems. Further, in order to be a cost effective control system in todays market it must be able to operate in extremely hostile environments.

A heat exchanging device capable of operating effectively under the aforementioned conditions should have the following design characteristics:

1. The device should be able to work in conjunction with a sealed enclosure such as NEMA-12.

2. If the device requires prime movers it would be desirable that they do not add to the heat load of the enclosure.

3. It would be highly desirable that the device require a minimum of enclosure volume.

4. The device should be applicable to a variety of enclosure designs without requiring major changes.

5. The device should operate under a closed system not requiring external system supply lines.

6. The device should be able to transfer high heat rates when small temperature differences exist between internal and ambient operating conditions.

7. The device should be able to be manufactured in a cost effective manner.

After extensive study and first hand experience in trying to effectively cool sophisticated computerized control systems the author feels that the only heat transfer device known today that would satisify the above design criteria would be some form of the device commonly referred to as a "Heat Pipe."

## BASIC HEAT PIPE OPERATION

A heat pipe within a given temperature range performs like a high conductance thermal conductor. This device has been referred to as; a thermal siphon, reflux condensor, thermal diode, two phase heat exchanger, as well as, many others. A typical heat pipe is constructed as shown in figure 1[2]. The high conductance properties of a heat pipe are directly attributed to the properties and the processes that the internal working fluid undergoes while operating. This device can have heat transfer rates several orders of magnitude greater than the best solid conductor of the same dimensions. This is a qualitative remark, however, since heat transfer is not by pure conduction. The basic heat pipe consists of a sealed tube made from materials that are structurally and thermally acceptable for the application along with a small amount of vaporizable fluid. The heat pipe utilizes a boiling-condensing cycle with capillary-aided condensate return to the evaporator as shown in figure 1. The boiling-condensing cycle is essentially isothermal due to the fact that there is very little pressure drop experienced between the evaporator and condensor.

## HISTORICAL BACKGROUND OF HEAT PIPES

Historically, these devices were first described in a patent issued to R.S.Gaugler in 1944[2]. This patent was assigned to General Motors Corporation. This concept lay dormant until 1962 when L. Trefethen of General Electric proposed its application in the space program[2]. Shortly thereafter in 1963, T. Wyatt of John Hopkins proposed this concept for temperature stabilization of a satellite[2]. The heat pipe technology best known today was in effect re-established in 1963 by George Grover and his associates

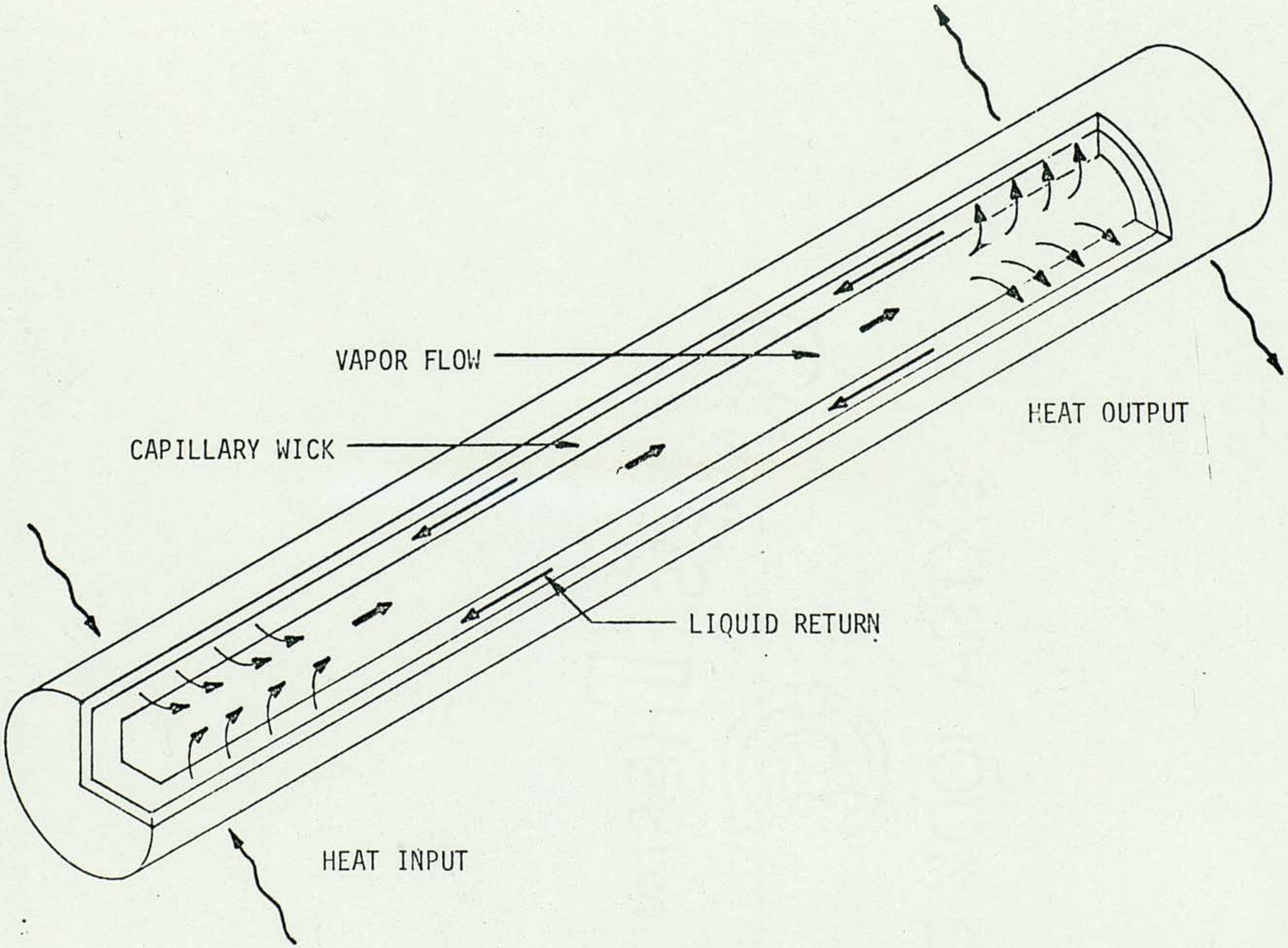


FIGURE 1. BASIC HEAT PIPE

of Los Alamos Scientific Laboratories[2]. Since the re-establishment in 1963 many applications have surfaced. For example, RCA demonstrated a variable conductance device in 1964[2]. The Air Force developed a cryogenic device in 1966[3] and in 1967 the first heat pipe was flown under zero gravity conditions in space[3].

VAPOR CHAMBER

After a literary survey, the author concluded that most applications of heat pipes have been on localized hot spot cooling. In order to satisify sealed enclosure thermal control a more macro device is required. In fact, it turns out that a rectangular shaped chamber that can be mounted on top of a sealed enclosure best fits the geometry of the application rather than a cylindrical shape. Furthermore, since the enclosure will operate under gravity conditions a wick to pump condensate from the condensor to the evaporator via capillary action will probably not be required. Because of the discrete differences between the above described heat pipe, the author has elected to classify the device as a vapor chamber.

# CHAPTER II

## GOVERNING EQUATIONS, VAPOR CHAMBER ANALYSIS

### INTRODUCTION

It is not the intent to this thesis to provide a detailed mathematical model of a vapor chamber but, to present a qualitative approach pointing out those parameters and considerations that should be included. Most of the specific details in this design application will be discussed in CHAPTER III.

### CONSERVATION OF ENERGY

A convenient starting point in the analysis would be to apply the conservation of energy principles to the vapor chamber. From conservation of energy we know that the rate of creation of energy in a system must equal zero. That is:

$$\text{Energy Outflow} - \text{Energy Inflow} + \text{Energy Stored} = 0 \quad (1)$$

First, let's define the closed system as the vapor chamber as depicted in figure 2.

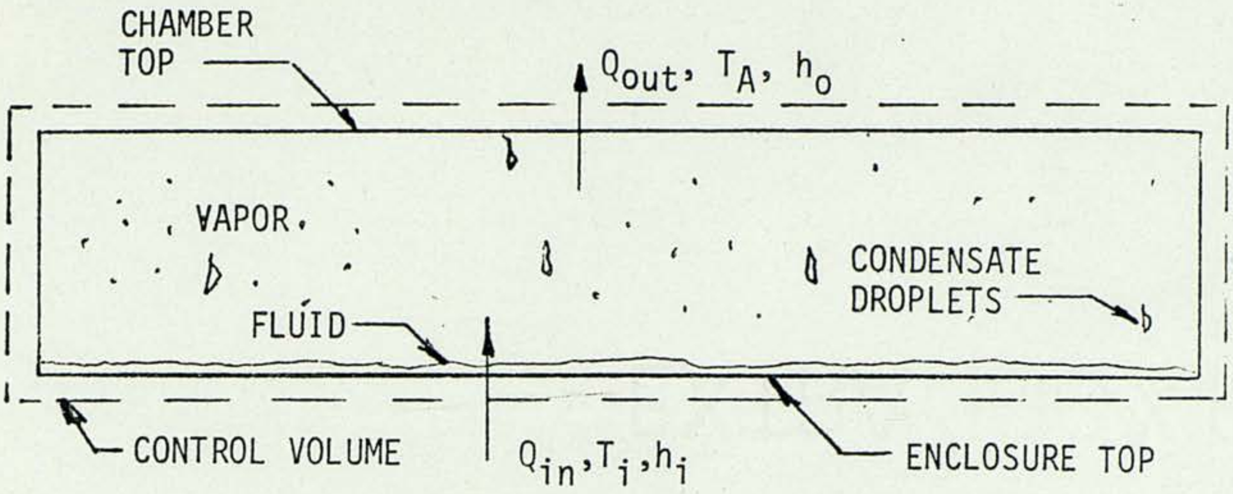


FIGURE 2. VAPOR CHAMBER CONTROL VOLUME

## FIRST LAW OF THERMODYNAMICS

From the First Law of Thermodynamics for a closed system with no energy in the form of mechanical work crossing the system boundary we have;

$$E_{tot} = Q + \not{W} = \Delta U \qquad (2)$$

where $E_{tot}$ = Total energy of the system

$Q$ = Energy in the form of heat

$W$ = Energy in the form of mechanical work

$\Delta U$ = Change in internal energy

Assume the system is initially in equillibrium and contains saturated vapor and liquid. There will be an initial warm-up time required to bring the system to its new equilibrium operating condition once $Q_{in}$ is applied. This warm-up time will be a function of the thermal mass of the system. For this analysis assume the system has reached steady-state and that $Q_{in}$ is a known value. It will also be assumed that the outside ambient $T_a$ and the inside $T_i$ temperatures are known.

HEAT TRANSFER MODE CONSIDERATIONS

Depending upon how $Q_{in}$ is generated it is obvious that one must consider convection, conduction and radiation heat transfer modes. Due to the low temperatures in this application (70°F to 200°F), the author has elected to disregard the heat transferred by radiation since it is very small compared to the heat transferred by the other modes.

$Q_{in}$ is force convected from the electronic packages within the enclosure up to the base of the vapor chamber. Depending on the internal air properties one can determine the external film coefficient $h_i$. Next, the heat is conducted through the evaporator base the rate of which is dependent upon the material geometry and properties.

Next, the heat is conducted from the evaporator base through the liquid layer where it will meet its next resistance to flow. This resistance manifests itself in the liquid surface to vapor interface. It is at this point where the liquid gives up its latent heat during its phase change to vapor. It is also at this interface where vapor molecules are recondensing back into the liquid.

The condensation rate at this liquid-vapor interface per unit area can be described by[4];

$$r_c = ap\sqrt{\frac{M}{2\pi RT}} \qquad (3)$$

where: $r_c$ = Condensation rate per unit area

a = Accomodation or sticking coefficient

p = Vapor pressure

M = Molecular weight

R = Universal gas constant

T = Absolute temperature of the vapor

The evaporation rate per unit area[4], $r_e$, can be described by the same equation except that

T = Absolute temperature of the liquid

p = Equilibrium vapor pressure at temperature T

If the vapor and liquid are at the same temperature and if the vapor pressure is identical to the equilibrium vapor pressure at that temperature then the evaporation and condensation rates are equivalent. However, if the liquid temperature exceeds the vapor temperature by dT and the vapor pressure exceeds the equilibrium vapor pressure by dp there will be a net mass transfer from the liquid surface to the vapor. This rate can be described as[4];

$$r_e - r_c = ap\sqrt{M/2\pi RT}\ (dp/p - dT/2T) \qquad (4)$$

Here, T can be taken as the liquid temperature and p as the equilibrium vapor pressure. It should be pointed out that equation (4) utilizes the usual kinetic gas theory assumption of a Maxwellian distribution of the gas molecules.

Now, one can determine the heat transfer rate by multiplying the mass transfer rate shown in equation (4) by the latent heat of vaporization for the liquid under study.

Thus far in the qualitative approach I have followed the heat transfer phenomena from its generation point inside the electronic enclosure to its latent heat vapor form inside the vapor chamber. The next event in the cycle would be the deposition of the vapor on the condensor and the subsequent phase change by which the latent heat of the vapor is given up. The condensation rate can be determined from equation (3). From a knowledge of heat of vaporization of the fluid one can determine the heat transfer rate. However, several physical complications occur at this vapor-liquid interface. For example, the probability that a given molecule contacts the cooler surface and sticks is difficult to obtain for a given fluid. This parameter is used in equation (3) and (4) as 'a' the accomodation coefficient[4]. This parameter depends not only on the fluid type[4] but, also on the surface finish condition of the condensor[5].

## CONDENSATION MECHANISMS

Specifically, condensation of a pure saturated vapor is exhibited by two mechanisms. One mechanism is referred to as "dropwise" condensation and the other is "film-type". On a rusty or etched plate the vapor will condense in a continuous film over the entire condensor plate. If the surface was smooth and polished the condensate will form in droplets which will grow in size rapidly[5]. It is also known that dropwise condensation can be brought about for a while by coating a surface with a petroleum based product, however, the condensate run off will soon wash this effect away[5]. It is obviously highly desireable to have condensation forming in droplets since at any instant of time a substantial portion of the condensing surface is free of condensate which allows the condensing process to continue at a high rate.

By utilizing the definition of viscosity and assuming that the velocity of the condensate on the condensor wall is zero and that the vapor molecules are at a maximum velocity at the liquid-vapor interface, theoretically, one can determine the thickness of the condensate film[5]. It is then possible to determine the local coefficient of heat transfer by assuming that the total thermal resistance lies in the condensate film. A more rigorous treatment of this subject can be referred to in reference 5.

The remaining portions of the vapor chamber heat transfer analysis lies in determining the heat transfer through the condensor plate to the outside ambient. These conditions are contingent upon the chamber material and the film coefficient on the outer wall.

## APPARENT LIMITATION

The most important limitation on the rate at which heat can be transferred through the vapor chamber appears to be the rate at which the condensate can return to the evaporator. This would be somewhat analogous to the capillary pumping rate versus evaporation rate that is referred to in the heat pipe literature.[2,3,4] For, if the evaporator burns out, the process fails.

As was pointed out earlier, the purpose of this chapter was to indicate through qualitative reasoning an approach to formulate a mathematical model of the vapor chamber system to predict the behavior.

## CHAPTER III

## ANALYSIS AND DESIGN OF A VAPOR CHAMBER

### INTRODUCTION

In this chapter the physical parameters will be developed for a vapor chamber that will be applied to a specific electronic enclosure. Two prototype vapor chambers were constructed. The first prototype chamber performance was quite marginal. These shortcomings are pointed out in detail. A second prototype vapor chamber was built embodying those refinements necessary to improve the design of the first unit.

### ANALYSIS OF THE ELECTRONIC ENCLOSURE

The analysis begins by determining the pressure drop balance. From this balance suitable vapor chamber parameters can be established. Even though this device behaves like a structure of high thermal conductance, it possesses heat transfer limitations established by the laws of fluid mechanics and the kinetic theory of gases. Some of the limitations are boiling rates, droplet formation and entrainment[4].

If the amount of heat to be transferred is known, the physical enclosure limitations are known and the safe operating temperatures are known the design procedure can begin.

For this application the enclosure mechanics are depicted in Figure 3. The overall height is 60 inches (152.4 cm.) with a width of 23 inches (58.42 cm.) and a depth of 38 inches (96.53 cm.). Inside this enclosure are electronic packages generating heat in the range of 1 to 2 kilowatts (3142 but/hr to 6284 btu/hr) depending on the specific control application. Refer to Chapter I page 2. The safe operating temperature inside the enclosure cannot exceed 132°F (55°C). The ambient temperature range is typically 75°F to 105°F (24°C to 41°C) in the majority of these operating control systems.

So as not to use internal enclosure space the vapor chamber will reside in the available space at the top of the enclosure, 19 inches by 34 inches by 6 inches (48.26 cm X 86.36 cm X 15.24 cm). This space availability, of course, dictates the maximum size of the chamber. Refer to Figure 3. Another reason for placing the vapor chamber here is to take advantage of any natural convection afforded by the conditions. The evaporator wall of the vapor chamber will in fact form the enclosure top so that it can be directly exposed to the internal enclosure environment.
In order to keep the vapor chamber costs low it was decided not to increase the evaporator and condensor surface areas by adding fins. This decision, of course, does not prohibit adding fins to future designs if warranted. With the external size limitations

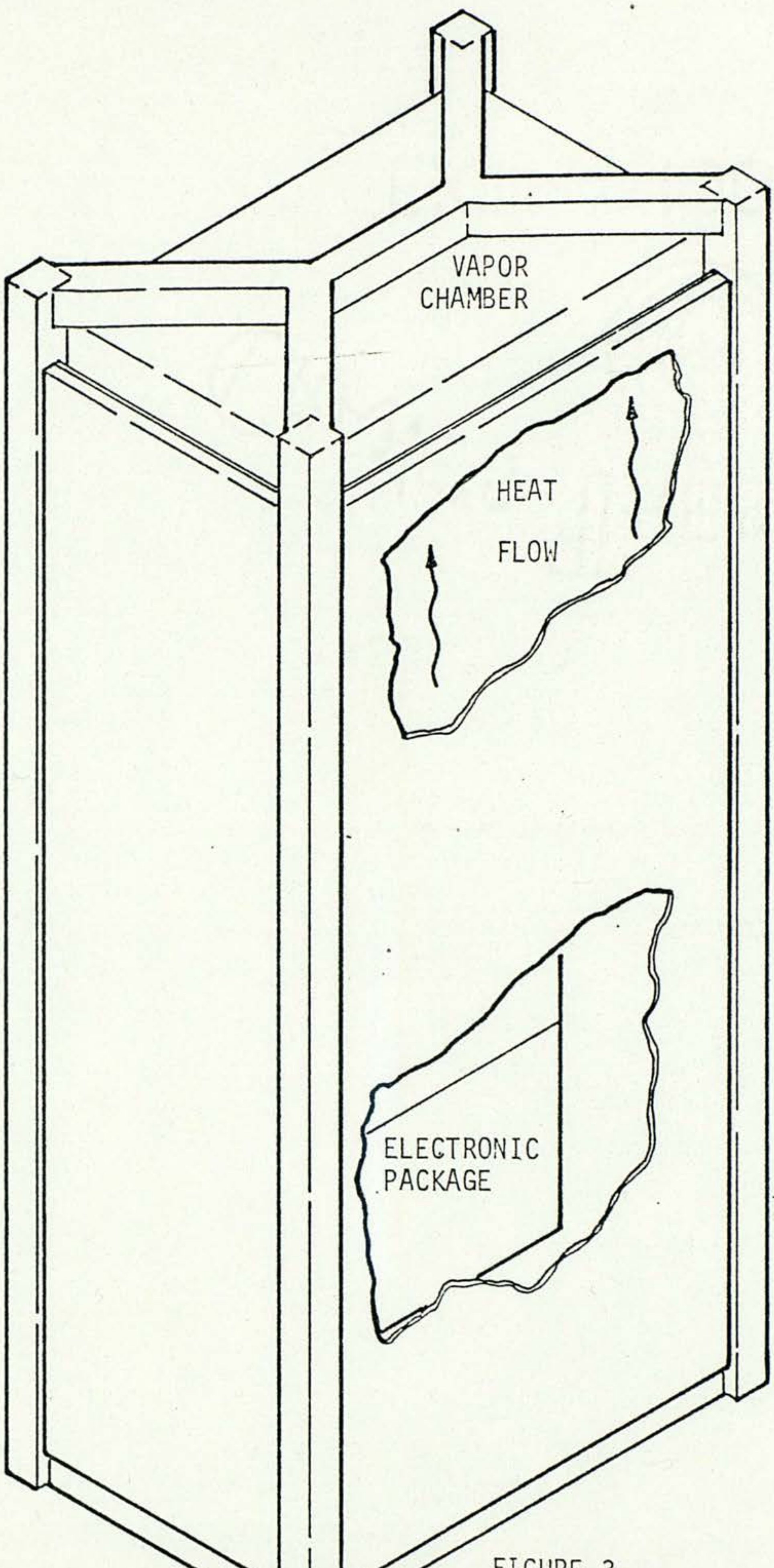


FIGURE 3.

INSTALLED VAPOR CHAMBER

determined, the working fluid and vapor chamber materials could be investigated.

WORKING FLUIDS

The vapor chamber operating temperature is dictated by the working fluid characteristics. Acceptable working fluid properties should include; high latent heat of vaporization, low viscosity, high surface tension, and should be compatable with the material of the vapor chamber[2,3,4]. Some working fluids are shown in Table 1 that were researched by early heat pipe investigators[6,7]. These investigators also conducted a study to determine what fluids would be compatible with a number of potential heat pipe envelope materials. A summary of this study is shown in Table 2. Water appears to have the most desirable characteristics in that it has the highest latent heat, high surface tension and low viscosity. However, from a knowledge of the thermodynamics of water it is known that at temperatures above 212°F (100°C) very high vapor pressures exist. Increasing the vapor chamber wall structure to account for this can only be done by paying higher cost penalties and lower thermal conductivity penalties. Reference to Table 2 also points out that in the presence of the materials surveyed that non-condensing gasses are formed when water is used except in the case of copper and nickel. Both Dowtherm-A and Dowtherm-E fluids have similar thermal capacities which results in performance approximately one-fourth that of water. Their flash points do present a

| FLUID | BOILING POINT (1 ATM) °F | LATENT HEAT BTU/LB | SURFACE TENSION DYNES/CM | PRESSURE AT 450°F PSIA | TOXIC | FLASH POINT °F | CRITICAL FLUX WATTS/IN $^2$ |
|---|---|---|---|---|---|---|---|
| WATER | 212 | 970 | 72 | 422 | NO | NONE | 703 |
| FC-43 | 345 | 30 | 16 | 23 | NO | NONE | 70 |
| DOWTHERM-E | 352 | 119 | 37 | 51 | SLIGHT | 285 | 192 |
| DOWTHERM-A | 495 | 128 | 40 | 8 | SLIGHT | 255 | 172 |
| CP-63 | 565 | 123 | 15 | N/A | N/A | N/A | 164 |
| CP-9 | 567 | 121 | 15 | N/A | N/A | N/A | 162 |

(N/A = Data not presently available)

TABLE 1 FLUID PROPERTIES [6]

| | $H_2O$ | ACETONE | AMONIA | METHONOL | DOWTHERM-A | DOWTHERM-E | FREON-113 |
|---|---|---|---|---|---|---|---|
| COPPER | RU | RU | NR | RU | RU | RU | UK |
| ALUMINUM | GNC | RL | RU | NR | UK | NR | RU |
| STAINLESS STEEL | GNT | PC | RU | GNT | RU | RU | UK |
| NICKLE | PC | PC | RU | RL | RU | RL | UK |

RU = Recommended by past successful usuage
RL = Recommended by literature
NR = Not recommended
UK = Unknown
GNC = Generates noncondensable gas at all temperatures
GNT = Generates noncondensable gas at high temperatures when oxide is present
PC = Probably compatable

TABLE 2 COMPATABILITY OF WORKING FLUIDS AND CHAMBER MATERIALS[7]

Potential fire hazard. It is also unknow according to the compatability study shown in Table 2 whether or not Dowtherm-A is compatible with aluminum. According to Dow Chemical Company[8], Dowtherm-A has very low vapor pressure at the temperatures in the range of 75°F to 132°F. These vapor pressures are on the order of .001 to .005 psia. Aparticular reason for avoiding low vapor pressures is that small amounts of air or other non-condensable gasses in the vapor chamber are most likely to interfere with the heat transfer process[4]. According to Reference 4, other suitable liquids that might be considered for this temperature range would be the Freons. Further investigation resulted in locating trichlorotrifluoroethane (FR-113) which has a boiling point of 117.6°F at 0 psig or 14.7 psia. The complete Thermodynamic Properties of FR-113 are given in Appendix A. Fr-113 is non-combustible and non-flamable (Underwriters' Laboratories Report MH3072, page 16) and much less toxic than Group 4 Classification (Same report, page 14). Using this fluid with a suitable vapor chamber material will allow steady-state operation at a minimal pressure condition thus alleviating the need to meet Boiler and Pressure Vessel Codes.

The latent heat of vaporization 117.6°F, 0 psig is approximately 63.09 btu/lb. and the heat content of the vapor is approximately 96.12 btu/lb. The viscosities of the vapor phase and the liquid phase conditions are approximately 0.0108 centipoise and 0.497 centipoise respectively. These properties compare favorably with previously mentioned working fluid requirements given on page 18 and shown in Table 1.

VAPOR CHAMBER MATERIALS

Depending on the operating state point of the system, the vapor chamber can sometimes be subjected to high internal pressures, as well as, be an integral structural member of a system. It is for these reasons that the chamber material should possess strength and compatibility with the fluid and the enclosure. The material selected must be readily available, possess the necessary properties to withstand the operating pressures of the fluid vapor, lend itself to standard manufacturing processes, exhibit high thermal conductivity, and be compatible with the selected working fluid. Of the materials shown in Table 3[7] copper is the best choice due to its high thermal conductivity, however, this material has a tendency to corrode in its natural state when subjected to hostile environments and its performance may deteriorate plus its cost per pound is relatively high compared to the other materials. Aluminum has a thermal conductivity higher than stainless steel and is also known to be easier to machine and form. On a cost basis aluminum and stainless steel compare favorably. For these reasons 6061 annealed aluminum was selected.

The freon family and aluminum are indeed compatible as is

| Material | Condition | Thermal Conductivity $\frac{\text{Btu-ft}}{\text{hr-ft}^2\text{-}^{\circ}\text{F}}$ | Yield Stress Psi | Density $10^{-2}$ lb/in$^3$ | Specific Heat $10^{-2}$ Btu/lb$^{\circ}$F | Cost Per Pound \$[10] |
|---|---|---|---|---|---|---|
| Aluminum | T-6 | .99 | 40 | 9.8 | 23 | 1.17 |
| | Annealed | | 8 | | | |
| Copper (OHFC) | Hard | 226 | 40 | 32.3 | 9.2 | 1.88 |
| | Annealed | | 10 | | | |
| Stainless Steel (304) | Hard | 9.4 | 75 | 29 | 12 | 1.24 |
| | Annealed | | 35 | | | |
| Monel (K-500) | Hard | 10.1 | 90 | 32 | 10 | 8.05 |
| | Annealed | | 40 | | | |

TABLE 3. VAPOR CHAMBER MATERIALS[7,10]

evidenced in their heavy uses in air conditioning systems where aluminum parts are continually subjected to freom fluid-vapor contact. It was assumed the strength of aluminum would be satisfactory since the steady-state operating point of FR-113 is 0 psig or below. This assumption was not adequate after completion and preliminary testing of the initial vapor chamber. This matter is discussed further in the later portion of this chapter.

## FIRST PROTOTYPE VAPOR CHAMBER

Based upon the foregoing investigation the first test chamber was designed and constructed. The structure is shown in Figure 4. Note should be taken of the diagonal creases on the upper and lower surfaces. Their purpose is twofold. First, it inherently strengthens the chamber and secondly it promotes increased efficiency in the return flow of the condensate much in the same manner as stalactites that are found in underground caves. Although the natural finish of 6061 aluminum is not polished, it can be considered smooth for all practical purposes. This is a desirable characteristic for the promotion of drop-wise condensation as was pointed out in the earlier discussion beginning on page 13 of this chapter.

## PERFORMANCE CHARACTERISTICS OF THE FIRST VAPOR CHAMBER

The performance characteristics of the first vapor chamber

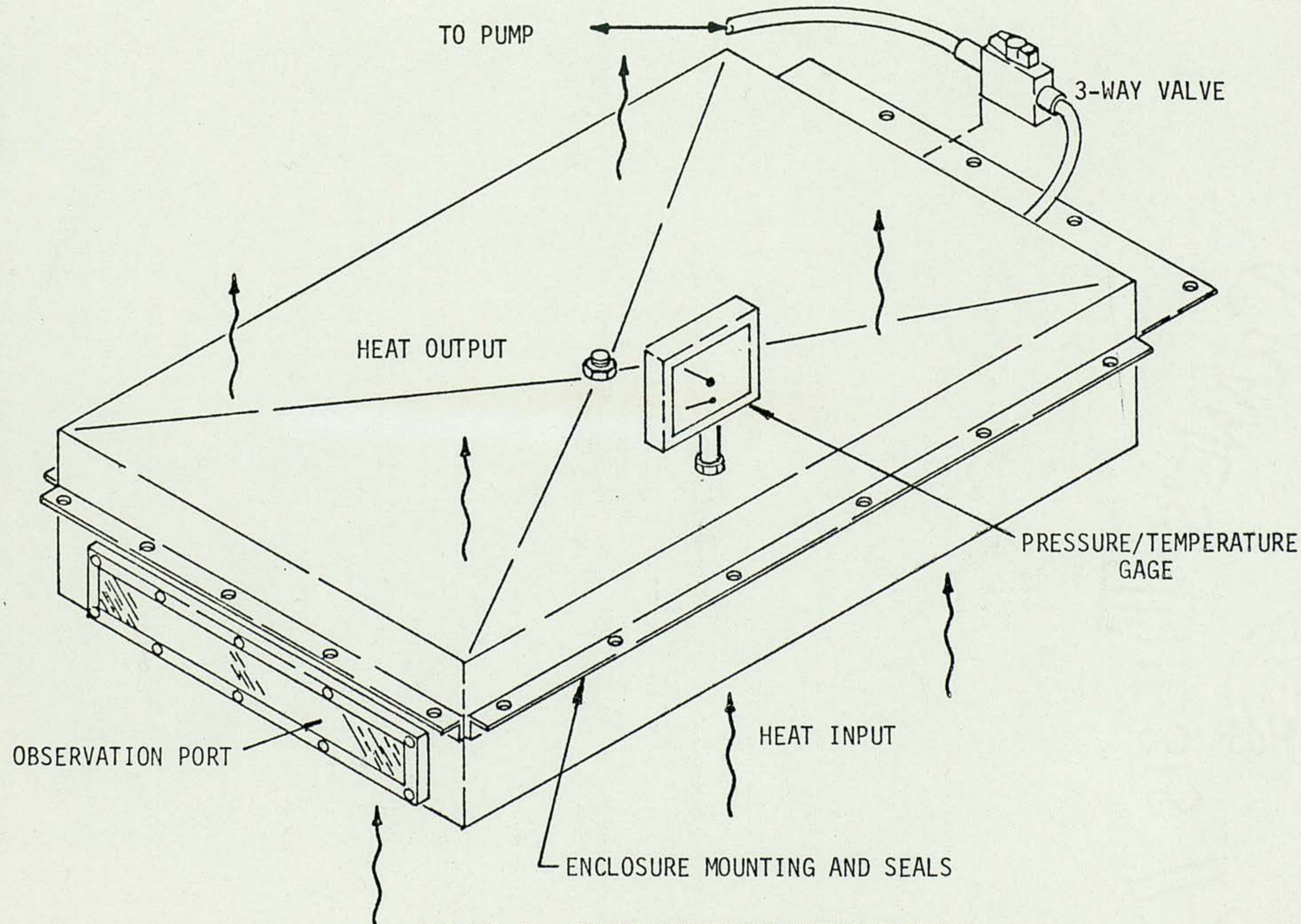


FIGURE 4. FIRST PROTOTYPE VAPOR CHAMBER

design were less than satisfactory for the following reasons.

The observation ports required numerous mechanical fasteners and gaskets. This requirement made it impossible to obtain a total seal in the chamber.

When the chamber was evacuated prior to operation, the condensor and evaporator deformed considerably even when a stiffening post was placed in the center. This deformation resulted in a non-uniform liquid level over the evaporator which in turn made for non-uniform evaporation when heat was subjected to the chamber base.

When the chamber reached the state point where the internal pressure was 0 psig, it became apparent that the apparatus had to be leveled in order to insure a uniform liquid layer over the evaporator. This leveling requirement may be difficult to achieve in a real system.

One gallon of Freon 113 was placed in the chamber. The working fluid along with the material of the chamber required a warm-up time of 30 minutes before reaching equilibrium. This amount of time could be detrimental to a real system.

Even in light of these short comings some positive results were obtained.

During one test run, the following conditions existed. The room temperature was 75$^{o}$F, the internal enclosure temperature stabilized at 135°F with a known heat input of 1600 watts (5460 btu/hr).

The overall heat transfer coefficient was calculated to be[11]:

$$U = \frac{Q}{A(T_i - T_o)} = 20.6 \frac{btu}{ft^2\text{-}°F} \qquad (5)$$

Where $U$ = Overall heat transfer coefficient

$Q$ = Heat load (btu/hr)

$A$ = Surface area ($ft^2$)

$T_i$ = Inside cabinet temperature (°F)

$T_o$ = Room ambient temperature (°F)

The vapor was observed to condense readily on the creased roof structure in the form of droplets and return at asteady rate via the creasess and center support post to the evaporator.

Due to the minimal success gained on the first chamber model the author decided to build a second embodying what was learned from the first.

SECOND PROTOTYPE VAPOR CHAMBER

The same working fluid and chamber material were used, however, a smaller amount of fluid to lower to lower the warm-up time was considered and the mechanical package of the vapor chamber turned out to be substantially different. The same external dimensions were used in the second chamber unit with the exception of the height. It was reduced to two inches. There appeared to be no advantage gained from the first unit which was five inches high except to provide suitable space for the observation ports. In the first model the condensate collection and return appeared to be sufficient, hence, there was no further need for the observation ports with their inherent sealing problems.

The problems associated with the deflection of the evaporator and the condensor plates were eliminated by placing an aluminum grid work inside the chamber. Assuming simply supported plate grid sections, the optimum spacing was obtained from[12]

$$\max y = \alpha \frac{wb^4}{Et^3} \qquad (6)$$

where
- $y$ = Maximum deflection at the center
- $\alpha$ = Shape factor
- $w$ = Load
- $b$ = Grid spacing
- $E$ = Modulus of elasticity
- $t$ = Plate thickness

A uniform load of 20 pounds per square inch would obtain a maximum deflection of .006 inches with a plate .062 inches thick. This grid space worked out to be approximately 2 inches by 2 inches. See Figure 5 for the resulting second design. In order to insure that the vapor circulates as freely as possible

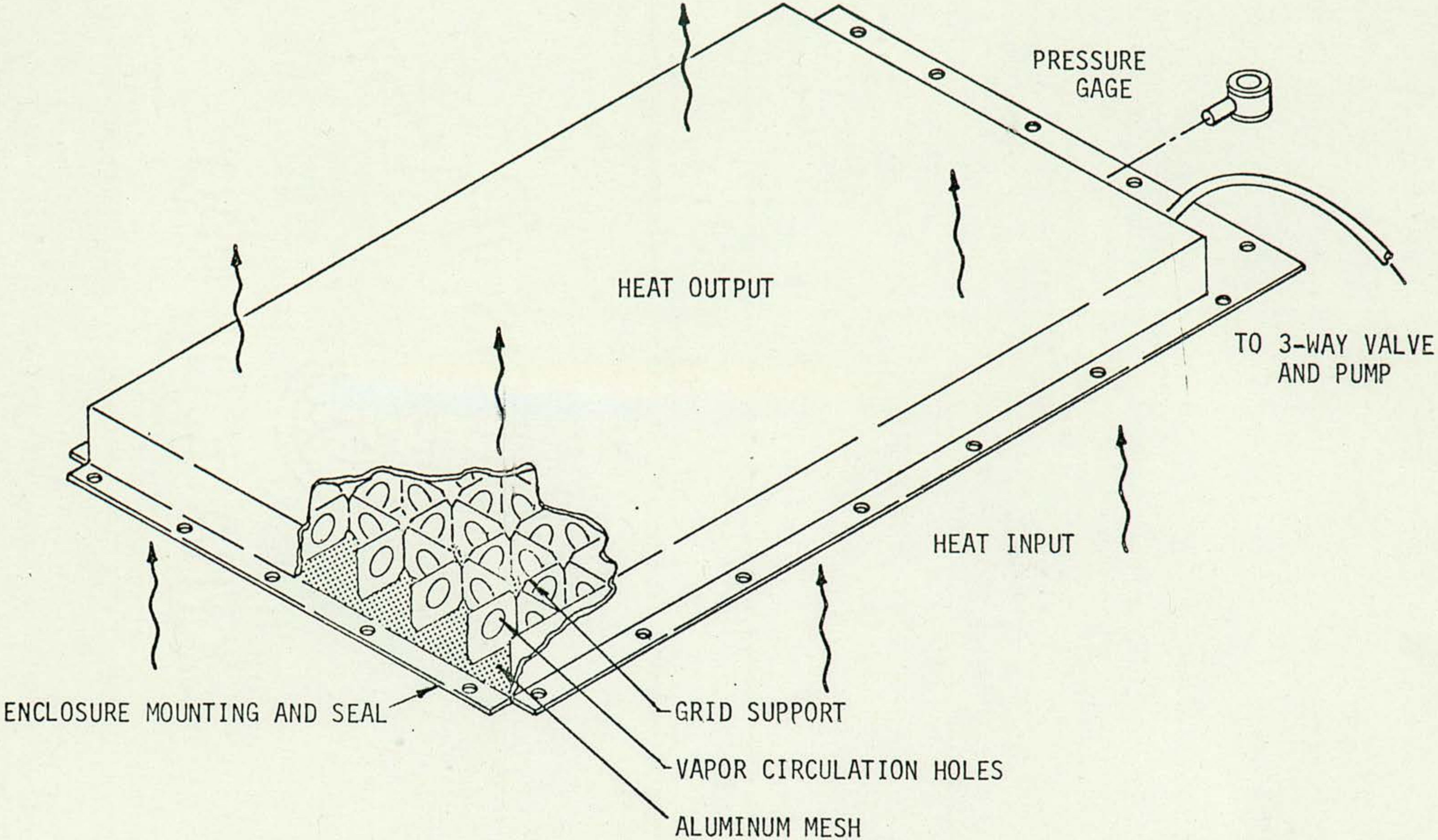


FIGURE 5. SECOND PROTOTYPE VAPOR CHAMBER

throughout the grid pattern, holes were strategically placed as shown in Figure 5. With this gridwork it became obvious that the fluid level in a given cell could burn out depending on how the input heat load was applied to the bottom of the evaporator. To prevent this from occuring, it was decided to place several layers of mesh aluminum screen wire between the grid supports and the evaporator plate. Refer to Figure 5.

ALUMINUM MESH CONSIDERATIONS

The mesh had to be designed to contain sufficient working fluid to operate satisfactorily for the intended heat load. This problem was solved by early heat pipe investigators and found to be[6]:

$$t_w = \frac{Q l_d \nu}{\gamma 4 L l_w r_c C_r} \qquad (7)$$

where $t_w$ = Screen thickness (inch)

$Q$ = Heat load (btu/hr)

$l_d$ = Distance between hot spots (inch)

$L$ = Latent heat of vaporization (btu/lb)

$l_w$ = Width of hot spots (inch)

$\gamma$ = Surface tension (lbs/hr$^2$)

$\nu$ = Kinematic viscosity (ft$^2$/hr)

$r_c$ = Pore size (inch)

$C_r$ = Capillary conductance

Reference 3 points out that this last term, $C_r$, is really a dimensionless ration of ($\epsilon$/b) where $\epsilon$ is defined as the wick porosity and b is a dimensionless geometrical factor that has approximate values of 8 for parallel non-connected cylindrical pores, and lies between 10 and 20 for realistic capillary structures with interconnected pores.

It turned out that this aluminum mesh solved another problem inherent in the first design. That is, a saturated mesh screen no longer required the evaporator to be precisely leveled in order to insure uniform liquid levels. The capillary pumping action provided by the screen insured that if burn-out did occur, working fluid would replenish that section.

It should be noted in passing that adding the aluminum mesh and the grid work complicates the mathematical model discussed in Chapter II. It was also discovered that during trials of the first prototype vapor chamber, no steps were taken to minimize any water vapor content that may be present in the chamber prior to operating. Conversations with heat transfer specialists pointed out that a 5% water vapor content can lower the heat transfer rate by as much as 50% in systems of this kind.[13]

FILLING PROCEDURE

In order to circumvent this possibility the following procedure was established. First an inert gas was introduced into the chamber to purge out as much water vapor as possible. Bottled nitrogen gas was utilized for this purpose. The vapor chamber was then evacuated with a vacuum pump. This vacuum in the chamber was utilized to introduce one quart of Freon 113. This amount of working fluid was sufficient to saturate the aluminum screen mesh. Finally, the vapor chamber was again evacuated to the state point required to start the trial runs.

TEST EQUIPMENT FOR THE FIRST VAPOR CHAMBER

The cost to instrument and measure the interface conditions inside the vapor chamber became too prohibitive. Hence, a multiple gage was mounted on the vapor chamber top of the first design to monitor gage pressure and temperature of the vapor. A three-way valve was installed to allow alteration of the beginning state point of the fluid via pumps. Refer to Figure 4. Suitable temperature probes were also placed inside the enclosure and on the vapor chamber top.

A heat source capable of 1600 watts (5460 Btu/Hr) continuous input was placed in the bottom of the electronic enclosure. With these known values including the outside and inside temperatures plus the vapor chamber geometry, the overall heat transfer coefficient could be determined from Equation (5) in this chapter.

TEST EQUIPMENT FOR THE SECOND VAPOR CHAMBER

It was felt that the measuring equipment used on the first vapor chamber was not adequate to measure the vapor pressure in that the multiple gage was only readable to + or - 2-1/2 psia. The following equipment and calibration procedure were used.

1. Statham Lab 0-15psia Pressure Transducer Model P96-15A-400
2. Digital Voltmeter. Triplett Model 8000
3. Trygon D.C. Power Supply. Model HR40-5B
4. U-Tube Manometer, Central Scientific Co. Model 44125
5. Vacuum Pump. Bendix Part Number 4-17125

CALIBRATION PROCEDURE

The above equipment was hooked up as is indicated in Figure 6. The excitation voltages used on the pressure transducer was 14 VDC. The digital voltmeter indicated 50 millivolts when measuring one atmosphere. The U-tube manometer indicated equal legs of 515 mm Hg when measuring one atmosphere.

For a U-tube manometer, the pressure relation is given by[14]

$$P - P_a = h(\rho_{hg} - \rho_a) \qquad (7)$$

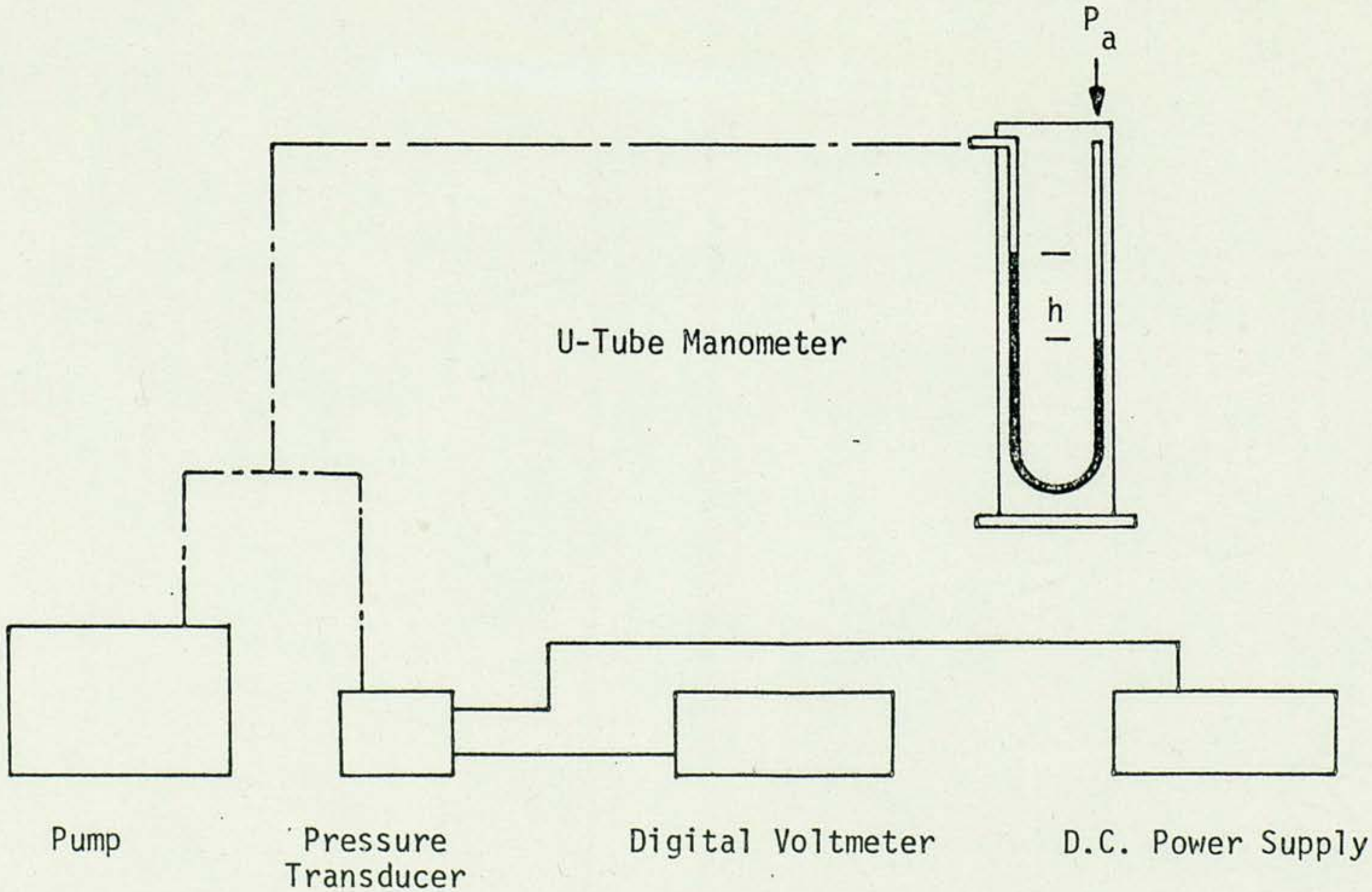


FIGURE 6. PRESSURE TRANSDUCER CALIBRATION SET UP

where $P$ = Unknown pressure (psia)

$P_a$ = Atmospheric pressure (psia)

$\rho_{Hg}$ = Density of mercury ($lb/ft^3$)

$\rho_a$ = Density of air ($lb/ft^3$)

$h$ = Differential column height of mercury. (inch)

The vacuum pump was turned on and adjusted to several pressure settings via a valve. At each of these settings the differential column of mercury was recorded along with a reading in millivolts sensed by the digital volt meter. The unknown pressure was calculated by using Equation (7) for each of 6 points. This data is tabulated in Table 4 shown below. The corresponding pressure curve versus millivolt readings are shown on Figure 7.

| h mm-Hg | h inch | P psia | Voltage millivolts |
|---|---|---|---|
| 0 | 0 | 14.70 | 50.00 |
| 57 | 2.24 | 13.60 | 44.50 |
| 91 | 3.58 | 12.95 | 41.40 |
| 291 | 11.46 | 9.08 | 28.80 |
| 392 | 15.43 | 7.14 | 21.80 |
| 491 | 19.33 | 5.23 | 15.50 |

TABLE 4. CALIBRATION POINTS

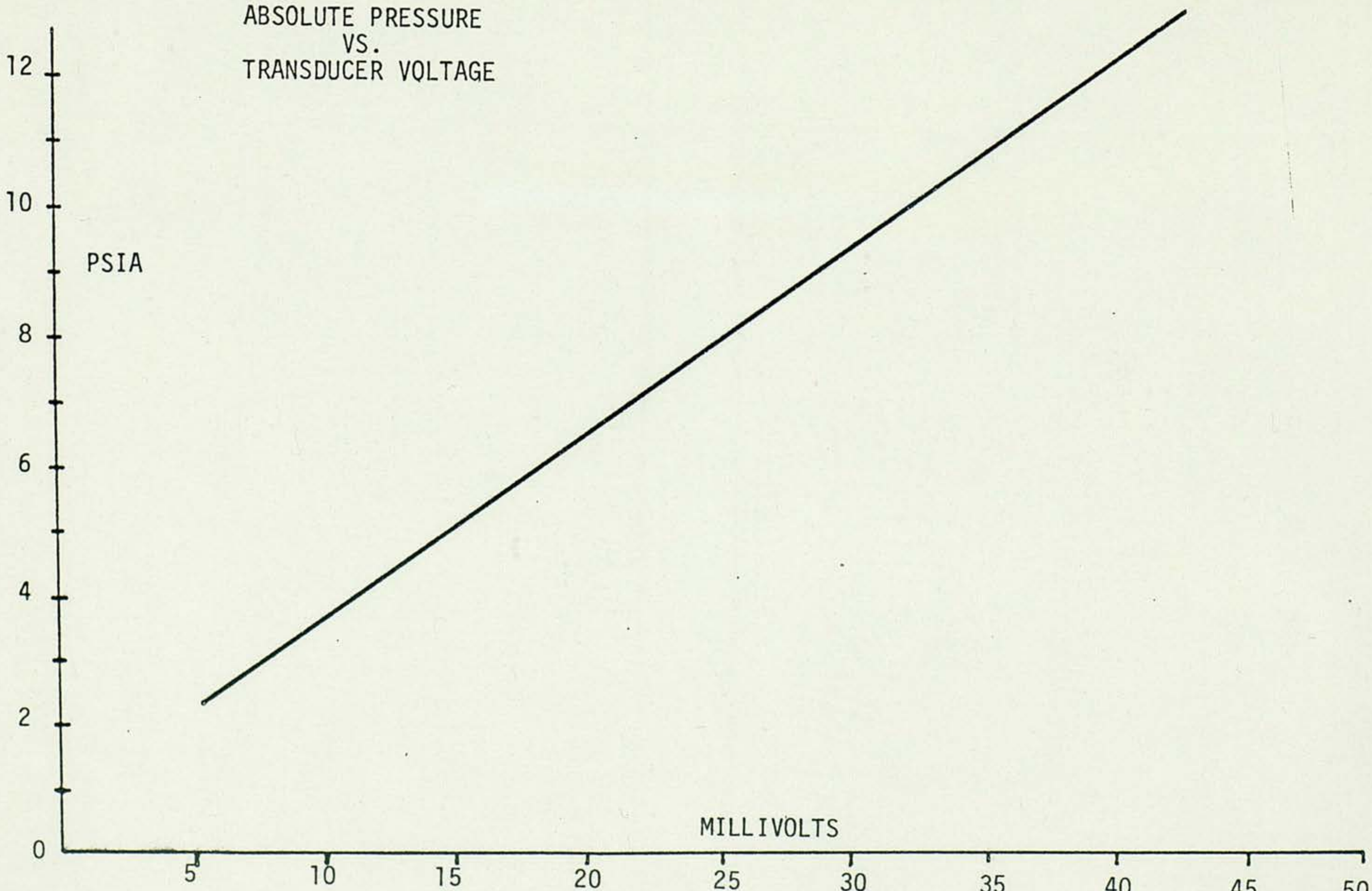


FIGURE 7. PRESSURE TRANSDUCER CALIBRATION CURVE

The maximum pressure that the transducer could be subjected to was 15 psia. Care had to be exercised when condtions of the test runs brought the pressure close to one atmosphere.

CHAPTER IV

# PERFORMANCE CHARACTERISTICS OF THE VAPOR CHAMBER

## INTRODUCTION

In this chapter the operating characteristics of the vapor chamber will be presented. The second chamber was constructed and installed in the equipment enclosure as shown in Figure 3 page 17. A series of heat test runs were completed. It was felt that the performance could be best measured by comparing the steady-state temperature difference between room ambient and the internal enclosure with the vapor chamber installed versus the same enclosure with a normal top.

## FIRST HEAT TEST RUN

Insulated foam board walls were used instead of the normal steel walls on the equipment enclosure. The insulated walls minimized the conductive heat losses so that the effects of the vapor chamber could be better evaluated. The internal cabinet temperature rate increase ($dT_i/dt$) with the input heat load of 1600 watts (5460 Btu/Hr) proved to be too much for the vapor chamber. The Freon 113 became super heated and the resulting vapor pressure deformed the condensor and evaporator walls of the chamber. Leaks resulted due to cracked welds. The minute cracks that were propogated from the overpressurization proved to be difficult to find. The overpressure condition put a permanent set in the evaporator and condensor plates. Also, some of the internal aluminum grid-work was deformed. The vapor chamber had to be cut open and some of the grid plates had to be replaced. Figure 8 shows that the cabinet temperature climbed very rapidly to approximately 212°F. Due to the vapor chamber deformation the first series of test runs were halted. It was not determined in this test what the ultimate equillibrium condition would be. The temperature was certainly much higher than was reached by the first chamber design under similar conditions. The warm-up time was noted to be considerably faster than the first chamber. The reason for this appears to be the reduced mass of the second vapor chamber design.

The high temperature reached in this first test may have been due to several reasons. One, there may have been insufficient fluid in the chamber and it boiled off faster than the condensate could be returned to the evaporator. Secondly, there may have been some water vapor or other non-condensable gasses prohibiting the heat transfer in the vapor chamber. Lastly, the deformation of the chamber as the vapor pressure exceeded one atmosphere may have resulted in separating the aluminum screen mesh from

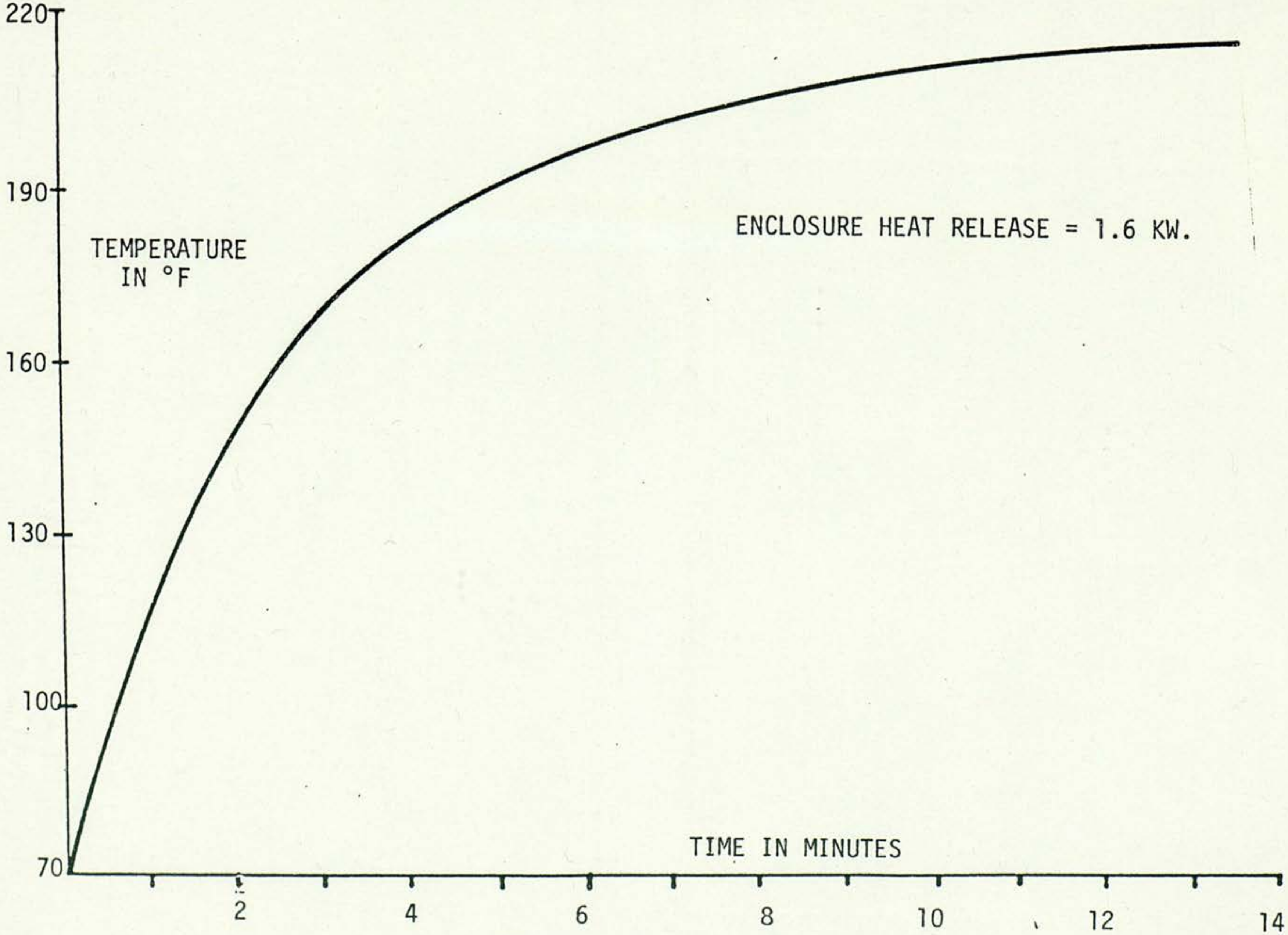


FIGURE 8. THERMAL RATE CURVE NO. 1

the evaporator increasing the thermal resistance.

When the vapor chamber was opened for repairs the following was noted. Some water drops were observed to be clining to the screen mesh. Some of the grid-work plates were deformed and the screen was separated from the evaporator. The defective parts were replaced and the vapor chamber was welded closed.

SECOND HEAT TEST RUN

Prior to making the second heat test, the vapor chamber was purged for 30 minutes with nitrogen gas to alleviate as much water vapor as possible that may have been present. Next, the chamber was evacuated to 2 psia and left untouched for 48 hours to insure no leaks were present. One quart of Freon 113 was introduced into the chamber and then evacuated to 2 psia for 24 hours. During this test run the heat source was cycled on and off to insure that the thermal shock would not repeat the chamber damage observed in the first test run. The temperature/time graph is shown on Figure 9. It is interesting to note that the equilibrium cabinet air temperature is substantially lower than that observed on the first test run. If the vapor chamber had withstood the dT/dt of the first heat test it may have stabilized to this temperature.

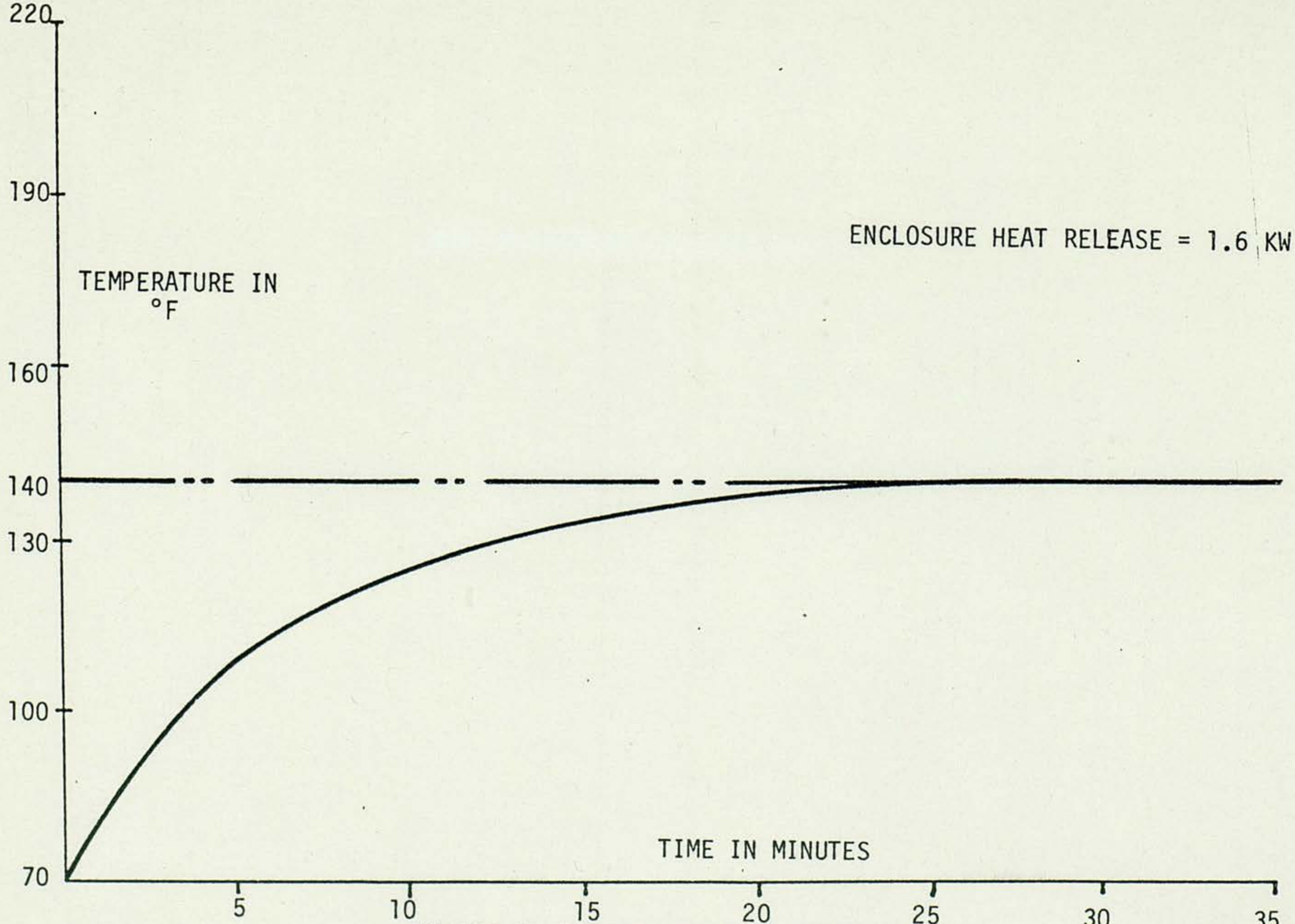


FIGURE 9. THERMAL RATE CURVE NO. 2

THIRD HEAT TEST RUN

In the concluding heat test run, the following changes were made to the test enclosure. First, the vapor chamber was removed and replaced by the normal top. This top was made from low carbon steel (1018) and had a polyurethane painted surface. Secondly, no attempt to lower the temperature rate of the enclosure was attempted. Figure 10 shows the results of this test run. Note should be taken of the time required to reach the equilibrium temperature of 170°F.

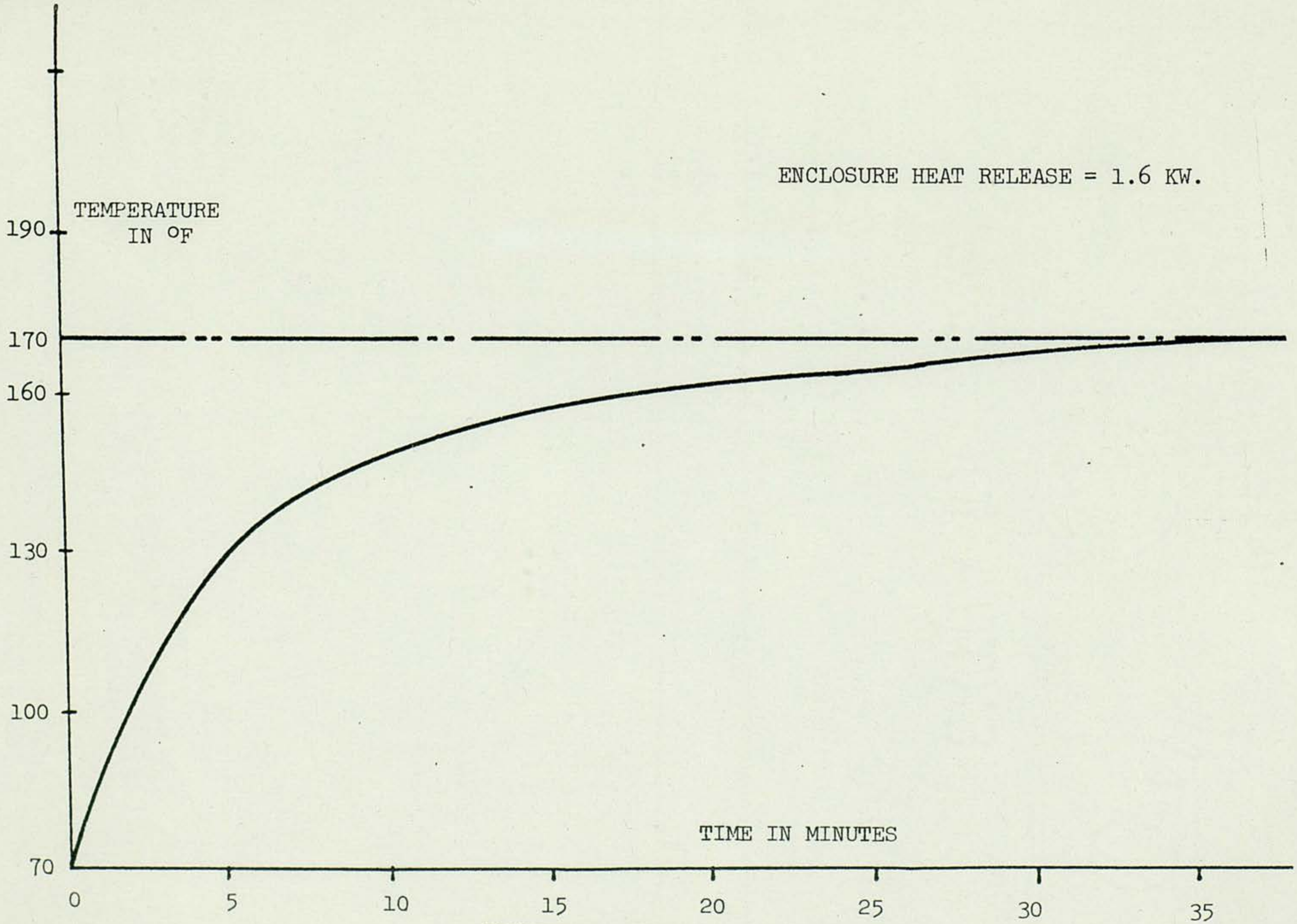

FIGURE 10. THERMAL RATE CURVE NO. 3

# CHAPTER V

# RESULTS AND CONCLUSIONS

## INTRODUCTION

It was concluded from the results outlined in Chapter IV that a heat exchanging device capable of operating effectively over a given temperature as might be experienced in a hostile environment as described in Chapter I is indeed feasible. Further, it can be made to meet the desired design characteristics as described on page 4 of Chapter I. These characteristics are repeated and discussed below.

## VAPOR CHAMBER DESIGN CRITERIA

1. The device should be able to work in conjunction with a sealed enclosure such as NEMA-12.

The electronic enclosure that the vapor chamber was tested on falls into the category of NEMA-12 rating when proper seals are applied at the wall and door joints.

2. If the device requires prime movers it would be desirable that they do not add to the heat load of the enclosure.

No prime movers were used in this particular application. It may be required to add an internal blower of some kind as well as an external blower to increase the heat transfer rate. This point will be discussed further in this chapter.

3. It would be highly desirable that the device require a minimum of enclosure volume.

The vapor chamber was placed on the electronic enclosure top which required no internal volume.

4. The device should be applicable to a variety of enclosure designs without requiring major changes.

It should be obvious to the reader that the simplicity of the vapor chamber design can be readily applied to most existing enclosure designs by simply fabricating the unit larger or smaller.

5. The device should operate under a closed system not requiring external supply lines.

The vapor chamber is indeed a closed system not requiring external sypply lines.

6. The device should be able to transfer high heat rates when small temperature differenced exist between internal and ambient operating conditions.

The heat load used in these tests on the vapor chamber resulted in a temperature difference of approximately 70°F. For this particular application, this is unsatisfactory since the safe operating temperature was specified as 132°F for the electronic packages in the enclosure. This point will be discussed further in this chapter.

7. The device should be able to be manufactured in a cost effective manner.

Preliminary cost data accumulated for the vapor chamber was $70.00. A 350 cfm base blower currently used to cool this enclosure cost $95.00. This of course does not include the cost of the vertical space of the enclosure housing the blower. Based upon this preliminary data the vapor chamber appears to be cost effective.

## ADDITIONAL RESULTS

A comparison of Figures 9 and 10 in Chapter IV shows that the vapor chamber under the heat load conditions pointed out actually resulted in the enclosure air temperature to be 30°F lower than when the normal equipment enclosure top was in place.

## CONCLUSIONS

It was pointed out earlier that heat pipes are capable of transferring heat at rates several orders of magnitudes greater than the best solid conductors of the same dimensions. In the tests performed comparing the vapor chamber installed and removed the only thing that could be concluded was that the vapor chamber performed better than the steel enclosure top when both were subjected to natural convection cooling to and from their external surfaces.

It seems reasonable to conclude that the performance of the vapor chamber could be improved by increasing the surface area of both the evaporator and condensor. It also seems reasonable to expect further performance enhancements by adding external and internal blowers to force convect the heat to and from the vapor chamber.

## HEAT PIPE HEAT EXCHANGER[15]

A new product called a Heat Pipe-Heat Exchanger has been developed by McLean Engineering Laboratories. The unit is 40-1/4 inches long by 16-1/2 inches wide by 8 inches deep, and consists of a bank of heat pipes and two dual centrifugal blowers. It is mounted on the door or mounting rails of an electronic rack and does not take up any interior cabinet space. Cabinet air is cooled and recirculated without introducing any outside contaminant. A dual centrifugal blower mounted in the bottom of the unit draws the hot cabinet air through the bottom half of the heat pipe bank, thus cooling it, and discharges this cool air into the cabinet at the rate of 350 CFM at0" S.P. A similar dual centrifugal blower mounted in teh top of the unit draws ambient air through the top half of the heat pipe bank, which in turn removes the heat from the heat pipes, and discharges this heated air to the atmosphere. Figure 11 shows the performance curve of this unit under conditions of no blower, bottom blower only, and both blowers operating. It is interesting to note

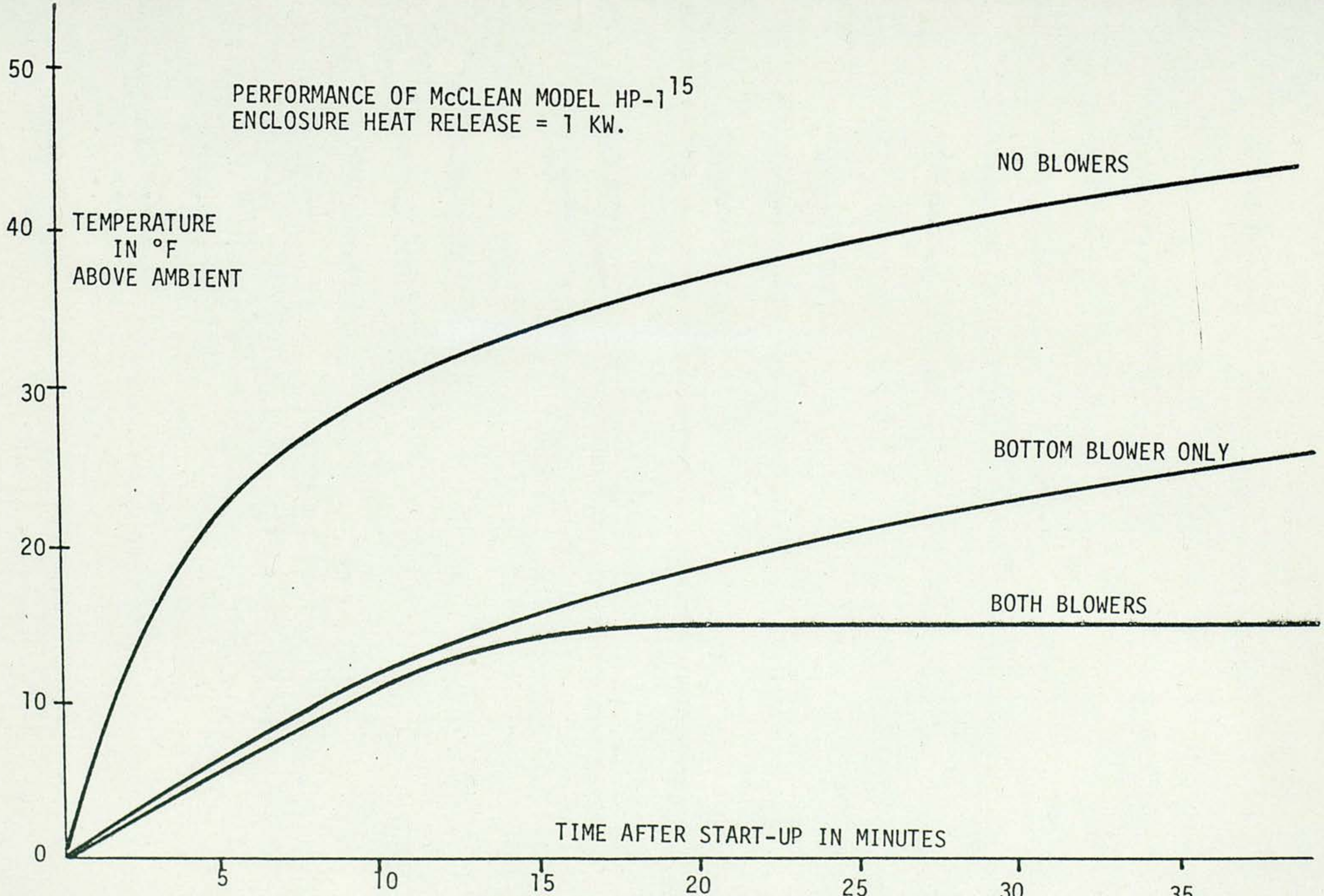


FIGURE 11. THERMAL RATE CURVE NO. 4

that the McClean unit operating under the conditions of no blowers shows that the enclosure temperature rises to approximately 45°F above ambient. Note should be taken that their tests were based upon using a heat load of 1000 watts as compared with 1600 watts used on the vapor chamber tests. The McClean heat exchanger employs copper heat pipes using water as the working fluid. The reader will recall that the working fluid used in the vapor chamber, Freon 113, had a latent heat of vaporization many times lower than that of water. The results obtained from McClean Laboratories further strengthens the author's conclusions as to what effect the blowers and increased surface area of the condensor and evaporator may have on the performance of the vapor chamber. It also strengthens the viability of the vapor chamber as a device for cooling electronic enclosure in hostile environments.

These results showed enough promise that a patent search was propogated by Westinghouse Electric Corporation. The search which resulted showed no activity of a device such as this being applied for enclosure cooling. A patent was formally written and filed. A copy of this document is contained in Appendix B. At this writing, the patent on the vapor chamber is pending.

FURTHER STUDY

It would be premature to release this concept for manufacturing before more study and tests can be performed. For example, the tests were performed on the vapor chamber at sea level conditions. A vapor chamber operating at higher altitudes may not perform the same. More tests need to be run in order to determine the transient warm-up time. In some instances expensive equipment could be destroyed if they are overheated before the vapor chamber can respond properly.

## DOWTHERM A

Late in the investigation of the vapor chamber it was learned from Dow Chemical Company that Dowtherm-A is indeed compatible with aluminum. It would be highly desirable to run further tests on the vapor chamber using Dowtherm-A since this particular working fluid has a latent heat of vaporization approximately three times as great as Freon 113[8]. The fluid is undesirable due to its flash point and toxicity, however, since only small amounts of the fluid are required in the vapor chamber it may turn out to be a more suitable working fluid.

## COMPUTER MATH MODEL

A math model of the operating vapor chamber in the form of a computer program is needed to accurately predict the design parameters needed to match a vapor chamber to a known set or required working conditions. This will minimize the engineering costs on new applications. A good starting point for such a program would be the programs developed on heat pipes shown in detail in Reference 3.

PRESSURE BUFFER

Further investigation needs to be done on a device to take care of those instances when superheated vapor is present causing high vapor pressures and subsequent structural damage to the vapor chamber. One consideration would be to attach some sort of a bellows that would be in contact with the vapor whose function would be to accomodate the high vapor pressure experienced during the warm-up period of a system.

CASCADED VAPOR CHAMBERS

Another application of this concept could be to cascade several vapor chambers in series each programmed to operate at different state points. This could be readily applied to a control system containing packages that can only be operate safely at different temperatures. A good example of this would be a mass-memory storage device such as a moving head disk. This piece of equipment has a safe operating upper temperature of 90°F. It is conceivable that the moving head disk could be placed in the same equipment enclosure housing a computer which operates at an upper temperature of 132°F. A small vapor chamber could be placed on the top of the moving head disk. Ths disk would in turn be placed below the computer electronic package. The small vapor chamber would allow the moving head disk to operate safely at 90°F and a second chamber on the enclosure as described in this thesis would allow the system to operate safely. The net result being that the system containing the packages of varying sensitivity could realistically be operated at higher net temperatures.

VAPOR CHAMBER AIDED BY HEAT PIPES

A final application worthy of further study would be to consider using heat pipes in conjunction with a vapor chamber as described in this thesis. Heat pipes could be used to bring the heat from localized hot spots within a given electronic package to the vapor chamber which is placed on the enclosure. The obvious advantage of a system comprised of these elements would be the elimination of small fans and blowers that are currently used to cool localized hot spots in electronic packages. These small fans and blowers are a constant maintenance problem as well as heat additions to the overall enclosure.

APPENDIX

# Thermodynamic Properties

of

# "FREON" 113

# TRICHLOROTRIFLUOROETHANE

# $CCl_2F\text{-}CClF_2$

With Addition

of

Other Physical Properties

# THE THERMODYNAMIC PROPERTIES OF "FREON" 113 ($CCl_2F$-$CClF_2$)

**A. F. Benning and R. C. McHarness**

THESE tables are the result of a research program which was undertaken to provide the refrigeration industry with tables of the thermodynamic properties of "Freon" 113 which would be characterized by completeness in both the saturated and superheat ranges, thermodynamic consistency, and a satisfactory degree of accuracy. Inasmuch as the literature contains very little information about "Freon" 113 it was necessary to determine experimentally all the physical properties that were needed for the calculation of the tables. The methods used were those generally accepted as giving results of sufficient accuracy. The experimental ranges covered were such as would permit the calculation of tables which were both complete and consistent.

The following physical properties were measured over the indicated ranges:

(1) Vapor pressure between 1.5 and 475 lbs. per sq. in. abs.

(2) Pressure-volume-temperature relationships of the superheated vapor over the pressure range of 5 to 310 lb. per sq. in. abs.

(3) Density of the liquid between −20°F. and +410°F.

(4) Specific heat of the vapor at constant pressure of one atmosphere ($c_p$) at 185°F. and 275°F.

(5) Specific heat of the liquid at 10°, 35°, 75°, 110° and 145°F.

(6) The ratio ($c_p/c_v$) of the vapor at 170°F. and 210°F.

The equations derived from the experimental measurements outlined above and which were used to calculate the tables of thermodynamic properties are given below.

t—temperature in °F.

T—temperature in °R. = °F. + 459.6

p—pressure in lb. per sq. in. abs.

v—volume of the vapor in ft.³ per lb.

d—density of the vapor in lb. per ft.³ = 1/v.

$d_f$—density of the liquid in lb. per ft.³

$c_p$—specific heat of the vapor at constant pressure in Btu. per lb. per °F.

(1) *Vapor pressure*

$$\log_{10} p = 33.0655 - \frac{4330.98}{T} - 9.2635 \log_{10} T + 0.0020539T.$$

(2) *Equation of State (Beattie-Bridgeman)*

$$p = (0.0000500T - 0.0214)d^4 + (0.002618T - 4.035)d^2 + 0.05728Td$$

(3) *Liquid Density*

$$d_f = 103.555 - 0.07126t - 0.0000636t^2$$

(4) *Specific heat of the Vapor at Constant Pressure.*

$$c_p \text{ (1 atm.)} = 0.1455 + 0.000111t$$

The equations given above, which represent the experimentally determined properties of this material, were used to define a complete consistent thermodynamic network. Equations interrelating the quantities needed for the tables were obtained therefrom and used for the calculation of the tabular values.

All the saturated values of the pressure, volume, density, latent heat of vaporization and entropy of vaporization were calculated directly from the equations. The tabular values of the heat content of the saturated vapor and entropy of the liquid were obtained by interpolation between exact values calculated at 50°F. intervals. This interpolation was of such a nature that the method did not introduce any significant deviation from values obtained directly from the equations.

A large scale plot of the deviation of the superheated vapor from the ideal gas equation was prepared from values calculated from the experimentally determined equation of state, at 20°F. intervals of temperature and intervals of approximately 2% in the deviation. The tabular values of the superheat volume were then obtained by individual calculation of the ideal gas volume followed by correction from the deviation plot. This method did not introduce errors greater than 0.1%.

The heat content of the superheated vapor was calculated at 10°F. intervals of temperature along isometrics at the lowest and highest densities occurring in the saturated table and at 50°F. intervals along three intermediate isometrics. The equations used in these calculations were those which show the change in the heat content of the vapor at constant volume and at constant temperature. They were derived from equations (1) to (4) by the use of various well known thermodynamic relationships. The heat contents at tabular values of pressure and temperature were obtained from these data by suitable methods of interpolation.

The entropy of the superheated vapor was calculated at 50°F. intervals of temperature and at tabular values of pressure with the aid of the table of superheat volumes and the equations showing the change in the entropy of the vapor at constant volume and at constant temperature. Intermediate values were determined by an interpolation method which made use of the previously calculated values of the heat content of the superheated vapor. In all cases the interpolation methods used were refined to such an extent that they introduced no appreciable errors into the results.

The tables are necessarily consistent because only the minimum number of equations necessary for their calculation were used and these equations were exactly interrelated. Arithmetical accuracy was checked by the independent calculation of one-fifth of the entire table. Less than one percent of these values showed any significant deviation from those in the complete tables and these were recalculated. All vertical differences in the final tables were checked, and any values that were out of line were recalculated. In addition, the differences between respective constant pressure tables in the superheat region were checked at two temperatures. As a result of these precautions it is felt that the tables are practically free from arithmetical errors.

The overall accuracy of the tables may be judged by calculating certain additional properties from the data at hand and comparing the results with those obtained from independent experimental measurements. Thus, the specific heat of the liquid can be determined from the heat contents of the liquid given in the table of saturated properties and compared with experimental values. The tables give values of 0.203, 0.214 and 0.233 B.T.U. per lb. per F. at 11°, 73° and 146°F. respectively. The corresponding quantities, as determined by direct calorimetric measurements, were 0.212, 0.220 and 0.223. The ratio of $c_p$ to $c_v$ at a pressure of one atmosphere was calculated as 1.077 at 171°F. and 1.073 at 212°F. The corresponding experimental values, as determined from the speed of sound in "Freon" 113 vapor, were 1.081 and 1.077. These quantities are in good agreement and constitute an excellent check on the accuracy of the tables and the data and equations from which they were derived.

In the low temperature portion of the table, namely below 10°F., the accuracy of the data is not as good as that of the remainder of the table. It is estimated that errors in this region may amount to several percent. Inaccuracies in this portion of the table do not affect the rest of the data because the methods of calculation were designed to eliminate such effects.

This work was made possible through the facilities of the Jackson Laboratory, E. I. du Pont de Nemours & Company.

NOTATION. The symbols used in this circular are taken from the American Standard Symbols for Heat and Thermodynamics, except in the case of tables of superheated properties for volume, heat content and entropy (V, H, S). Properly these are unit quantities and should be symbolized by lower case letters but the capitals are retained for legibility.

## PHYSICAL PROPERTIES OF TRICHLOROTRIFLUOROETHANE "FREON" 113

Chemical Formula—$CCl_2F\text{-}CClF_2$
Molecular Weight—187.39
Boiling Point (760 mm—1 atm.)
117.6°F. (47.6°C.)
Melting Point -31°F. (-35°C.)
Critical Temperature—417.4°F. (214.1°C.)
Critical Pressure—495 lbs./in.$^2$ abs.
Color—Clear and water white
Odor—Ethereal and similar to Carbon tetrachloride
Moisture—Not more than 0.0025% by weight
High Boiling Impurities—Not more than 0.05% by volume
Chlorides—None
Toxicity—Much less toxic than Group 4. Classification of Underwriters' Laboratories Report MH 3072—page 14.
Flammability—Noncombustible and nonflammable. Underwriters' Laboratories Report MH3072—page 16.

| | Temp. °F. | $c_p$ | $c_v$ | $c_p/c_v$ |
|---|---|---|---|---|
| Specific Heat | 160 | 0.1633 | 0.1516 | 1.077 |
| of Vapor | 210 | .1688 | .1573 | 1.073 |
| (1 atm.) | 260 | 0.1744 | 0.1630 | 1.070 |

| | °F. | Vapor | Liquid (Saturation Pressure) |
|---|---|---|---|
| | | Centipoises | |
| | -20 | 0.0090 | 1.566 |
| | 0 | .0093 | 1.263 |
| | 20 | .0095 | 1.043 |
| | 40 | .0098 | 0.876 |
| | 60 | .0101 | .747 |
| | 80 | .0103 | .646 |
| Viscosity | 100 | .0106 | .564 |
| | 120 | .0108 | .497 |
| | 140 | .0111 | .442 |
| | 160 | .0113 | .395 |
| | 180 | .0116 | .356 |
| | 200 | .0118 | .322 |
| | 220 | .0120 | .293 |
| | 240 | 0.0123 | 0.268 |

## PROPERTIES OF SATURATED VAPOR

| Temp | Pressure | | Volume | | Density | | Heat Content from —40° | | | Entropy from —40° | | Temp. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| °F t | Abs. lb./in.² $p$ | Gage lb./in.² $p_d$ | Liquid ft.³/lb. $v_f$ | Vapor ft.³/lb. $v_g$ | Liquid lb./ft.³ $1/v_f$ | Vapor lb./ft.³ $1/v_g$ | Liquid Btu./lb. $h_f$ | Latent Btu./lb. $h$ | Vapor Btu./lb. $h_g$ | Liquid Btu./lb. °F. $s_f$ | Vapor Btu./lb. °F. $s_g$ | °F. t |
| −30 | 0.2987 | 29.31* | 0.00947 | 82.26 | 105.64 | 0.01216 | 1.97 | 72.68 | 74.65 | 0.0047 | 0.1738 | −30 |
| −28 | .3214 | 29.27* | .00948 | 76.81 | 105.50 | .01302 | 2.36 | 72.57 | 74.93 | .0056 | .1737 | −28 |
| −26 | .3458 | 29.22* | .00949 | 71.71 | 105.37 | .01395 | 2.76 | 72.45 | 75.21 | .0065 | .1736 | −26 |
| −24 | .3718 | 29.16* | .00950 | 66.99 | 105.23 | .01493 | 3.16 | 72.33 | 75.49 | .0074 | .1735 | −24 |
| −22 | .3995 | 29.11* | .00952 | 62.63 | 105.09 | .01597 | 3.56 | 72.21 | 75.77 | .0083 | .1733 | −22 |
| −20 | 0.4288 | 29.05* | 0.00953 | 58.61 | 104.96 | 0.01706 | 3.96 | 72.09 | 76.05 | 0.0092 | 0.1732 | −20 |
| −18 | .4600 | 28.98* | .00954 | 54.88 | 104.82 | .01822 | 4.36 | 71.98 | 76.34 | .0101 | .1731 | −18 |
| −16 | .4931 | 28.92* | .00955 | 51.42 | 104.68 | .01945 | 4.76 | 71.86 | 76.62 | .0110 | .1730 | −16 |
| −14 | .5280 | 28.85* | .00957 | 48.23 | 104.54 | .02074 | 5.16 | 71.74 | 76.90 | .0119 | .1729 | −14 |
| −12 | .5652 | 28.77* | .00958 | 45.25 | 104.40 | .02210 | 5.56 | 71.62 | 77.18 | .0128 | .1729 | −12 |
| −10 | 0.6046 | 28.69* | 0.00959 | 42.48 | 104.26 | 0.02354 | 5.96 | 71.51 | 77.47 | 0.0137 | 0.1728 | −10 |
| − 8 | .6462 | 28.60* | .00960 | 39.92 | 104.12 | .02505 | 6.36 | 71.39 | 77.75 | .0146 | .1727 | − 8 |
| − 6 | .6902 | 28.51* | .00962 | 37.54 | 103.98 | .02664 | 6.76 | 71.27 | 78.03 | .0155 | .1726 | − 6 |
| − 4 | .7369 | 28.42* | .00963 | 35.31 | 103.84 | .02832 | 7.17 | 71.15 | 78.32 | .0164 | .1726 | − 4 |
| − 2 | .7860 | 28.32* | .00964 | 33.24 | 103.70 | .03009 | 7.57 | 71.03 | 78.60 | .0173 | .1725 | − 2 |
| 0 | 0.8377 | 28.21* | 0.00966 | 31.31 | 103.56 | 0.03194 | 7.98 | 70.92 | 78.89 | 0.0182 | 0.1725 | 0 |
| 2 | .8924 | 28.10* | .00967 | 29.52 | 103.41 | .03388 | 8.38 | 70.80 | 79.18 | .0190 | .1724 | 2 |
| 4 | .9503 | 27.99* | .00968 | 27.84 | 103.27 | .03592 | 8.78 | 70.68 | 79.46 | .0199 | .1724 | 4 |
| 5† | 0.9802 | 27.92* | .00969 | 27.04 | 103.20 | .03698 | 8.98 | 70.62 | 79.60 | .0203 | .1723 | 5† |
| 6 | 1.011 | 27.86* | .00970 | 26.27 | 103.13 | .03806 | 9.19 | 70.56 | 79.75 | .0208 | .1723 | 6 |
| 8 | 1.075 | 27.73* | .00971 | 24.81 | 102.98 | .04031 | 9.59 | 70.44 | 80.03 | .0216 | .1723 | 8 |
| 10 | 1.142 | 27.60* | 0.00972 | 23.45 | 102.84 | 0.04265 | 10.00 | 70.32 | 80.32 | 0.0225 | 0.1723 | 10 |
| 12 | 1.213 | 27.45* | .00974 | 22.17 | 102.69 | .04511 | 10.41 | 70.20 | 80.61 | .0234 | .1722 | 12 |
| 14 | 1.288 | 27.30* | .00975 | 20.97 | 102.55 | .04769 | 10.81 | 70.08 | 80.89 | .0242 | .1722 | 14 |
| 16 | 1.366 | 27.14* | .00977 | 19.84 | 102.40 | .05040 | 11.22 | 69.96 | 81.18 | .0251 | .1722 | 16 |
| 18 | 1.448 | 26.97* | .00978 | 18.79 | 102.25 | .05322 | 11.62 | 69.84 | 81.46 | .0259 | .1722 | 18 |
| 20 | 1.534 | 26.80* | 0.00979 | 17.81 | 102.10 | 0.05616 | 12.03 | 69.72 | 81.75 | 0.0268 | 0.1722 | 20 |
| 22 | 1.624 | 26.61* | .00981 | 16.89 | 101.96 | .05922 | 12.44 | 69.60 | 82.04 | .0276 | .1721 | 22 |
| 24 | 1.719 | 26.42* | .00982 | 16.02 | 101.81 | .06243 | 12.85 | 69.48 | 82.33 | .0285 | .1721 | 24 |
| 26 | 1.818 | 26.22* | .00984 | 15.20 | 101.66 | .06579 | 13.26 | 69.36 | 82.62 | .0293 | .1722 | 26 |
| 28 | 1.922 | 26.01* | .00985 | 14.43 | 101.51 | .06929 | 13.67 | 69.24 | 82.91 | .0302 | .1722 | 28 |
| 30 | 2.031 | 25.79* | 0.00987 | 13.71 | 101.36 | 0.07294 | 14.08 | 69.12 | 83.20 | 0.0310 | 0.1722 | 30 |
| 32 | 2.145 | 25.55* | .00988 | 13.03 | 101.21 | .07675 | 14.49 | 69.00 | 83.49 | .0318 | .1722 | 32 |
| 34 | 2.264 | 25.31* | .00990 | 12.39 | 101.06 | .08071 | 14.91 | 68.87 | 83.78 | .0327 | .1722 | 34 |
| 36 | 2.388 | 25.06* | .00991 | 11.79 | 100.91 | .08483 | 15.32 | 68.75 | 84.07 | .0335 | .1722 | 36 |
| 38 | 2.519 | 24.79* | .00993 | 11.22 | 100.76 | .08913 | 15.74 | 68.62 | 84.36 | .0343 | .1722 | 38 |
| 40 | 2.655 | 24.52* | 0.00994 | 10.68 | 100.60 | 0.09361 | 16.16 | 68.50 | 84.65 | 0.0352 | 0.1723 | 40 |
| 42 | 2.797 | 24.23* | .00996 | 10.18 | 100.45 | .09826 | 16.57 | 68.37 | 84.94 | .0360 | .1723 | 42 |
| 44 | 2.944 | 23.93* | .00997 | 9.703 | 100.30 | .1031 | 16.99 | 68.25 | 85.24 | .0368 | .1723 | 44 |
| 46 | 3.098 | 23.61* | .00999 | 9.253 | 100.14 | .1081 | 17.41 | 68.12 | 85.53 | .0377 | .1724 | 46 |
| 48 | 3.258 | 23.29* | .01000 | 8.830 | 99.99 | .1133 | 17.82 | 68.00 | 85.82 | .0385 | .1724 | 48 |
| 50 | 3.427 | 22.94* | 0.01002 | 8.426 | 99.83 | 0.1187 | 18.24 | 67.87 | 86.11 | 0.0393 | 0.1725 | 50 |
| 52 | 3.602 | 22.59* | .01003 | 8.044 | 99.68 | .1243 | 18.66 | 67.74 | 86.40 | .0401 | .1726 | 52 |
| 54 | 3.784 | 22.22* | .01005 | 7.682 | 99.52 | .1302 | 19.08 | 67.61 | 86.69 | .0410 | .1726 | 54 |
| 56 | 3.973 | 21.83* | .01006 | 7.342 | 99.37 | .1362 | 19.50 | 67.48 | 86.98 | .0418 | .1727 | 56 |
| 58 | 4.170 | 21.43* | .01008 | 7.018 | 99.21 | .1425 | 19.93 | 67.35 | 87.28 | .0426 | .1727 | 58 |
| 60 | 4.374 | 21.02* | 0.01010 | 6.713 | 99.05 | 0.1490 | 20.35 | 67.22 | 87.57 | 0.0434 | 0.1728 | 60 |
| 62 | 4.586 | 20.59* | .01011 | 6.424 | 98.89 | .1557 | 20.77 | 67.09 | 87.86 | .0442 | .1729 | 62 |
| 64 | 4.807 | 20.14* | .01013 | 6.149 | 98.73 | .1626 | 21.19 | 66.96 | 88.15 | .0450 | .1729 | 64 |
| 66 | 5.036 | 19.67* | .01015 | 5.889 | 98.58 | .1698 | 21.62 | 66.83 | 88.45 | .0459 | .1730 | 66 |
| 68 | 5.275 | 19.18* | .01016 | 5.640 | 98.42 | .1773 | 22.05 | 66.69 | 88.74 | .0467 | .1731 | 68 |
| 70 | 5.523 | 18.68* | 0.01018 | 5.404 | 98.26 | 0.1851 | 22.48 | 66.56 | 89.04 | 0.0475 | 0.1731 | 70 |
| 72 | 5.780 | 18.16* | .01019 | 5.180 | 98.10 | .1931 | 22.90 | 66.43 | 89.33 | .0483 | .1732 | 72 |
| 74 | 6.042 | 17.62* | .01021 | 4.971 | 97.93 | .2012 | 23.33 | 66.29 | 89.62 | .0491 | .1733 | 74 |
| 76 | 6.320 | 17.06* | .01023 | 4.769 | 97.77 | .2097 | 23.76 | 66.16 | 89.92 | .0499 | .1734 | 76 |
| 78 | 6.607 | 16.47* | .01025 | 4.574 | 97.61 | .2186 | 24.19 | 66.02 | 90.21 | .0507 | .1735 | 78 |
| 80 | 6.902 | 15.87* | 0.01026 | 4.392 | 97.45 | 0.2277 | 24.63 | 65.88 | 90.51 | 0.0515 | 0.1736 | 80 |
| 82 | 7.208 | 15.25* | .01028 | 4.218 | 97.28 | .2371 | 25.06 | 65.74 | 90.80 | .0523 | .1737 | 82 |
| 84 | 7.527 | 14.60* | .01030 | 4.051 | 97.12 | .2468 | 25.49 | 65.60 | 91.09 | .0531 | .1738 | 84 |
| 86† | 7.856 | 13.93* | .01031 | 3.893 | 96.96 | .2569 | 25.93 | 65.46 | 91.39 | .0539 | .1739 | 86† |
| 88 | 8.194 | 13.24* | .01033 | 3.742 | 96.79 | .2672 | 26.36 | 65.32 | 91.68 | .0547 | .1740 | 88 |

* Inches of mercury below one atmosphere.
† Standard ton temperatures.

## PROPERTIES OF SATURATED VAPOR

| Temp. | Pressure | | Volume | | Density | | Heat Content from —40° | | | Entropy from —40° | | Temp. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| °F. $t$ | Abs. lb./in.² $p$ | Gage lb./in.² $p_d$ | Liquid ft.³/lb. $v_f$ | Vapor ft.³/lb. $v_g$ | Liquid lb./ft.³ $1/v_f$ | Vapor lb./ft.³ $1/v_g$ | Liquid Btu./lb. $h_f$ | Latent Btu./lb. $h$ | Vapor Btu./lb. $h_g$ | Liquid Btu./lb.°F. $s_f$ | Vapor Btu./lb.°F. $s_g$ | °F. $t$ |
| **90** | 8.545 | 12.53* | 0.01035 | 3.600 | 96.63 | 0.2778 | 26.80 | 65.18 | 91.98 | 0.0555 | 0.1741 | 90 |
| **92** | 8.908 | 11.79* | .01037 | 3.463 | 96.46 | .2888 | 27.24 | 65.04 | 92.28 | .0563 | .1742 | 92 |
| **94** | 9.281 | 11.03* | .01039 | 3.333 | 96.30 | .3001 | 27.67 | 64.90 | 92.57 | .0571 | .1743 | 94 |
| **96** | 9.668 | 10.24* | .01040 | 3.208 | 96.13 | .3117 | 28.11 | 64.75 | 92.86 | .0578 | .1744 | 96 |
| **98** | 10.07 | 9.42* | .01042 | 3.089 | 95.96 | .3237 | 28.55 | 64.60 | 93.15 | .0586 | .1745 | 98 |
| **100** | 10.48 | 8.59* | 0.01044 | 2.976 | 95.79 | 0.3360 | 28.99 | 64.46 | 93.45 | 0.0594 | 0.1746 | 100 |
| **102** | 10.91 | 7.71* | .01046 | 2.867 | 95.63 | .3488 | 29.44 | 64.31 | 93.75 | .0602 | .1747 | 102 |
| **104** | 11.35 | 6.82* | .01048 | 2.762 | 95.46 | .3620 | 29.89 | 64.16 | 94.05 | .0610 | .1748 | 104 |
| **106** | 11.81 | 5.88* | .01050 | 2.662 | 95.29 | .3756 | 30.33 | 64.01 | 94.34 | .0618 | .1750 | 106 |
| **108** | 12.28 | 4.93* | .01051 | 2.567 | 95.12 | .3896 | 30.78 | 63.86 | 94.64 | .0626 | .1751 | 108 |
| **110** | 12.76 | 3.95* | 0.01053 | 2.477 | 94.95 | 0.4038 | 31.22 | 63.71 | 94.93 | 0.0634 | 0.1752 | 110 |
| **112** | 13.25 | 2.95* | .01055 | 2.391 | 94.78 | .4182 | 31.67 | 63.56 | 95.23 | .0641 | .1753 | 112 |
| **114** | 13.76 | 1.91* | .01057 | 2.308 | 94.61 | .4333 | 32.12 | 63.40 | 95.52 | .0649 | .1755 | 114 |
| **116** | 14.29 | 0.83* | .01059 | 2.228 | 94.43 | .4489 | 32.57 | 63.25 | 95.82 | .0657 | .1756 | 116 |
| **118** | 14.84 | 0.14 | .01061 | 2.151 | 94.26 | .4649 | 33.03 | 63.09 | 96.12 | .0665 | .1757 | 118 |
| **120** | 15.40 | 0.70 | 0.01063 | 2.078 | 94.09 | 0.4813 | 33.48 | 62.93 | 96.41 | 0.0673 | 0.1758 | 120 |
| **122** | 15.97 | 1.27 | .01065 | 2.008 | 93.92 | .4981 | 33.93 | 62.78 | 96.71 | .0680 | .1760 | 122 |
| **124** | 16.56 | 1.86 | .01067 | 1.941 | 93.74 | .5153 | 34.38 | 62.62 | 97.00 | .0688 | .1761 | 124 |
| **126** | 17.17 | 2.47 | .01069 | 1.876 | 93.57 | .5330 | 34.83 | 62.46 | 97.29 | .0696 | .1763 | 126 |
| **128** | 17.80 | 3.10 | .01071 | 1.814 | 93.39 | .5514 | 35.29 | 62.30 | 97.59 | .0704 | .1764 | 128 |
| **130** | 18.45 | 3.74 | 0.01073 | 1.754 | 93.22 | 0.5702 | 35.75 | 62.14 | 97.89 | 0.0712 | 0.1765 | 130 |
| **132** | 19.11 | 4.41 | .01075 | 1.697 | 93.04 | .5894 | 36.21 | 61.97 | 98.18 | .0719 | .1767 | 132 |
| **134** | 19.79 | 5.09 | .01077 | 1.642 | 92.86 | .6091 | 36.67 | 61.80 | 98.47 | .0727 | .1768 | 134 |
| **136** | 20.48 | 5.78 | .01079 | 1.590 | 92.69 | .6290 | 37.13 | 61.64 | 98.77 | .0735 | .1770 | 136 |
| **138** | 21.19 | 6.49 | .01081 | 1.540 | 92.51 | .6494 | 37.59 | 61.48 | 99.06 | .0742 | .1771 | 138 |
| **140** | 21.93 | 7.23 | 0.01083 | 1.491 | 92.33 | 0.6707 | 38.05 | 61.31 | 99.36 | 0.0750 | 0.1773 | 140 |
| **142** | 22.69 | 7.99 | .01085 | 1.444 | 92.15 | .6926 | 38.52 | 61.13 | 99.65 | .0758 | .1774 | 142 |
| **144** | 23.47 | 8.77 | .01087 | 1.399 | 91.98 | .7150 | 38.98 | 60.96 | 99.94 | .0765 | .1775 | 144 |
| **146** | 24.27 | 9.57 | .01089 | 1.355 | 91.80 | .7379 | 39.45 | 60.79 | 100.24 | .0773 | .1777 | 146 |
| **148** | 25.09 | 10.39 | .01092 | 1.313 | 91.62 | .7615 | 39.92 | 60.61 | 100.53 | .0781 | .1778 | 148 |
| **150** | 25.93 | 11.23 | 0.01094 | 1.273 | 91.44 | 0.7856 | 40.38 | 60.44 | 100.82 | 0.0789 | 0.1780 | 150 |
| **152** | 26.79 | 12.09 | .01096 | 1.234 | 91.25 | .8102 | 40.85 | 60.27 | 101.11 | .0796 | .1782 | 152 |
| **154** | 27.67 | 12.97 | .01098 | 1.197 | 91.07 | .8353 | 41.32 | 60.09 | 101.41 | .0804 | .1783 | 154 |
| **156** | 28.56 | 13.86 | .01100 | 1.162 | 90.89 | .8608 | 41.79 | 59.91 | 101.70 | .0812 | .1785 | 156 |
| **158** | 29.48 | 14.78 | .01102 | 1.128 | 90.71 | .8869 | 42.26 | 59.73 | 101.99 | .0819 | .1786 | 158 |
| **160** | 30.44 | 15.74 | 0.01105 | 1.094 | 90.53 | 0.9141 | 42.74 | 59.55 | 102.29 | 0.0827 | 0.1788 | 160 |
| **170** | 35.53 | 20.83 | .01116 | 0.9442 | 89.60 | 1.059 | 45.12 | 58.62 | 103.74 | .0865 | .1796 | 170 |
| **180** | 41.22 | 26.52 | .01128 | .8193 | 88.67 | 1.221 | 47.53 | 57.66 | 105.19 | .0903 | .1804 | 180 |
| **190** | 47.60 | 32.90 | .01140 | .7134 | 87.72 | 1.402 | 49.97 | 56.66 | 106.63 | .0940 | .1813 | 190 |
| **200** | 54.66 | 39.96 | .01153 | .6241 | 86.76 | 1.602 | 52.45 | 55.62 | 108.07 | .0978 | .1821 | 200 |
| **210** | 62.50 | 47.80 | .01166 | .5477 | 85.79 | 1.826 | 54.96 | 54.54 | 109.50 | .1015 | .1830 | 210 |
| **220** | 71.07 | 56.37 | 0.01179 | 0.4827 | 84.80 | 2.072 | 57.49 | 53.43 | 110.92 | 0.1052 | 0.1839 | 220 |

## PROPERTIES OF SUPERHEATED VAPOR—Continued

| Temp. °F | Abs. Pressure 0.3 lb./in.² Gauge Pressure 29.31 in. Vac. (Sat'n. Temp. −29.9° F.) | | | Abs. Pressure 0.4 lb./in.² Gauge Pressure 29.11 in. Vac. (Sat'n. Temp. −22.0° F.) | | | Abs. Pressure 0.5 lb./in.² Gauge Pressure 28.90 in. Vac. (Sat'n. Temp. −15.6° F.) | | | Abs. Pressure 0.6 lb./in.² Gauge Pressure 28.70 in. Vac. (Sat'n. Temp. −10.2° F.) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| t | V | H | S | V | H | S | V | H | S | V | H | S |
| (At sat'n.) | (81.95) | (74.66) | (0.1738) | (62.55) | (75.77) | (0.1733) | (50.70) | (76.68) | (0.1730) | (42.81) | (77.44) | (0.1728) |
| −20 | 83.83 | 76.06 | 0.1770 | 62.82 | 76.05 | 0.1740 | ..... | ..... | ..... | ..... | ..... | ..... |
| −10 | 85.74 | 77.48 | .1802 | 64.25 | 77.47 | .1772 | 51.43 | 77.47 | 0.1748 | 42.83 | 77.47 | 0.1729 |
| 0 | 87.65 | 78.91 | 0.1834 | 65.68 | 78.90 | 0.1803 | 52.58 | 78.90 | 0.1779 | 43.79 | 78.90 | 0.1760 |
| 10 | 89.55 | 80.35 | .1865 | 67.11 | 80.34 | .1834 | 53.72 | 80.34 | .1810 | 44.74 | 80.34 | .1791 |
| 20 | 91.46 | 81.80 | .1895 | 68.63 | 81.80 | .1865 | 54.87 | 81.79 | .1841 | 45.70 | 81.79 | .1822 |
| 30 | 93.37 | 83.26 | .1925 | 70.06 | 83.26 | .1895 | 56.01 | 83.26 | .1871 | 46.65 | 83.25 | .1852 |
| 40 | 95.27 | 84.74 | .1955 | 71.49 | 84.74 | .1925 | 57.16 | 84.73 | .1901 | 47.61 | 84.73 | .1882 |
| 50 | 97.18 | 86.23 | 0.1985 | 72.92 | 86.22 | 0.1954 | 58.31 | 86.22 | 0.1931 | 48.56 | 86.22 | 0.1911 |
| 60 | 99.09 | 87.73 | .2014 | 74.35 | 87.72 | .1983 | 59.47 | 87.72 | .1960 | 49.52 | 87.72 | .1940 |
| 70 | 101.0 | 89.24 | .2043 | 75.79 | 89.23 | .2012 | 60.63 | 89.23 | .1989 | 50.47 | 89.23 | .1969 |
| 80 | 102.9 | 90.76 | .2071 | 77.22 | 90.76 | .2041 | 61.78 | 90.75 | .2017 | 51.43 | 90.75 | .1998 |
| 90 | 104.8 | 92.29 | .2099 | 78.65 | 92.29 | .2069 | 62.93 | 92.28 | .2045 | 52.38 | 92.28 | .2026 |
| 100 | 106.7 | 93.83 | 0.2127 | 80.08 | 93.83 | 0.2097 | 64.07 | 93.83 | 0.2073 | 53.34 | 93.82 | 0.2054 |
| 110 | 108.6 | 95.40 | .2155 | 81.51 | 95.39 | .2124 | 65.21 | 95.39 | .2101 | 54.31 | 95.39 | .2081 |
| 120 | 110.5 | 96.97 | .2182 | 82.94 | 96.96 | .2152 | 66.36 | 96.96 | .2128 | 55.27 | 96.96 | .2109 |
| 130 | 112.4 | 98.55 | .2209 | 84.37 | 98.54 | .2179 | 67.51 | 98.54 | .2155 | 56.22 | 98.54 | .2136 |
| 140 | 114.3 | 100.14 | .2236 | 85.80 | 100.13 | .2206 | 68.65 | 100.13 | .2182 | 57.18 | 100.13 | .2162 |
| 150 | 116.3 | 101.74 | 0.2262 | 87.23 | 101.74 | 0.2232 | 69.80 | 101.73 | 0.2208 | 58.13 | 101.73 | 0.2189 |
| 160 | 118.2 | 103.36 | .2289 | 88.66 | 103.35 | .2258 | 70.94 | 103.35 | .2234 | 59.09 | 103.34 | .2215 |
| 170 | 120.1 | 104.98 | .2315 | 90.10 | 104.98 | .2284 | 72.09 | 104.98 | .2260 | 60.04 | 104.97 | .2241 |
| 180 | 122.0 | 106.62 | .2341 | 91.53 | 106.62 | .2310 | 73.23 | 106.61 | .2286 | 60.99 | 106.61 | .2267 |
| 190 | 124.0 | 108.27 | .2366 | 92.96 | 108.27 | .2336 | 74.38 | 108.26 | .2312 | 61.95 | 108.26 | .2293 |
| 200 | 125.9 | 109.93 | 0.2392 | 94.39 | 109.93 | 0.2361 | 75.52 | 109.92 | 0.2337 | 62.90 | 109.92 | 0.2318 |
| 210 | 127.8 | 111.61 | .2417 | 95.82 | 111.61 | .2386 | 76.67 | 111.60 | .2363 | 63.85 | 111.60 | .2343 |
| 220 | 129.7 | 113.30 | .2442 | 97.25 | 113.30 | .2411 | 77.81 | 113.29 | .2388 | 64.81 | 113.29 | .2368 |
| 230 | 131.6 | 115.00 | .2467 | 98.68 | 114.99 | .2436 | 78.96 | 114.99 | .2412 | 65.76 | 114.99 | .2393 |
| 240 | 133.6 | 116.71 | .2491 | 100.1 | 116.70 | .2461 | 80.10 | 116.70 | .2437 | 66.71 | 116.70 | .2418 |
| 250 | 135.5 | 118.42 | 0.2516 | 101.5 | 118.42 | 0.2485 | 81.25 | 118.42 | 0.2461 | 67.67 | 118.41 | 0.2442 |
| 260 | 137.4 | 120.15 | .2540 | 103.0 | 120.15 | .2509 | 82.39 | 120.15 | .2486 | 68.62 | 120.14 | .2466 |
| 270 | 139.3 | 121.89 | .2564 | 104.4 | 121.88 | .2533 | 83.54 | 121.88 | .2510 | 69.57 | 121.87 | .2490 |
| 280 | 141.2 | 123.64 | 0.2588 | 105.9 | 123.63 | 0.2557 | 84.68 | 123.63 | .2533 | 70.53 | 123.62 | .2514 |
| 290 | ..... | ..... | ..... | ..... | ..... | ..... | 85.83 | 125.40 | 0.2557 | 71.48 | 125.39 | 0.2538 |

| Temp. °F. | Abs. Pressure 0.7 lb./in.² Gauge Pressure 28.50 in. Vac. (Sat'n. Temp. −5.6° F.) | | | Abs. Pressure 0.8 lb./in.² Gauge Pressure 28.29 in. Vac. (Sat'n. Temp. −1.5° F.) | | | Abs. Pressure 0.9 lb./in.² Gauge Pressure 28.09 in. Vac. (Sat'n. Temp. +2.3° F.) | | | Abs. Pressure 1.0 lb./in.² Gauge Pressure 27.88 in. Vac. (Sat'n. Temp. 5.6° F.) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (At sat'n.) | (37.05) | (78.10) | (0.1726) | (32.71) | (78.68) | (0.1725) | (29.30) | (79.22) | (0.1724) | (26.54) | (79.69) | (0.1723) |
| 0 | 37.49 | 78.90 | 0.1743 | 32.81 | 78.89 | 0.1729 | ..... | ..... | ..... | ..... | ..... | ..... |
| 10 | 38.32 | 80.34 | .1774 | 33.53 | 80.33 | .1760 | 29.79 | 80.33 | 0.1748 | 26.79 | 80.32 | 0.1737 |
| 20 | 39.15 | 81.79 | .1805 | 34.25 | 81.78 | .1791 | 30.43 | 81.78 | .1779 | 27.38 | 81.78 | .1768 |
| 30 | 39.98 | 83.25 | .1835 | 34.97 | 83.25 | .1821 | 31.07 | 83.24 | .1809 | 27.96 | 83.24 | .1798 |
| 40 | 40.80 | 84.72 | .1865 | 35.69 | 84.72 | .1851 | 31.71 | 84.72 | .1839 | 28.53 | 84.71 | .1828 |
| 50 | 41.62 | 86.21 | 0.1895 | 36.41 | 86.21 | 0.1881 | 32.35 | 86.20 | 0.1868 | 29.10 | 86.20 | 0.1857 |
| 60 | 42.43 | 87.71 | .1924 | 37.13 | 87.71 | .1910 | 32.99 | 87.70 | .1897 | 29.67 | 87.70 | .1886 |
| 70 | 43.25 | 89.22 | .1953 | 37.85 | 89.22 | .1939 | 33.63 | 89.21 | .1926 | 30.25 | 89.21 | .1915 |
| 80 | 44.07 | 90.74 | .1981 | 38.57 | 90.74 | .1967 | 34.27 | 90.74 | .1955 | 30.82 | 90.73 | .1943 |
| 90 | 44.89 | 92.28 | .2009 | 39.29 | 92.27 | .1995 | 34.91 | 92.27 | .1983 | 31.39 | 92.27 | .1972 |
| 100 | 45.71 | 93.82 | 0.2037 | 40.01 | 93.82 | 0.2023 | 35.55 | 93.81 | 0.2011 | 31.97 | 93.81 | 0.2000 |
| 110 | 46.53 | 95.38 | .2065 | 40.72 | 95.38 | .2051 | 36.19 | 95.37 | .2038 | 32.56 | 95.37 | .2027 |
| 120 | 47.35 | 96.95 | .2092 | 41.44 | 96.95 | .2078 | 36.83 | 96.94 | .2066 | 33.14 | 96.94 | .2054 |
| 130 | 48.18 | 98.53 | .2119 | 42.16 | 98.53 | .2105 | 37.47 | 98.52 | .2093 | 33.71 | 98.52 | .2081 |
| 140 | 49.00 | 100.12 | .2146 | 42.88 | 100.12 | .2132 | 38.11 | 100.12 | .2119 | 34.28 | 100.11 | .2108 |
| 150 | 49.83 | 101.73 | 0.2172 | 43.60 | 101.72 | 0.2158 | 38.75 | 101.72 | 0.2146 | 34.85 | 101.72 | 0.2135 |
| 160 | 50.65 | 103.34 | .2199 | 44.32 | 103.34 | .2185 | 39.39 | 103.33 | .2172 | 35.42 | 103.33 | .2161 |
| 170 | 51.47 | 104.97 | .2225 | 45.04 | 104.96 | .2211 | 40.03 | 104.96 | .2198 | 35.99 | 104.96 | .2187 |
| 180 | 52.29 | 106.61 | .2251 | 45.75 | 106.60 | .2236 | 40.67 | 106.60 | .2224 | 36.57 | 106.60 | .2213 |
| 190 | 53.10 | 108.26 | .2276 | 46.47 | 108.25 | .2262 | 41.31 | 108.25 | .2249 | 37.15 | 108.25 | .2238 |
| 200 | 53.92 | 109.92 | 0.2302 | 47.18 | 109.91 | 0.2288 | 41.94 | 109.91 | 0.2275 | 37.73 | 109.91 | 0.2264 |
| 210 | 54.74 | 111.60 | .2327 | 47.90 | 111.59 | .2313 | 42.57 | 111.59 | .2300 | 38.30 | 111.59 | .2289 |
| 220 | 55.56 | 113.29 | .2352 | 48.61 | 113.28 | .2338 | 43.21 | 113.28 | .2325 | 38.88 | 113.28 | .2314 |
| 230 | 56.37 | 114.98 | .2377 | 49.33 | 114.98 | .2363 | 43.84 | 114.98 | .2350 | 39.46 | 114.97 | .2339 |
| 240 | 57.19 | 116.69 | .2401 | 50.04 | 116.69 | .2387 | 44.48 | 116.69 | .2375 | 40.03 | 116.68 | .2363 |
| 250 | 58.01 | 118.41 | 0.2426 | 50.76 | 118.41 | 0.2412 | 45.12 | 118.40 | 0.2399 | 40.60 | 118.40 | 0.2388 |
| 260 | 58.83 | 120.14 | .2450 | 51.47 | 120.13 | .2436 | 45.75 | 120.13 | .2423 | 41.18 | 120.13 | .2412 |
| 270 | 59.64 | 121.87 | .2474 | 52.19 | 121.86 | .2460 | 46.39 | 121.86 | .2447 | 41.75 | 121.86 | .2436 |
| 280 | 60.46 | 123.62 | .2498 | 52.90 | 123.61 | .2484 | 47.02 | 123.61 | .2471 | 42.32 | 123.62 | .2460 |
| 290 | 61.28 | 125.39 | .2522 | 53.62 | 125.38 | .2507 | 47.66 | 125.38 | .2495 | 42.89 | 125.38 | .2484 |
| 300 | 62.10 | 127.18 | 0.2545 | 54.34 | 127.17 | 0.2531 | 48.30 | 127.17 | 0.2518 | 43.46 | 127.16 | 0.2507 |
| 310 | ..... | ..... | ..... | ..... | ..... | ..... | 48.93 | 128.97 | 0.2542 | 44.04 | 128.96 | 0.2531 |

## PROPERTIES OF SUPERHEATED VAPOR—Continued

| Temp. °F. | Abs. Pressure 1.1 lb./in.² Gauge Pressure 27.68 in. Vac. (Sat'n. Temp. 8.7° F.) | | | Abs. Pressure 1.2 lb./in.² Gauge Pressure 27.48 in. Vac. (Sat'n. Temp. 11.6° F.) | | | Abs. Pressure 1.3 lb./in.² Gauge Pressure 27.27 in. Vac. (Sat'n. Temp. 14.3° F.) | | | Abs. Pressure 1.4 lb./in.² Gauge Pressure 27.07 in. Vac. (Sat'n. Temp. 16.8° F.) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| t | V | H | S | V | H | S | V | H | S | V | H | S |
| (At sat'n.) | (24.29) | (80.13) | (0.1723) | (22.40) | (80.55) | (0.1722) | (20.79) | (80.93) | (0.1722) | (19.40) | (81.30) | (0.1722) |
| 10 | 24.35 | 80.32 | 0.1726 | ..... | ..... | ..... | ..... | ..... | ..... | ..... | ..... | ..... |
| 20 | 24.87 | 81.77 | .1757 | 22.80 | 81.77 | 0.1748 | 21.03 | 81.76 | 0.1740 | 19.52 | 81.76 | 0.1731 |
| 30 | 25.39 | 83.24 | .1787 | 23.28 | 83.23 | .1778 | 21.47 | 83.23 | .1770 | 19.93 | 83.23 | .1762 |
| 40 | 25.91 | 84.71 | .1817 | 23.75 | 84.71 | .1808 | 21.91 | 84.70 | .1800 | 20.35 | 84.70 | .1792 |
| 50 | 26.43 | 86.20 | 0.1847 | 24.23 | 86.19 | 0.1837 | 22.36 | 86.19 | 0.1829 | 20.76 | 86.19 | 0.1821 |
| 60 | 26.96 | 87.70 | .1876 | 24.71 | 87.69 | .1866 | 22.80 | 87.69 | .1858 | 21.17 | 87.69 | .1850 |
| 70 | 27.49 | 89.21 | .1905 | 25.19 | 89.20 | .1895 | 23.24 | 89.20 | .1887 | 21.58 | 89.20 | .1879 |
| 80 | 28.01 | 90.73 | .1933 | 25.67 | 90.72 | .1924 | 23.68 | 90.72 | .1915 | 21.99 | 90.72 | .1907 |
| 90 | 28.53 | 92.26 | .1961 | 26.15 | 92.26 | .1952 | 24.13 | 92.26 | .1944 | 22.40 | 92.25 | .1935 |
| 100 | 29.05 | 93.81 | 0.1989 | 26.63 | 93.80 | 0.1980 | 24.58 | 93.80 | 0.1971 | 22.81 | 93.80 | 0.1963 |
| 110 | 29.57 | 95.37 | .2017 | 27.11 | 95.36 | .2007 | 25.02 | 95.36 | .1999 | 23.22 | 95.36 | .1991 |
| 120 | 30.09 | 96.94 | .2044 | 27.59 | 96.93 | .2035 | 25.46 | 96.93 | .2026 | 23.63 | 96.93 | .2018 |
| 130 | 30.62 | 98.52 | .2071 | 28.07 | 98.51 | .2062 | 25.90 | 98.51 | .2053 | 24.04 | 98.51 | .2045 |
| 140 | 31.15 | 100.11 | .2098 | 28.55 | 100.10 | .2089 | 26.34 | 100.10 | .2080 | 24.45 | 100.10 | .2072 |
| 150 | 31.68 | 101.71 | 0.2124 | 29.03 | 101.71 | 0.2115 | 26.78 | 101.70 | 0.2106 | 24.86 | 101.70 | 0.2099 |
| 160 | 32.20 | 103.33 | .2151 | 29.51 | 103.32 | .2141 | 27.23 | 103.32 | .2133 | 25.27 | 103.32 | .2125 |
| 170 | 32.72 | 104.95 | .2177 | 29.99 | 104.95 | .2167 | 27.68 | 104.95 | .2159 | 25.68 | 104.94 | .2151 |
| 180 | 33.24 | 106.59 | .2202 | 30.47 | 106.59 | .2193 | 28.12 | 106.59 | .2185 | 26.10 | 106.58 | .2177 |
| 190 | 33.76 | 108.24 | .2228 | 30.95 | 108.24 | .2219 | 28.56 | 108.24 | .2211 | 26.52 | 108.23 | .2202 |
| 200 | 34.28 | 109.90 | 0.2253 | 31.43 | 109.90 | 0.2244 | 29.00 | 109.90 | 0.2236 | 26.93 | 109.89 | 0.2228 |
| 210 | 34.80 | 111.58 | .2279 | 31.91 | 111.58 | .2270 | 29.44 | 111.58 | .2261 | 27.34 | 111.57 | .2253 |
| 220 | 35.32 | 113.27 | .2304 | 32.39 | 113.27 | .2295 | 29.88 | 113.27 | .2286 | 27.75 | 113.26 | .2278 |
| 230 | 35.85 | 114.97 | .2329 | 32.87 | 114.97 | .2319 | 30.32 | 114.96 | .2311 | 28.16 | 114.96 | .2303 |
| 240 | 36.37 | 116.68 | .2353 | 33.35 | 116.68 | .2344 | 30.76 | 116.67 | .2335 | 28.57 | 116.67 | .2328 |
| 250 | 36.90 | 118.40 | 0.2378 | 33.83 | 118.39 | 0.2368 | 31.20 | 118.39 | 0.2360 | 28.98 | 118.39 | 0.2352 |
| 260 | 37.43 | 120.13 | .2402 | 34.31 | 120.12 | .2393 | 31.64 | 120.12 | .2384 | 29.39 | 120.12 | .2376 |
| 270 | 37.95 | 121.86 | .2426 | 34.79 | 121.86 | .2417 | 32.08 | 121.86 | .2408 | 29.80 | 121.85 | .2400 |
| 280 | 38.47 | 123.61 | .2450 | 35.26 | 123.61 | .2441 | 32.53 | 123.61 | .2432 | 30.21 | 123.60 | .2424 |
| 290 | 38.99 | 125.38 | .2474 | 35.74 | 125.38 | .2464 | 32.98 | 125.37 | .2456 | 30.62 | 125.37 | .2448 |
| 300 | 39.51 | 127.16 | 0.2497 | 36.22 | 127.16 | 0.2488 | 33.43 | 127.16 | 0.2479 | 31.03 | 127.16 | 0.2471 |
| 310 | 40.03 | 128.96 | 0.2521 | 36.69 | 128.96 | .2511 | 33.88 | 128.96 | .2503 | 31.44 | 128.95 | .2495 |
| 320 | ..... | ..... | ..... | 37.17 | 130.76 | 0.2535 | 34.32 | 130.76 | 0.2526 | 31.85 | 130.75 | 0.2518 |

| Temp. °F. | Abs. Pressure 1.6 lb./in.² Gauge Pressure 26.66 in. Vac. (Sat'n. Temp. 21.5° F.) | | | Abs. Pressure 1.8 lb./in.² Gauge Pressure 26.26 in. Vac. (Sat'n. Temp. 25.6° F.) | | | Abs. Pressure 2.0 lb./in.² Gauge Pressure 25.85 in. Vac. (Sat'n. Temp. 29.4° F.) | | | Abs. Pressure 2.2 lb./in.² Gauge Pressure 25.44 in. Vac. (Sat'n. Temp. 32.9° F.) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (At sat'n.) | (17.13) | (81.97) | (0.1721) | (15.35) | (82.57) | (0.1722) | (13.91) | (83.12) | (0.1722) | (12.74) | (83.62) | (0.1722) |
| 30 | 17.43 | 83.22 | 0.1747 | 15.49 | 83.21 | 0.1735 | 13.92 | 83.20 | 0.1724 | ..... | ..... | ..... |
| 40 | 17.79 | 84.69 | .1777 | 15.81 | 84.68 | .1765 | 14.21 | 84.68 | .1753 | 12.92 | 84.67 | 0.1743 |
| 50 | 18.15 | 86.18 | 0.1807 | 16.13 | 86.17 | 0.1794 | 14.50 | 86.16 | 0.1783 | 13.18 | 86.16 | 0.1773 |
| 60 | 18.51 | 87.68 | .1836 | 16.45 | 87.67 | .1823 | 14.79 | 87.66 | .1812 | 13.44 | 87.66 | .1802 |
| 70 | 18.87 | 89.19 | .1865 | 16.77 | 89.18 | .1852 | 15.08 | 89.17 | .1841 | 13.70 | 89.17 | .1831 |
| 80 | 19.23 | 90.71 | .1893 | 17.09 | 90.70 | .1881 | 15.37 | 90.69 | .1869 | 13.96 | 90.69 | .1859 |
| 90 | 19.59 | 92.24 | .1921 | 17.41 | 92.24 | .1909 | 15.66 | 92.23 | .1898 | 14.22 | 92.22 | .1887 |
| 100 | 19.95 | 93.79 | 0.1949 | 17.73 | 93.78 | 0.1937 | 15.95 | 93.77 | 0.1926 | 14.48 | 93.77 | 0.1915 |
| 110 | 20.31 | 95.35 | .1977 | 18.05 | 95.34 | .1964 | 16.24 | 95.33 | .1953 | 14.75 | 95.33 | .1943 |
| 120 | 20.67 | 96.92 | .2004 | 18.37 | 96.91 | .1992 | 16.53 | 96.90 | .1980 | 15.02 | 96.90 | .1970 |
| 130 | 21.03 | 98.50 | .2031 | 18.69 | 98.49 | .2019 | 16.82 | 98.49 | .2007 | 15.28 | 98.49 | .1997 |
| 140 | 21.39 | 100.09 | .2058 | 19.01 | 100.08 | .2045 | 17.11 | 100.09 | .2034 | 15.54 | 100.08 | .2024 |
| 150 | 21.75 | 101.69 | 0.2084 | 19.33 | 101.69 | 0.2072 | 17.39 | 101.69 | 0.2061 | 15.81 | 101.68 | 0.2051 |
| 160 | 22.11 | 103.31 | .2111 | 19.65 | 103.31 | .2098 | 17.68 | 103.31 | .2087 | 16.07 | 103.30 | .2077 |
| 170 | 22.47 | 104.94 | .2137 | 19.97 | 104.93 | .2124 | 17.96 | 104.93 | .2113 | 16.33 | 104.93 | .2103 |
| 180 | 22.83 | 106.58 | .2163 | 20.29 | 106.57 | .2150 | 18.25 | 106.57 | .2139 | 16.59 | 106.56 | .2129 |
| 190 | 23.19 | 108.22 | .2188 | 20.61 | 108.22 | .2176 | 18.54 | 108.22 | .2164 | 16.85 | 108.21 | .2154 |
| 200 | 23.55 | 109.89 | 0.2214 | 20.93 | 109.88 | 0.2201 | 18.83 | 109.88 | 0.2190 | 17.11 | 109.88 | 0.2180 |
| 210 | 23.91 | 111.57 | .2239 | 21.25 | 111.56 | .2226 | 19.12 | 111.56 | .2215 | 17.38 | 111.55 | .2205 |
| 220 | 24.27 | 113.26 | .2264 | 21.57 | 113.25 | .2251 | 19.40 | 113.24 | .2240 | 17.64 | 113.24 | .2230 |
| 230 | 24.63 | 114.95 | .2289 | 21.89 | 114.95 | .2276 | 19.69 | 114.94 | .2265 | 17.90 | 114.93 | .2255 |
| 240 | 24.99 | 116.66 | .2313 | 22.21 | 116.66 | .2301 | 19.97 | 116.65 | .2290 | 18.16 | 116.64 | .2279 |
| 250 | 25.35 | 118.38 | 0.2338 | 22.53 | 118.38 | 0.2325 | 20.26 | 118.37 | 0.2314 | 18.42 | 118.36 | 0.2304 |
| 260 | 25.71 | 120.11 | .2362 | 22.85 | 120.11 | .2349 | 20.55 | 120.10 | .2338 | 18.68 | 120.09 | .2328 |
| 270 | 26.07 | 121.85 | .2386 | 23.17 | 121.84 | .2373 | 20.84 | 121.84 | .2362 | 18.94 | 121.83 | .2352 |
| 280 | 26.43 | 123.60 | .2410 | 23.49 | 123.59 | .2397 | 21.13 | 123.59 | .2386 | 19.20 | 123.58 | .2376 |
| 290 | 26.78 | 125.37 | .2434 | 23.81 | 125.36 | .2421 | 21.42 | 125.36 | .2409 | 19.47 | 125.35 | .2400 |
| 300 | 27.14 | 127.16 | 0.2457 | 24.12 | 127.15 | 0.2445 | 21.71 | 127.15 | 0.2433 | 19.74 | 127.14 | 0.2423 |
| 310 | 27.50 | 128.95 | .2481 | 24.44 | 128.94 | .2468 | 22.00 | 128.94 | .2457 | 20.00 | 128.93 | .2447 |
| 320 | 27.86 | 130.75 | .2504 | 24.76 | 130.74 | .2491 | 22.28 | 130.74 | .2480 | 20.26 | 130.73 | .2470 |
| 330 | 28.23 | 132.56 | 0.2527 | 25.08 | 132.56 | 0.2514 | 22.57 | 132.55 | 0.2503 | 20.52 | 132.55 | .2493 |
| 340 | ..... | ..... | ..... | ..... | ..... | ..... | ..... | ..... | ..... | 20.78 | 134.37 | 0.2516 |

## PROPERTIES OF SUPERHEATED VAPOR—Continued

| Temp. °F | Abs. Pressure 2.4 lb./in.² Gauge Pressure 25.04 in. Vac. (Sat'n. Temp. 36.2° F.) | | | Abs. Pressure 2.6 lb./in.² Gauge Pressure 24.63 in. Vac. (Sat'n. Temp. 39.2° F.) | | | Abs. Pressure 2.8 lb./in.² Gauge Pressure 24.22 in. Vac. (Sat'n. Temp. 42.0° F.) | | | Abs. Pressure 3.0 lb./in.² Gauge Pressure 23.81 in. Vac. (Sat'n. Temp. 44.7° F.) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| t | V | H | S | V | H | S | V | H | S | V | H | S |
| (At sat'n.) | (11.74) | (84.10) | (0.1722) | (10.89) | (84.53) | (0.1723) | (10.17) | (84.94) | (0.1723) | (9.537) | (85.34) | (0.1723) |
| 40 | 11.84 | 84.66 | 0.1734 | 10.91 | 84.65 | 0.1725 | ..... | ..... | ..... | ..... | ..... | ..... |
| 50 | 12.08 | 86.15 | 0.1763 | 11.13 | 86.14 | 0.1755 | 10.33 | 86.13 | 0.1747 | 9.637 | 86.12 | 0.1739 |
| 60 | 12.32 | 87.65 | .1792 | 11.35 | 87.64 | .1784 | 10.54 | 87.63 | .1776 | 9.831 | 87.62 | .1769 |
| 70 | 12.56 | 89.16 | .1821 | 11.58 | 89.15 | .1813 | 10.75 | 89.14 | .1805 | 10.02 | 89.13 | .1797 |
| 80 | 12.80 | 90.68 | .1850 | 11.80 | 90.67 | .1841 | 10.95 | 90.66 | .1833 | 10.22 | 90.66 | .1826 |
| 90 | 13.04 | 92.21 | .1878 | 12.02 | 92.21 | .1869 | 11.16 | 92.20 | .1861 | 10.41 | 92.19 | .1854 |
| 100 | 13.28 | 93.76 | 0.1906 | 12.24 | 93.75 | 0.1897 | 11.37 | 93.74 | 0.1889 | 10.60 | 93.74 | 0.1882 |
| 110 | 13.52 | 95.32 | .1934 | 12.47 | 95.31 | .1925 | 11.58 | 95.30 | .1917 | 10.80 | 95.30 | .1910 |
| 120 | 13.76 | 96.89 | .1961 | 12.69 | 96.88 | .1952 | 11.79 | 96.87 | .1944 | 10.99 | 96.87 | .1937 |
| 130 | 14.00 | 98.48 | .1988 | 12.91 | 98.47 | .1979 | 11.99 | 98.46 | .1971 | 11.18 | 98.46 | .1964 |
| 140 | 14.24 | 100.07 | .2015 | 13.13 | 100.06 | .2006 | 12.20 | 100.06 | .1998 | 11.38 | 100.05 | .1991 |
| 150 | 14.48 | 101.68 | 0.2041 | 13.36 | 101.67 | 0.2033 | 12.40 | 101.66 | 0.2025 | 11.57 | 101.65 | 0.2017 |
| 160 | 14.72 | 103.29 | .2068 | 13.58 | 103.28 | .2059 | 12.61 | 103.28 | .2051 | 11.76 | 103.27 | .2044 |
| 170 | 14.96 | 104.92 | .2094 | 13.80 | 104.91 | .2085 | 12.82 | 104.90 | .2077 | 11.95 | 104.90 | .2070 |
| 180 | 15.20 | 106.56 | .2099 | 14.02 | 106.55 | .2111 | 13.02 | 106.54 | .2103 | 12.15 | 106.54 | .2095 |
| 190 | 15.44 | 108.21 | .2145 | 14.25 | 108.20 | .2137 | 13.23 | 108.19 | .2129 | 12.34 | 108.19 | .2121 |
| 200 | 15.68 | 109.87 | 0.2171 | 14.47 | 109.86 | 0.2162 | 13.44 | 109.86 | 0.2154 | 12.53 | 109.85 | 0.2147 |
| 210 | 15.93 | 111.54 | .2196 | 14.69 | 111.54 | .2187 | 13.65 | 111.54 | .2179 | 12.72 | 111.53 | .2172 |
| 220 | 16.17 | 113.23 | .2221 | 14.91 | 113.22 | .2212 | 13.85 | 113.23 | .2204 | 12.92 | 113.22 | .2197 |
| 230 | 16.41 | 114.93 | .2246 | 15.13 | 114.92 | .2237 | 14.05 | 114.92 | .2229 | 13.11 | 114.92 | .2222 |
| 240 | 16.65 | 116.64 | .2270 | 15.35 | 116.63 | .2262 | 14.26 | 116.63 | .2254 | 13.30 | 116.63 | .2246 |
| 250 | 16.89 | 118.35 | 0.2295 | 15.58 | 118.35 | 0.2286 | 14.46 | 118.35 | 0.2278 | 13.49 | 118.35 | 0.2271 |
| 260 | 17.13 | 120.08 | .2319 | 15.80 | 120.08 | .2310 | 14.67 | 120.08 | .2302 | 13.68 | 120.08 | .2295 |
| 270 | 17.37 | 121.82 | .2343 | 16.02 | 121.82 | .2334 | 14.88 | 121.82 | .2326 | 13.87 | 121.82 | .2319 |
| 280 | 17.61 | 123.58 | .2367 | 16.24 | 123.57 | .2358 | 15.09 | 123.57 | .2350 | 14.06 | 123.57 | .2343 |
| 290 | 17.85 | 125.35 | .2391 | 16.46 | 125.34 | .2382 | 15.29 | 125.34 | .2374 | 14.26 | 125.33 | .2367 |
| 300 | 18.09 | 127.14 | 0.2414 | 16.68 | 127.13 | 0.2406 | 15.50 | 127.13 | 0.2398 | 14.46 | 127.11 | 0.2390 |
| 310 | 18.33 | 128.93 | .2437 | 16.90 | 128.92 | .2429 | 15.70 | 128.92 | .2421 | 14.65 | 128.91 | .2414 |
| 320 | 18.57 | 130.73 | .2461 | 17.12 | 130.72 | .2452 | 15.90 | 130.73 | .2444 | 14.84 | 130.71 | .2437 |
| 330 | 18.81 | 132.54 | .2484 | 17.34 | 132.54 | .2475 | 16.11 | 132.54 | .2467 | 15.03 | 132.52 | .2460 |
| 340 | 19.05 | 134.36 | 0.2507 | 17.56 | 134.36 | 0.2498 | 16.31 | 134.36 | .2490 | 15.22 | 134.35 | .2483 |
| 350 | ..... | ..... | ..... | ..... | ..... | ..... | 16.52 | 136.20 | 0.2513 | 15.41 | 136.19 | 0.2505 |

| Temp. °F. | Abs. Pressure 3.2 lb./in.² Gauge Pressure 23.41 in. Vac. (Sat'n. Temp. 47.3° F.) | | | Abs. Pressure 3.4 lb./in.² Gauge Pressure 23.00 in. Vac. (Sat'n. Temp. 49.7° F.) | | | Abs. Pressure 3.6 lb./in.² Gauge Pressure 22.59 in. Vac. (Sat'n. Temp. 52.0° F.) | | | Abs. Pressure 3.8 lb./in.² Gauge Pressure 22.19 in. Vac. (Sat'n. Temp. 54.2° F.) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (At sat'n) | (8.983) | (85.71) | (0.1724) | (8.489) | (86.06) | (0.1725) | (8.047) | (86.40) | (0.1725) | (7.653) | (86.72) | (0.1726) |
| 50 | 9.030 | 86.12 | 0.1733 | 8.493 | 86.11 | 0.1726 | .... | .... | ..... | .... | .... | ..... |
| 60 | 9.209 | 87.62 | .1762 | 8.665 | 87.61 | .1755 | 8.177 | 87.60 | 0.1749 | 7.742 | 87.59 | 0.1743 |
| 70 | 9.391 | 89.13 | .1791 | 8.837 | 89.12 | .1784 | 8.338 | 89.11 | .1778 | 7.895 | 89.10 | .1772 |
| 80 | 9.573 | 90.65 | .1819 | 9.009 | 90.64 | .1813 | 8.499 | 90.63 | .1806 | 8.048 | 90.62 | .1800 |
| 90 | 9.755 | 92.18 | .1847 | 9.181 | 92.18 | .1841 | 8.659 | 92.17 | .1834 | 8.201 | 92.16 | .1829 |
| 100 | 9.938 | 93.73 | 0.1875 | 9.353 | 93.72 | 0.1869 | 8.819 | 93.71 | 0.1862 | 8.354 | 93.71 | 0.1857 |
| 110 | 10.12 | 95.29 | .1903 | 9.525 | 95.28 | .1896 | 8.980 | 95.27 | .1890 | 8.506 | 95.27 | .1884 |
| 120 | 10.30 | 96.86 | .1930 | 9.697 | 96.85 | .1924 | 9.141 | 96.84 | .1917 | 8.659 | 96.84 | .1911 |
| 130 | 10.48 | 98.45 | .1957 | 9.869 | 98.44 | .1951 | 9.305 | 98.43 | .1944 | 8.812 | 98.43 | .1938 |
| 140 | 10.66 | 100.04 | .1984 | 10.03 | 100.03 | .1977 | 9.466 | 100.03 | .1971 | 8.965 | 100.02 | .1965 |
| 150 | 10.84 | 101.65 | 0.2010 | 10.20 | 101.64 | 0.2004 | 9.627 | 101.63 | 0.1998 | 9.118 | 101.62 | 0.1992 |
| 160 | 11.02 | 103.26 | .2037 | 10.37 | 103.26 | .2030 | 9.788 | 103.25 | .2024 | 9.271 | 103.24 | .2018 |
| 170 | 11.20 | 104.89 | .2063 | 10.54 | 104.89 | .2056 | 9.948 | 104.88 | .2050 | 9.423 | 104.87 | .2044 |
| 180 | 11.38 | 106.54 | .2089 | 10.71 | 106.53 | .2082 | 10.11 | 106.53 | .2076 | 9.576 | 106.52 | .2070 |
| 190 | 11.56 | 108.19 | .2114 | 10.88 | 108.18 | .2108 | 10.27 | 108.18 | .2102 | 9.729 | 108.17 | .2096 |
| 200 | 11.74 | 109.85 | 0.2140 | 11.05 | 109.85 | 0.2133 | 10.43 | 109.84 | 0.2127 | 9.882 | 109.83 | 0.2121 |
| 210 | 11.92 | 111.53 | .2165 | 11.22 | 111.52 | .2159 | 10.59 | 111.51 | .2153 | 10.03 | 111.51 | .2147 |
| 220 | 12.10 | 113.21 | .2190 | 11.39 | 113.21 | .2184 | 10.75 | 113.20 | .2178 | 10.19 | 113.19 | .2172 |
| 230 | 12.28 | 114.91 | .2215 | 11.56 | 114.90 | .2208 | 10.91 | 114.90 | .2202 | 10.34 | 114.89 | .2196 |
| 240 | 12.47 | 116.62 | .2240 | 11.73 | 116.61 | .2233 | 11.07 | 116.61 | .2227 | 10.49 | 116.60 | .2221 |
| 250 | 12.65 | 118.34 | 0.2264 | 11.90 | 118.33 | 0.2257 | 11.23 | 118.32 | 0.2252 | 10.64 | 118.32 | 0.2245 |
| 260 | 12.83 | 120.06 | .2288 | 12.07 | 120.05 | .2282 | 11.40 | 120.05 | .2276 | 10.79 | 120.04 | .2270 |
| 270 | 13.01 | 121.80 | .2312 | 12.24 | 121.79 | .2306 | 11.56 | 121.79 | .2300 | 10.95 | 121.78 | .2294 |
| 280 | 13.19 | 123.55 | .2336 | 12.41 | 123.55 | .2330 | 11.72 | 123.54 | .2324 | 11.10 | 123.53 | .2318 |
| 290 | 13.37 | 125.32 | .2360 | 12.58 | 125.32 | .2353 | 11.88 | 125.31 | .2347 | 11.25 | 125.30 | .2341 |
| 300 | 13.56 | 127.11 | 0.2383 | 12.75 | 127.11 | 0.2377 | 12.04 | 127.10 | 0.2371 | 11.40 | 127.09 | 0.2365 |
| 310 | 13.74 | 128.90 | .2407 | 12.92 | 128.90 | .2400 | 12.20 | 128.89 | .2394 | 11.55 | 128.89 | .2388 |
| 320 | 13.92 | 130.70 | .2430 | 13.09 | 130.70 | .2423 | 12.36 | 130.69 | .2417 | 11.70 | 130.69 | .2412 |
| 330 | 14.09 | 132.52 | .2453 | 13.26 | 132.51 | .2446 | 12.52 | 132.51 | .2441 | 11.85 | 132.50 | .2435 |
| 340 | 14.27 | 134.34 | .2476 | 13.43 | 134.34 | .2469 | 12.68 | 134.33 | .2464 | 12.00 | 134.33 | .2458 |
| 350 | 14.45 | 136.18 | 0.2499 | 13.60 | 136.18 | 0.2492 | 12.84 | 136.17 | 0.2486 | 12.15 | 136.17 | 0.2481 |
| 360 | .... | ..... | ..... | .... | ..... | ..... | 13.00 | 138.02 | 0.2509 | 12.31 | 138.01 | 0.2503 |

## PROPERTIES OF SUPERHEATED VAPOR—Continued

| Temp. °F | Abs. Pressure 4.0 lb./in.² Gauge Pressure 21.73 in. Vac. (Sat'n. Temp. 56.3° F.) | | | Abs. Pressure 4.5 lb./in.² Gauge Pressure 20.76 in. Vac. (Sat'n. Temp. 61.2° F.) | | | Abs. Pressure 5.0 lb./in.² Gauge Pressure 19.74 in. Vac. (Sat'n. Temp. 65.7° F.) | | | Abs. Pressure 5.5 lb./in.² Gauge Pressure 18.73 in. Vac. (Sat'n. Temp. 69.8° F.) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| t | V | H | S | V | H | S | V | H | S | V | H | S |
| (At sat'n.) | (7.297) | (87.03) | (0.1727) | (6.542) | (87.74) | (0.1728) | (5.930) | (88.41) | (0.1730) | (5.428) | (89.01) | (0.1731) |
| 60 | 7.351 | 87.58 | 0.1738 | ..... | ..... | ..... | ..... | ..... | ..... | ..... | ..... | ..... |
| 70 | 7.497 | 89.10 | .1767 | 6.657 | 89.08 | 0.1754 | 5.979 | 89.06 | 0.1742 | 5.428 | 89.04 | 0.1732 |
| 80 | 7.642 | 90.62 | .1795 | 6.786 | 90.60 | .1782 | 6.096 | 90.58 | .1771 | 5.533 | 90.56 | .1761 |
| 90 | 7.787 | 92.15 | .1823 | 6.915 | 92.13 | .1810 | 6.213 | 92.12 | .1799 | 5.638 | 92.10 | .1789 |
| 100 | 7.932 | 93.70 | 0.1851 | 7.044 | 93.68 | 0.1838 | 6.329 | 93.67 | 0.1827 | 5.743 | 93.64 | 0.1817 |
| 110 | 8.077 | 95.26 | .1879 | 7.173 | 95.24 | .1866 | 6.445 | 95.22 | .1855 | 5.849 | 95.20 | .1844 |
| 120 | 8.222 | 96.83 | .1906 | 7.302 | 96.81 | .1893 | 6.562 | 96.79 | .1882 | 5.955 | 96.77 | .1872 |
| 130 | 8.367 | 98.42 | .1933 | 7.431 | 98.40 | .1920 | 6.678 | 98.38 | .1909 | 6.061 | 98.36 | .1899 |
| 140 | 8.522 | 100.01 | .1960 | 7.560 | 99.99 | .1947 | 6.795 | 99.98 | .1936 | 6.168 | 99.96 | .1925 |
| 150 | 8.667 | 101.62 | 0.1986 | 7.689 | 101.60 | 0.1974 | 6.912 | 101.58 | 0.1962 | 6.274 | 101.57 | 0.1952 |
| 160 | 8.812 | 103.23 | .2013 | 7.818 | 103.22 | .2000 | 7.029 | 103.20 | .1989 | 6.380 | 103.19 | .1978 |
| 170 | 8.957 | 104.86 | .2039 | 7.947 | 104.85 | .2026 | 7.146 | 104.83 | .2015 | 6.485 | 104.82 | .2004 |
| 180 | 9.102 | 106.51 | .2065 | 8.076 | 106.49 | .2052 | 7.263 | 106.48 | .2041 | 6.589 | 106.47 | .2030 |
| 190 | 9.247 | 108.16 | .2091 | 8.205 | 108.14 | .2078 | 7.380 | 108.13 | .2066 | 6.795 | 108.12 | .2056 |
| 200 | 9.387 | 109.82 | 0.2116 | 8.334 | 109.81 | 0.2103 | 7.497 | 109.80 | 0.2092 | 6.801 | 109.78 | 0.2081 |
| 210 | 9.532 | 111.50 | .2141 | 8.463 | 111.49 | .2128 | 7.614 | 111.48 | .2117 | 6.907 | 111.46 | .2107 |
| 220 | 9.677 | 113.19 | .2166 | 8.592 | 113.18 | .2153 | 7.731 | 113.16 | .2142 | 7.013 | 113.15 | .2132 |
| 230 | 9.822 | 114.88 | .2191 | 8.721 | 114.88 | .2178 | 7.848 | 114.86 | .2167 | 7.120 | 114.84 | .2157 |
| 240 | 9.967 | 116.59 | .2216 | 8.850 | 116.59 | .2203 | 7.965 | 116.57 | .2192 | 7.226 | 116.55 | .2181 |
| 250 | 10.11 | 118.31 | 0.2240 | 8.979 | 118.31 | 0.2228 | 8.082 | 118.29 | 0.2216 | 7.332 | 118.27 | 0.2206 |
| 260 | 10.25 | 120.04 | .2264 | 9.108 | 120.03 | .2252 | 8.199 | 120.02 | .2240 | 7.438 | 120.00 | .2230 |
| 270 | 10.40 | 121.78 | .2288 | 9.237 | 121.77 | .2276 | 8.316 | 121.76 | .2264 | 7.544 | 121.74 | .2254 |
| 280 | 10.54 | 123.53 | .2312 | 9.366 | 123.52 | .2300 | 8.422 | 123.51 | .2288 | 7.651 | 123.49 | .2278 |
| 290 | 10.69 | 125.30 | .2336 | 9.495 | 125.29 | .2323 | 8.538 | 125.28 | .2312 | 7.758 | 125.26 | .2302 |
| 300 | 10.83 | 127.09 | 0.2359 | 9.624 | 127.08 | 0.2347 | 8.654 | 127.07 | 0.2336 | 7.864 | 127.05 | 0.2325 |
| 310 | 10.97 | 128.88 | .2383 | 9.753 | 128.88 | .2370 | 8.771 | 128.86 | .2359 | 7.970 | 128.85 | .2349 |
| 320 | 11.12 | 130.68 | .2406 | 9.882 | 130.68 | .2394 | 8.887 | 130.67 | .2383 | 8.077 | 130.65 | .2372 |
| 330 | 11.26 | 132.50 | .2429 | 10.01 | 132.49 | .2417 | 9.003 | 132.48 | .2406 | 8.182 | 132.47 | .2395 |
| 340 | 11.40 | 134.32 | .2452 | 10.14 | 134.32 | .2440 | 9.120 | 134.31 | .2429 | 8.287 | 134.29 | .2418 |
| 350 | 11.54 | 136.16 | 0.2475 | 10.27 | 136.16 | 0.2463 | 9.236 | 136.14 | 0.2451 | 8.392 | 136.13 | 0.2441 |
| 360 | 11.69 | 138.01 | 0.2498 | 10.39 | 138.01 | .2485 | 9.352 | 137.99 | .2474 | 8.497 | 137.98 | .2464 |
| 370 | ..... | ..... | ..... | 10.52 | 139.86 | 0.2508 | 9.468 | 139.85 | 0.2497 | 8.602 | 139.84 | 0.2486 |

| Temp. °F. | Abs. Pressure 6.0 lb./in.² Gauge Pressure 17.71 in. Vac. (Sat'n. Temp. 73.7° F.) | | | Abs. Pressure 6.5 lb./in.² Gauge Pressure 16.69 in. Vac. (Sat'n. Temp. 77.3° F.) | | | Abs. Pressure 7.0 lb./in.² Gauge Pressure 15.67 in. Vac. (Sat'n. Temp. 80.6° F.) | | | Abs. Pressure 7.5 lb./in.² Gauge Pressure 14.65 in. Vac. (Sat'n. Temp. 83.8° F.) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (At. sat'n.) | (5.004) | (89.58) | (0.1733) | (4.646) | (90.10) | (0.1735) | (4.336) | (90.60) | (0.1736) | (4.064) | (91.06) | (0.1738) |
| 80 | 5.066 | 90.54 | 0.1751 | 4.671 | 90.52 | 0.1743 | ..... | ..... | ..... | ..... | ..... | ..... |
| 90 | 5.163 | 92.08 | .1779 | 4.762 | 92.06 | .1771 | 4.414 | 92.05 | 0.1763 | 4.111 | 92.03 | 0.1755 |
| 100 | 5.260 | 93.62 | 0.1807 | 4.853 | 93.60 | 0.1799 | 4.498 | 93.60 | 0.1791 | 4.190 | 93.58 | 0.1783 |
| 110 | 5.357 | 95.18 | .1835 | 4.944 | 95.16 | .1827 | 4.581 | 95.16 | .1818 | 4.269 | 95.14 | .1811 |
| 120 | 5.454 | 96.76 | .1862 | 5.035 | 96.74 | .1854 | 4.666 | 96.73 | .1845 | 4.348 | 96.71 | .1838 |
| 130 | 5.551 | 98.35 | .1889 | 5.125 | 98.33 | .1881 | 4.749 | 98.32 | .1872 | 4.427 | 98.30 | .1865 |
| 140 | 5.649 | 99.95 | .1916 | 5.215 | 99.93 | .1908 | 4.834 | 99.91 | .1899 | 4.507 | 99.90 | .1892 |
| 150 | 5.746 | 101.56 | 0.1943 | 5.305 | 101.54 | 0.1934 | 4.919 | 101.52 | 0.1926 | 4.585 | 101.50 | 0.1919 |
| 160 | 5.843 | 103.17 | .1969 | 5.394 | 103.16 | .1961 | 5.003 | 103.14 | .1952 | 4.663 | 103.12 | .1945 |
| 170 | 5.940 | 104.80 | .1995 | 5.484 | 104.79 | .1987 | 5.086 | 104.77 | .1978 | 4.741 | 104.75 | .1971 |
| 180 | 6.037 | 106.45 | .2021 | 5.573 | 106.43 | .2013 | 5.169 | 106.42 | .2004 | 4.819 | 106.40 | .1997 |
| 190 | 6.134 | 108.10 | .2047 | 5.663 | 108.09 | .2038 | 5.253 | 108.07 | .2030 | 4.897 | 108.05 | .2023 |
| 200 | 6.233 | 109.77 | 0.2072 | 5.752 | 109.75 | 0.2064 | 5.337 | 109.73 | 0.2056 | 4.975 | 109.72 | 0.2048 |
| 210 | 6.330 | 111.44 | .2097 | 5.841 | 111.43 | .2089 | 5.420 | 111.41 | .2081 | 5.053 | 111.39 | .2073 |
| 220 | 6.427 | 113.13 | .2122 | 5.930 | 113.11 | .2114 | 5.504 | 113.10 | .2106 | 5.131 | 113.08 | .2098 |
| 230 | 6.525 | 114.83 | .2147 | 6.021 | 114.81 | .2139 | 5.587 | 114.80 | .2131 | 5.209 | 114.78 | .2123 |
| 240 | 6.622 | 116.54 | .2172 | 6.110 | 116.52 | .2164 | 5.671 | 116.50 | .2156 | 5.286 | 116.49 | .2148 |
| 250 | 6.719 | 118.26 | 0.2197 | 5.200 | 118.24 | 0.2188 | 5.755 | 118.22 | 0.2180 | 5.365 | 118.21 | 0.2173 |
| 260 | 6.816 | 119.99 | .2221 | 6.290 | 119.97 | .2212 | 5.838 | 119.95 | .2204 | 5.444 | 119.94 | .2197 |
| 270 | 6.913 | 121.73 | .2245 | 6.381 | 121.71 | .2236 | 5.921 | 121.69 | .2228 | 5.523 | 121.68 | .2221 |
| 280 | 7.011 | 123.48 | .2269 | 6.470 | 123.46 | .2260 | 6.004 | 123.45 | .2252 | 5.602 | 123.44 | .2245 |
| 290 | 7.108 | 125.25 | .2293 | 6.558 | 125.23 | .2284 | 6.087 | 125.22 | .2276 | 5.680 | 125.21 | .2269 |
| 300 | 7.205 | 127.04 | 0.2316 | 6.647 | 127.02 | 0.2308 | 6.170 | 127.01 | 0.2300 | 5.757 | 127.00 | 0.2292 |
| 310 | 7.302 | 128.84 | .2340 | 6.737 | 128.82 | .2331 | 6.254 | 128.81 | .2323 | 5.834 | 128.80 | .2316 |
| 320 | 7.398 | 130.64 | .2363 | 6.827 | 130.63 | .2354 | 6.337 | 130.61 | .2346 | 5.911 | 130.60 | .2339 |
| 330 | 7.495 | 132.46 | .2386 | 6.917 | 132.44 | .2377 | 6.420 | 132.43 | .2370 | 5.988 | 132.42 | .2362 |
| 340 | 7.591 | 134.28 | .2409 | 7.008 | 134.27 | .2400 | 6.504 | 134.26 | .2393 | 6.064 | 134.24 | .2385 |
| 350 | 7.687 | 136.12 | 0.2432 | 7.097 | 136.11 | 0.2423 | 6.587 | 136.09 | 0.2415 | 6.142 | 136.08 | 0.2408 |
| 360 | 7.784 | 137.97 | .2455 | 7.186 | 137.96 | .2446 | 6.670 | 137.94 | .2438 | 6.221 | 137.93 | .2431 |
| 370 | 7.880 | 139.83 | .2477 | 7.274 | 139.82 | .2469 | 6.752 | 139.80 | .2461 | 6.299 | 139.79 | .2453 |
| 380 | 7.975 | 141.70 | 0.2500 | 7.362 | 141.69 | 0.2491 | 6.834 | 141.68 | .2483 | 6.378 | 141.67 | .2476 |
| 390 | ..... | ..... | ..... | .. | .. | ..... | 6.916 | 143.57 | 0.2506 | 6.457 | 143.56 | 0.2498 |

# PROPERTIES OF SUPERHEATED VAPOR—Continued

| Temp. °F. | Abs. Pressure 8.0 lb./in.² Gauge Pressure 13.64 in. Vac. (Sat'n. Temp. 86.[illegible]° F.) | | | Abs. Pressure 9.0 lb./in.² Gauge Pressure 11.60 in. Vac. (Sat'n. Temp. 92.5° F.) | | | Abs. Pressure 10.0 lb./in.² Gauge Pressure 9.57 in. Vac. (Sat'n. Temp. 97.6° F.) | | | Abs. Pressure 11 lb./in.² Gauge Pressure 7.53 in. Vac. (Sat'n. Temp. 102.4° F.) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| t | V | H | S | V | H | S | V | H | S | V | H | S |
| (At sat'n.) | (3.828) | (91.52) | (0.1739) | (3.431) | (92.35) | (0.1742) | (3.110) | (93.11) | (0.1745) | (2.845) | (93.81) | (0.1747) |
| 90 | 3.850 | 92.01 | 0.1748 | ..... | ..... | ..... | ..... | ..... | ..... | ..... | ..... | ..... |
| 100 | 3.924 | 93.56 | 0.1776 | 3.481 | 93.52 | 0.1763 | 3.124 | 93.48 | 0.1751 | ..... | ..... | ..... |
| 110 | 3.999 | 95.12 | .1804 | 3.547 | 95.08 | .1791 | 3.183 | 95.04 | .1779 | 2.887 | 95.01 | 0.1769 |
| 120 | 4.073 | 96.69 | .1831 | 3.613 | 96.66 | .1819 | 3.242 | 96.62 | .1806 | 2.941 | 96.58 | .1796 |
| 130 | 4.147 | 98.28 | .1858 | 3.679 | 98.25 | .1846 | 3.301 | 98.21 | .1834 | 3.995 | 98.17 | .1823 |
| 140 | 4.221 | 99.88 | .1885 | 3.745 | 99.84 | .1872 | 3.361 | 99.81 | .1860 | 3.049 | 99.77 | .1850 |
| 150 | 4.295 | 101.48 | 0.1912 | 3.810 | 101.45 | 0.1899 | 3.420 | 101.41 | 0.1887 | 3.103 | 101.38 | 0.1877 |
| 160 | 4.369 | 103.10 | .1938 | 3.874 | 103.07 | .1925 | 3.480 | 103.03 | .1914 | 3.157 | 103.00 | .1903 |
| 170 | 4.442 | 104.74 | .1964 | 3.940 | 104.70 | .1951 | 3.539 | 104.66 | .1940 | 3.211 | 104.63 | .1929 |
| 180 | 4.515 | 106.38 | .1990 | 4.004 | 106.34 | .1977 | 3.599 | 106.31 | .1966 | 3.265 | 106.28 | .1955 |
| 190 | 4.588 | 108.04 | .2016 | 4.070 | 108.00 | .2003 | 3.658 | 107.96 | .1991 | 3.319 | 107.93 | .1981 |
| 200 | 4.661 | 109.71 | 0.2041 | 4.135 | 109.67 | 0.2028 | 3.716 | 109.63 | 0.2017 | 3.373 | 109.60 | 0.2006 |
| 210 | 4.734 | 111.38 | .2066 | 4.199 | 111.35 | .2054 | 3.774 | 111.32 | .2042 | 3.426 | 111.28 | .2032 |
| 220 | 4.807 | 113.07 | .2091 | 4.265 | 113.04 | .2079 | 3.832 | 113.01 | .2067 | 3.480 | 112.97 | .2057 |
| 230 | 4.880 | 114.77 | .2116 | 4.330 | 114.74 | .2104 | 3.891 | 114.71 | .2092 | 3.533 | 114.67 | .2082 |
| 240 | 4.952 | 116.48 | .2141 | 4.395 | 116.45 | .2129 | 3.950 | 116.42 | .2117 | 3.586 | 116.38 | .2106 |
| 250 | 5.024 | 118.20 | 0.2166 | 4.460 | 118.17 | 0.2153 | 4.010 | 118.14 | 0.2141 | 3.639 | 118.10 | 0.2131 |
| 260 | 5.096 | 119.93 | .2190 | 4.525 | 119.91 | .2177 | 4.068 | 119.87 | .2166 | 3.692 | 119.84 | .2155 |
| 270 | 5.168 | 121.67 | .2214 | 4.590 | 121.64 | .2201 | 4.126 | 121.61 | .2190 | 3.745 | 121.58 | .2179 |
| 280 | 5.240 | 123.42 | .2238 | 4.656 | 123.40 | .2225 | 4.185 | 123.37 | .2214 | 3.798 | 123.34 | .2203 |
| 290 | 5.313 | 125.19 | .2261 | 4.721 | 125.17 | .2249 | 4.243 | 125.15 | .2237 | 3.852 | 125.12 | .2227 |
| 300 | 5.387 | 126.98 | 0.2285 | 4.787 | 126.96 | 0.2273 | 4.302 | 126.94 | 0.2261 | 3.906 | 126.91 | 0.2250 |
| 310 | 5.460 | 128.78 | .2309 | 4.852 | 128.76 | .2296 | 4.360 | 128.74 | .2285 | 3.960 | 128.71 | .2274 |
| 320 | 5.533 | 130.58 | .2332 | 4.918 | 130.57 | .2319 | 4.419 | 130.54 | .2308 | 4.014 | 130.51 | .2298 |
| 330 | 5.607 | 132.40 | .2355 | 4.983 | 132.39 | .2343 | 4.477 | 132.36 | .2331 | 4.068 | 132.33 | .2321 |
| 340 | 5.682 | 134.23 | .2378 | 5.048 | 134.21 | .2366 | 4.537 | 134.19 | .2354 | 4.122 | 134.16 | .2344 |
| 350 | 5.756 | 136.07 | 0.2401 | 5.112 | 136.05 | 0.2388 | 4.596 | 136.03 | 0.2377 | 4.175 | 136.00 | 0.2367 |
| 360 | 5.830 | 137.92 | .2424 | 5.178 | 137.90 | .2411 | 4.656 | 137.88 | .2400 | 4.229 | 137.85 | .2389 |
| 370 | 5.904 | 139.78 | .2447 | 5.243 | 139.76 | .2434 | 4.714 | 139.74 | .2422 | 4.283 | 139.71 | .2412 |
| 380 | 5.975 | 141.66 | .2470 | 5.307 | 141.64 | .2456 | 4.772 | 141.62 | .2445 | 4.336 | 141.59 | .2434 |
| 390 | 6.047 | 143.55 | 0.2492 | 5.372 | 143.52 | .2479 | 4.829 | 143.50 | .2467 | 4.389 | 143.48 | .2457 |
| 400 | ..... | ..... | ..... | 5.436 | 145.41 | 0.2501 | 4.887 | 145.39 | 0.2489 | 4.441 | 145.37 | 0.2479 |
| 410 | ..... | ..... | ..... | ..... | ..... | ..... | ..... | ..... | ..... | 4.493 | 147.28 | 0.2501 |

| Temp. °F. | Abs. Pressure 12 lb./in.² Gauge Pressure 5.50 in. Vac. (Sat'n. Temp. 106.8° F.) | | | Abs. Pressure 13 lb./in.² Gauge Pressure 3.46 in Vac. (Sat'n. Temp. 111.0° F.) | | | Abs. Pressure 14 lb./in.² Gauge Pressure 1.42 in. Vac. (Sat'n. Temp. 114.9° F.) | | | Abs. Pressure 16 lb./in.² Gauge Pressure 1.3 lb./in.² (Sat'n. Temp. 122.1° F.) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (At sat'n.) | (2.624) | (94.46) | (0.1750) | (2.435) | (95.08) | (0.1753) | (2.271) | (95.66) | (0.1755) | (2.004) | (96.72) | (0.1760) |
| 110 | 2.640 | 94.97 | 0.1759 | ..... | ..... | ..... | ..... | ..... | ..... | ..... | ..... | ..... |
| 120 | 2.689 | 96.55 | .1786 | 2.477 | 96.51 | 0.1778 | 2.291 | 96.47 | 0.1770 | ..... | ..... | ..... |
| 130 | 2.738 | 98.14 | .1813 | 2.522 | 98.10 | .1805 | 2.334 | 98.06 | .1797 | 2.034 | 97.99 | 0.1782 |
| 140 | 2.788 | 99.73 | .1840 | 2.567 | 99.70 | .1832 | 2.377 | 99.66 | .1823 | 2.072 | 99.59 | .1809 |
| 150 | 2.838 | 101.34 | 0.1867 | 2.613 | 101.31 | 0.1858 | 2.421 | 101.27 | 0.1850 | 2.110 | 101.20 | 0.1835 |
| 160 | 2.888 | 102.97 | .1894 | 2.659 | 102.94 | .1885 | 2.465 | 102.90 | .1876 | 2.148 | 102.83 | .1862 |
| 170 | 2.938 | 104.60 | .1920 | 2.704 | 104.57 | .1911 | 2.508 | 104.53 | .1902 | 2.186 | 104.46 | .1888 |
| 180 | 2.987 | 106.25 | .1946 | 2.749 | 106.21 | .1937 | 2.550 | 106.18 | .1928 | 2.224 | 106.11 | .1914 |
| 190 | 3.037 | 107.90 | .1972 | 2.795 | 107.87 | .1963 | 2.593 | 107.84 | .1954 | 2.262 | 107.77 | .1940 |
| 200 | 3.086 | 109.57 | 0.1997 | 2.841 | 109.54 | 0.1988 | 2.635 | 109.51 | 0.1980 | 2.299 | 109.44 | 0.1965 |
| 210 | 3.135 | 111.26 | .2022 | 2.887 | 111.23 | .2013 | 2.678 | 111.20 | .2005 | 2.336 | 111.13 | .1991 |
| 220 | 3.184 | 112.95 | .2047 | 2.933 | 112.92 | .2039 | 2.720 | 112.89 | .2030 | 2.374 | 112.83 | .2016 |
| 230 | 3.234 | 114.65 | .2072 | 2.979 | 114.62 | .2064 | 2.763 | 114.59 | .2055 | 2.411 | 114.53 | .2041 |
| 240 | 3.283 | 116.36 | .2097 | 3.025 | 116.33 | .2088 | 2.806 | 116.30 | .2080 | 2.448 | 116.24 | .2065 |
| 250 | 3.332 | 118.08 | 0.2121 | 3.071 | 118.05 | 0.2113 | 2.848 | 118.02 | 0.2105 | 2.486 | 117.96 | 0.2090 |
| 260 | 3.382 | 119.81 | .2146 | 3.117 | 119.79 | .2137 | 2.890 | 119.76 | .2129 | 2.523 | 119.70 | .2114 |
| 270 | 4.431 | 121.55 | .2170 | 3.162 | 121.53 | .2162 | 2.932 | 121.50 | .2153 | 2.560 | 121.45 | .2138 |
| 280 | 3.479 | 123.31 | .2194 | 3.208 | 123.29 | .2186 | 2.975 | 123.26 | .2177 | 2.596 | 123.21 | .2162 |
| 290 | 3.528 | 125.09 | .2218 | 3.254 | 125.07 | .2209 | 3.018 | 125.04 | .2201 | 2.633 | 124.99 | .2186 |
| 300 | 3.578 | 126.88 | 0.2241 | 3.300 | 126.86 | 0.2232 | 3.060 | 126.84 | 0.2225 | 2.671 | 126.78 | 0.2210 |
| 310 | 3.627 | 128.68 | .2265 | 3.345 | 128.66 | .2256 | 3.103 | 128.64 | .2248 | 2.709 | 128.58 | .2233 |
| 320 | 3.676 | 130.49 | .2288 | 3.391 | 130.47 | .2279 | 3.145 | 130.44 | .2271 | 2.746 | 130.39 | .2257 |
| 330 | 3.725 | 132.31 | .2311 | 3.436 | 132.29 | .2302 | 3.187 | 132.26 | .2294 | 2.783 | 132.21 | .2280 |
| 340 | 3.774 | 134.14 | .2334 | 3.481 | 134.12 | .2325 | 3.229 | 134.09 | .2317 | 2.820 | 134.04 | .2303 |
| 350 | 3.823 | 135.98 | 0.2357 | 3.526 | 135.96 | 0.2348 | 3.271 | 135.94 | 0.2340 | 2.857 | 135.88 | 0.2326 |
| 360 | 3.872 | 137.83 | .2380 | 3.572 | 137.81 | .2371 | 3.313 | 137.79 | .2363 | 2.895 | 137.74 | .2349 |
| 370 | 3.922 | 139.69 | .2402 | 3.617 | 139.68 | .2394 | 3.355 | 139.65 | .2386 | 2.932 | 139.60 | .2371 |
| 380 | 3.972 | 141.57 | .2425 | 3.662 | 141.56 | .2416 | 3.397 | 141.52 | .2408 | 2.968 | 141.47 | .2394 |
| 390 | 4.021 | 143.45 | .2447 | 3.707 | 143.44 | .2439 | 3.429 | 143.41 | .2430 | 3.005 | 143.36 | .2416 |
| 400 | 4.069 | 145.34 | 0.2469 | 3.752 | 145.33 | 0.2461 | 3.481 | 145.31 | 0.2453 | 3.042 | 145.26 | 0.2438 |
| 410 | 4.117 | 147.25 | 0.2491 | 3.797 | 147.24 | .2483 | 3.522 | 147.22 | .2475 | 3.079 | 147.17 | .2460 |
| 420 | ..... | ..... | ..... | 3.841 | 149.16 | 0.2505 | 3.562 | 149.14 | 0.2497 | 3.115 | 149.10 | .2482 |
| 430 | ..... | ..... | ..... | .... | ..... | ..... | ..... | ..... | ..... | 3.152 | 151.03 | 0.2504 |

# PROPERTIES OF SUPERHEATED VAPOR—Continued

| Temp. °F. | Abs. Pressure 18 lb./in.² Gauge Pressure 3.3 lb./in.² (Sat'n. Temp. 123.8° F.) | | | Abs. Pressure 20 lb./in.² Gauge Pressure 5.3 lb./in.² (Sat'n. Temp. 134.6° F.) | | | Abs. Pressure 25 lb./in.² Gauge Pressure 10.3 lb./in.² (Sat'n. Temp. 147.3° F.) | | | Abs. Pressure 30 lb./in.² Gauge Pressure 15.3 lb./in.² (Sat'n. Temp. 159.1° F.) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| t | V | H | S | V | H | S | V | H | S | V | H | S |
| (At sat'n.) | (1.795) | (97.68) | (0.1761) | (1.625) | (98.56) | (0.1769) | (1.317) | (100.50) | (0.1778) | (1.109) | (102.15) | (0.1787) |
| 130 | 1.799 | 97.91 | 0.1769 | ..... | ..... | ..... | ..... | ..... | ..... | ..... | ..... | ..... |
| 140 | 1.833 | 99.51 | .1795 | 1.640 | 99.43 | 0.1783 | ..... | ..... | ..... | ..... | ..... | ..... |
| 150 | 1.867 | 101.12 | 0.1822 | 1.672 | 101.05 | 0.1810 | 1.322 | 100.87 | 0.1784 | ..... | ..... | ..... |
| 160 | 1.901 | 102.75 | .1848 | 1.703 | 102.68 | .1836 | 1.348 | 102.50 | .1811 | 1.111 | 102.31 | 0.1790 |
| 170 | 1.935 | 104.39 | .1875 | 1.734 | 104.32 | .1862 | 1.373 | 104.14 | .1837 | 1.132 | 103.96 | .1816 |
| 180 | 1.968 | 106.04 | .1901 | 1.765 | 105.97 | .1888 | 1.398 | 105.80 | .1863 | 1.153 | 105.62 | .1842 |
| 190 | 2.002 | 107.71 | .1926 | 1.796 | 107.64 | .1914 | 1.423 | 107.47 | .1889 | 1.173 | 107.29 | .1868 |
| 200 | 2.036 | 109.39 | 0.1952 | 1.827 | 109.32 | 0.1940 | 1.448 | 109.15 | 0.1915 | 1.194 | 108.97 | 0.1894 |
| 210 | 2.069 | 111.08 | .1977 | 1.857 | 111.01 | .1966 | 1.472 | 110.84 | .1940 | 1.215 | 110.67 | .1919 |
| 220 | 2.103 | 112.77 | .2003 | 1.887 | 112.70 | .1991 | 1.497 | 112.54 | .1966 | 1.236 | 112.37 | .1945 |
| 230 | 2.136 | 114.47 | .2028 | 1.917 | 114.40 | .2016 | 1.522 | 114.25 | .1991 | 1.257 | 114.08 | .1970 |
| 240 | 2.169 | 116.18 | .2052 | 1.947 | 116.12 | .2041 | 1.546 | 115.96 | .2015 | 1.278 | 115.80 | .1995 |
| 250 | 2.203 | 117.90 | 0.2077 | 1.977 | 117.84 | 0.2065 | 1.571 | 117.69 | 0.2040 | 1.299 | 117.53 | 0.2019 |
| 260 | 2.236 | 119.64 | .2101 | 2.007 | 119.58 | .2090 | 1.595 | 119.44 | .2064 | 1.320 | 119.28 | .2044 |
| 270 | 2.269 | 121.39 | .2125 | 2.037 | 121.33 | .2114 | 1.619 | 121.19 | .2089 | 1.341 | 121.03 | .2068 |
| 280 | 2.303 | 123.15 | .2149 | 2.068 | 123.09 | .2138 | 1.643 | 122.95 | .2113 | 1.362 | 122.80 | .2092 |
| 290 | 2.336 | 124.92 | .2173 | 2.098 | 124.87 | .2162 | 1.667 | 124.73 | .2137 | 1.382 | 124.59 | .2116 |
| 300 | 2.370 | 126.72 | 0.2197 | 2.128 | 126.67 | 0.2185 | 1.691 | 126.53 | 0.2160 | 1.402 | 126.39 | 0.2140 |
| 310 | 2.403 | 128.53 | .2220 | 2.158 | 128.47 | .2209 | 1.716 | 128.34 | .2184 | 1.422 | 128.20 | .2163 |
| 320 | 2.436 | 130.34 | .2244 | 2.187 | 130.28 | .2232 | 1.741 | 130.16 | .2207 | 1.442 | 130.02 | .2187 |
| 330 | 2.469 | 132.16 | .2267 | 2.217 | 132.10 | .2255 | 1.765 | 131.98 | .2231 | 1.462 | 131.85 | .2210 |
| 340 | 2.502 | 133.99 | .2290 | 2.247 | 133.94 | .2278 | 1.789 | 133.82 | .2254 | 1.483 | 133.69 | .2233 |
| 350 | 2.535 | 135.83 | 0.2313 | 2.277 | 135.78 | 0.2301 | 1.813 | 135.66 | 0.2277 | 1.503 | 135.54 | 0.2256 |
| 360 | 2.569 | 137.69 | .2336 | 2.308 | 137.64 | .2324 | 1.838 | 137.52 | .2300 | 1.524 | 137.40 | .2279 |
| 370 | 2.602 | 139.55 | .2358 | 2.338 | 139.50 | .2347 | 1.862 | 139.39 | .2322 | 1.545 | 139.27 | .2302 |
| 380 | 2.635 | 141.43 | .2381 | 2.368 | 141.38 | .2369 | 1.886 | 141.26 | .2345 | 1.565 | 141.15 | .2324 |
| 390 | 2.667 | 143.32 | .2403 | 2.398 | 143.27 | .2392 | 1.910 | 143.15 | .2367 | 1.585 | 143.05 | .2347 |
| 400 | 2.700 | 145.22 | 0.2425 | 2.427 | 145.17 | 0.2414 | 1.933 | 145.05 | 0.2389 | 1.604 | 144.95 | 0.2369 |
| 410 | 2.733 | 147.13 | .2447 | 2.456 | 147.08 | .2436 | 1.957 | 146.97 | .2411 | 1.624 | 146.86 | .2391 |
| 420 | 2.765 | 149.05 | .2469 | 2.485 | 149.01 | .2458 | 1.981 | 148.90 | .2433 | 1.645 | 148.79 | .2413 |
| 430 | 2.797 | 150.99 | 0.2491 | 2.515 | 150.94 | .2480 | 2.005 | 150.83 | .2455 | 1.665 | 150.73 | .2435 |
| 440 | ..... | ..... | ..... | 2.544 | 152.89 | 0.2501 | 2.029 | 152.78 | .2477 | 1.685 | 152.68 | .2457 |
| 450 | ..... | ..... | ..... | ..... | ..... | ..... | 2.052 | 154.74 | 0.2498 | 1.706 | 154.65 | 0.2479 |
| 460 | ..... | ..... | ..... | ..... | ..... | ..... | ..... | ..... | ..... | 1.726 | 156.62 | 0.2500 |

| Temp. °F. | Abs. Pressure 35 lb./in.² Gauge Pressure 20.3 lb./in.² (Sat'n. Temp. 169.0° F.) | | | Abs. Pressure 40 lb./in.² Gauge Pressure 25.3 lb./in.² (Sat'n. Temp. 177.9° F.) | | | Abs. Pressure 50 lb./in.² Gauge Pressure 35.3 lb./in.² (Sat'n. Temp. 193.5° F.) | | | Abs. Pressure 60 lb./in.² Gauge Pressure 45.3 lb./in.² (Sat'n. Temp. 206.9° F.) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| t | V | H | S | V | H | S | V | H | S | V | H | S |
| (At sat'n.) | (0.9580) | (105.60) | (0.1795) | (0.8435) | (104.90) | (0.1802) | (0.6809) | (107.14) | (0.1816) | (0.5705) | (109.06) | (0.1827) |
| 170 | 0.9594 | 103.77 | 0.1797 | ..... | ..... | ..... | .... | ..... | ..... | ..... | ..... | ..... |
| 180 | 0.9780 | 105.43 | .1824 | 0.8462 | 105.26 | 0.1808 | .... | ..... | ..... | ..... | ..... | ..... |
| 190 | 0.9963 | 107.10 | .1850 | .8627 | 106.94 | .1834 | .... | ..... | ..... | ..... | ..... | ..... |
| 200 | 1.015 | 108.79 | 0.1876 | 0.8791 | 108.62 | 0.1860 | 0.6899 | 108.27 | 0.1833 | ..... | ..... | ..... |
| 210 | 1.033 | 110.49 | .1901 | .8953 | 110.32 | .1885 | .7031 | 109.97 | .1858 | 0.5738 | 109.60 | 0.1835 |
| 220 | 1.051 | 112.20 | .1927 | .9114 | 112.03 | .1911 | .7163 | 111.69 | .1884 | .5853 | 111.31 | .1861 |
| 230 | 1.069 | 113.91 | .1952 | .9274 | 113.74 | .1936 | .7296 | 113.41 | .1909 | .5968 | 113.04 | .1886 |
| 240 | 1.088 | 115.63 | .1977 | .9435 | 115.47 | .1961 | .7430 | 115.14 | .1934 | .6082 | 114.78 | .1912 |
| 250 | 1.106 | 117.37 | 0.2002 | 0.9596 | 117.21 | 0.1986 | 0.7562 | 116.90 | 0.1959 | 0.6193 | 116.54 | 0.1937 |
| 260 | 1.124 | 119.12 | .2026 | .9756 | 118.97 | .2010 | .7693 | 118.67 | .1984 | .6303 | 118.32 | .1961 |
| 270 | 1.142 | 120.88 | .2051 | 0.9915 | 120.74 | .2035 | .7821 | 120.45 | .2008 | .6413 | 120.11 | .1986 |
| 280 | 1.160 | 122.66 | .2075 | 1.008 | 122.52 | .2059 | .7950 | 122.23 | .2033 | .6525 | 121.91 | .2010 |
| 290 | 1.177 | 124.45 | .2099 | 1.023 | 124.31 | .2086 | .8079 | 124.03 | .2057 | .6639 | 123.72 | .2035 |
| 300 | 1.195 | 126.26 | 0.2122 | 1.038 | 126.12 | 0.2107 | 0.8207 | 125.84 | 0.2081 | 0.6751 | 125.53 | 0.2059 |
| 310 | 1.212 | 128.07 | .2146 | 1.054 | 127.94 | .2131 | .8335 | 127.66 | .2104 | .6860 | 127.36 | .2083 |
| 320 | 1.230 | 129.89 | .2169 | 1.070 | 129.76 | .2154 | .8463 | 129.48 | .2128 | .6969 | 129.19 | .2106 |
| 330 | 1.248 | 131.72 | .2193 | 1.085 | 131.59 | .2178 | .8591 | 131.31 | .2152 | .7079 | 131.03 | .2130 |
| 340 | 1.266 | 133.56 | .2216 | 1.101 | 133.44 | .2201 | .8716 | 133.16 | .2175 | .7188 | 132.89 | .2153 |
| 350 | 1.284 | 135.41 | 0.2239 | 1.117 | 135.29 | 0.2224 | 0.8844 | 135.02 | 0.2198 | 0.7296 | 134.75 | 0.2176 |
| 360 | 1.302 | 137.27 | .2262 | 1.133 | 137.16 | .2247 | .8973 | 136.89 | .2221 | .7403 | 136.63 | .2199 |
| 370 | 1.319 | 139.15 | .2285 | 1.148 | 139.03 | .2269 | .9101 | 138.77 | .2244 | .7510 | 138.52 | .2222 |
| 380 | 1.336 | 141.03 | .2307 | 1.164 | 140.91 | .2292 | .9228 | 140.67 | .2266 | .7619 | 140.42 | .2245 |
| 390 | 1.353 | 142.93 | .2329 | 1.179 | 142.81 | .2314 | .9354 | 142.57 | .2289 | .7725 | 142.33 | .2267 |
| 400 | 1.370 | 144.83 | 0.2352 | 1.194 | 144.72 | 0.2337 | 0.9480 | 144.48 | 0.2311 | 0.7831 | 144.24 | 0.2290 |
| 410 | 1.388 | 146.75 | .2374 | 1.210 | 146.64 | .2359 | .9605 | 146.41 | .2333 | .7937 | 146.16 | .2312 |
| 420 | 1.405 | 148.68 | .2396 | 1.225 | 148.57 | .2381 | .9728 | 148.35 | .2356 | .8043 | 148.10 | .2334 |
| 430 | 1.422 | 150.62 | .2418 | 1.240 | 150.51 | .2403 | .9851 | 150.30 | .2378 | .8151 | 150.06 | .2356 |
| 440 | 1.439 | 152.58 | .2440 | 1.256 | 152.47 | .2425 | 0.9974 | 152.25 | .2400 | .8257 | 152.02 | .2378 |
| 450 | 1.457 | 154.54 | 0.2461 | 1.271 | 154.44 | 0.2447 | 1.010 | 154.22 | 0.2421 | 0.8362 | 154.00 | 0.2400 |
| 460 | 1.474 | 156.52 | .2483 | 1.286 | 156.41 | .2468 | 1.023 | 156.21 | .2443 | .8466 | 155.98 | .2422 |
| 470 | 1.491 | 158.51 | 0.2505 | 1.302 | 158.40 | .2490 | 1.036 | 158.20 | .2464 | .8570 | 157.98 | .2443 |
| 480 | .... | ..... | ..... | 1.317 | 160.40 | 0.2511 | 1.048 | 160.20 | .2486 | .8675 | 159.98 | .2465 |
| 490 | .... | ..... | ..... | .... | ..... | ..... | 1.060 | 162.22 | .2507 | .8776 | 162.00 | .2486 |
| 500 | .... | ..... | ..... | .... | ..... | ..... | 1.072 | 164.24 | 0.2528 | 0.8880 | 164.03 | 0.2508 |
| 510 | .... | ..... | ..... | .... | ..... | ..... | ..... | ..... | ..... | 0.8987 | 166.07 | 0.2529 |

CLOSED ELECTRICAL APPARATUS CABINET
EMBODYING A VAPORIZATION CHAMBER
AND CABINET TOP THEREOF


ABSTRACT OF THE DISCLOSURE

A cabinet for electrical equipment to be protected from a hostile environment comprising a sealed top section consisting of a vaporization chamber containing trichlorotrifluoroethane, with the upper surface having a generally recessed polyhedral shape to promote accumulation of condensate at the roof of the vaporization chamber to replenish the liquid to the chamber base.


BACKGROUND OF THE INVENTION

This invention relates to a housing for electrical apparatus providing, in an overall light and rigid structure, total isolation of the electrical apparatus from ambient conditions while preserving excellent heat transfer proficiency.

When electrical apparatus must be placed inside an enclosure, it is necessary to prevent temperature build-up due to heat accumulation in, or around, the electrical parts. Usually external air is blown inside and through the enclosure in order to evacuate the accumulated heat. However, it is not desirable to do so when the equipment is operated in a dirty, hostile atmosphere, since particles introduced into the enclosure could cause electrical defects.

It is known to cool electrical equipment with air-to-air or liquid-to-liquid or liquid-to-air heat exchangers in direct contact with the critical electrical parts (for instance electrodes) or rather with a heat sink, in order to remove the heat toward a heat dissipator.

It is also known to remove the heat of an electrical apparatus with a heat pipe, e.g. a sealed off device containing a liquid which is vaporized on a side exposed to the heat sink, and condensed on the side exposed to the heat dissipator. Vaporization chambers are known which contain a fluid which takes up heat by vaporization against a hot wall, the vapor being spread onto a cool wall where it is being condensed and returned by gravity for reuse along the hot wall thereof. The essential distinction between a heat pipe and a vaporization chamber, resides in that the former carries away the vaporized fluid and returns the condensate across a smaller cross section and along a longer path, sometimes with the assist of a wick element utilizing capillary action.

SUMMARY OF THE INVENTION

The present invention resides in using a vaporization chamber as the top section of an enclosure housing totally enclosed electrical apparatus, so that the heat generated by the electrical apparatus is absorbed by the lower surface of the vaporization chamber, while the condensate of the vaporized fluid is being returned by gravity from the top surface of the vaporization chamber used as a heat dissipator.

The invention distinguishes over vaporization chamber, or heat pipes, of the prior art in that the cooling structure itself is part of the overall housing structure of the electrical apparatus, rather than being merely a cooling device embodied within a predetermined bessel structure. The invention also provides for a working fluid within the vaporization chamber having a temperature of vaporization at one atmosphere pressure which is under the critical temperature of the enclosed electric apparatus so that the vapor build-up within the vaporization chamber substantially remains at the ambient atmospheric pressure. As a result, no particular reinforcing structure is needed, in general, for the vaporization chamber.

The invention, further provides that the metallic wall defining the surfaces of the vaporization chamber, in particular the heat evaporator and the heat dissipator of the vaporization chamber, are given a minimum thickness, with the additional feature that areas of the heat dissipator are inclined at an angle to the overall horizontal plane of the top surface which create internal protrusions in the vaporization chamber which provide condensate return by gravity from the heat dissipator, or condensor, to the surface of the working fluid, while at the same time providing structural reinforcement compensating for the minimum thickness chosen. As a result, maximum heat dissipation at the top surface and maximum condensate return circulation are obtained in conjunction with improving the housing structure solidity.

The invention will be more fully understood from a consideration of the preferred embodiment described hereinafter as an illustration of how the invention can best be readily carried into practice.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 shows the cabinet according to the present invention.

Figure 2 show another illustration of the present invention with an amovable vaporization chamber forming the top section of a cabinet containing electrical equipment to be protected from the outside.

THE PREFERRED EMBODIMENT OF THE INVENTION

Figure 1 represents an electrical cabinet for electrical apparatus, preferrable for computer equipment, defined between a top surface having four apices 1, 2, 3, 4 and a bottom surface having four apices 9, 10, 11, 12. This This cabinet has seal-proof metallic walls (1, 2, 3, 4) (9, 10, 11, 12) (1, 4, 9, 12), (4, 12, 11, 3), (10, 11, 3, 2) and (9, 10, 2, 1), within which two sealed compartments AR and VC are provided. The AR compartment contains the electrical equipment in the form of electronic components and electrical supply thereof, mounted on racks (not shown) across the vertical walls. Preferablly, the AR compartment contains the entire package of a minicomputer.

The VC compartment is sealed and constitutes essentially a vaporization chamber defined between planes (5, 8, 7, 6) and (1, 2, 3, 4) at the top of the cabinet. A sufficient quantity of trichlorotrifluoroethane (Freon 113) or other suitable working fluid is enclosed within compartment VC so as to maintain at all times a layer of liquid on the lower surface (5, 6, 7, 8) even when some of the liquid has been vaporized therefrom. This layer is replenished by liquid which is continuously returned in the form of condensate from beneath the top surface (1, 2, 3, 4) i.e., a continuous cyclic flow of working fluid is created.

The temperature of vaporization of Freon 113 is 117°f at 0 p.s.i.g. (47°C at one atmosphere).

The apparatus enclosed in the AR compartment may for instance be a computer, its power sypply and auxillary circuitry. It is desirable that the equipment contained in the cabinet not be subjected to temperatures 132°F (55°C). This would require an evacuation of excess heat through the heat sink or condensor surface (5, 6, 7, 8) of the vaporization chamber in the order of 1.5 to w kilowatts. Considering the ususal dimensions of a minicomputer with properly distributed racks of components, this excess of heat represents an evacuation of the order of 3 watts/square inch of the heat sink surface or more, depending on cabinet dimensions. For such requirement, the distance between the two planes defining the heat sink and heat dissipator of the vaporization chamber VC is selected to be between 2 and 6 inches when Freon 113 is used as the working fluid.

The thermodynamics of operation of a vaporization chamber is well known. The heat received through the heat sink (5, 6, 7, 8) converts an equivalent quantity of liquid into vapor (latent heat of vaporization) which reaches the cooler surface of the heat dissipator and gives up its latent heat, then condenses and falls back back by gravity to the liquid reservoir. This process is self-sustaining and no exterior means other than the presence of a temperature gradient are necessary to evacuate the heated medium or supply working fluid to the reservoir, as would be the case in a normal heat exchanger using pumps or fans to move the working fluid. Gravity dispenses from the provision of any particular means to force the circulation of the cooling medium.

The choice of Freon 113 allows the vaporization chamber to be operative at normal atmospheric pressure at a given temperature range. Therefore, there is no build-up of pressure inside the sealed compartment VC which otherwise would require reinforced wall structures. Normal cabinet walls can be used and the vaporization chamber may be self-contained and assembled to form the top section of the cabinet structure.

In addition, special provision is made of a thin metallic wall for such cabinet structure. For instance an aluminum sheet can be used. The thinness of the metal is favorable in providing maximum effeciency in the heat transfer both for the heat sink or evaporator (5. 6. 7. 8) and the heat dissipator, or condensor (1, 2, 3, 4). This requirement of a thin wall is satisfied, in accordance with the present invention, without any reduction in the overall cabinet strength by providing at the top-surface of the cabinet a certain configuration, as shown by planes A, B, D, C which are defined by creases formed in the metal and a dimple. This particular structural feature of the top of the cabinet enhances the efficiency of the vaporization chamber by presenting to the vaporized fluid inclined surfaces which tend to accelerate the formation of heavy accumulation of liquid and cause the condensate to run from the roof of the chamber down to the pool, or reservoir resting by gravity on the heat sink or evaporator surface.

The cabinet, according to the present invention, is made of sheet metal for the side walls as well as for the top and the bottom sections. The heat dissipator of the vaporization chamber VC is a metal sheet which may be made integral with the four vertical cabinet walls. As earlier explained, the thickness of the metal used is selected to be as small as acceptable for the cabinet strength in order to strengthen the top section of the cabinet while keeping such minimal acceptable metal thickness. As previously stated, inclined planes are formed to facilitate the return of the condensate by gravity from the heat dissipator down to the heat sink. The top surface may also be made disc-shaped, or incurvated, in any way to create and consist of a surface inclined downward from the periphery. A similar structural shape may also be formed in the opposite direction, e.g., upward to strengthen the heat sink or condensor metal plates.

Figure 1 shows four planes A, B, C, D defined by creases extending in the top metal sheet from the peripheral apices 1, 2, 3, 4, downward. As a result, the roof of the vaporization chamber VC has a generally polyhedral shape providing preferential directions of flow along which the condensate accumulates and runs back down to the mass of fluid in the liquid state.

The heat sink (5, 6, 7, 8) of the vaporization chamber preferrabley consists of a transverse plate of metal integrally united with the side walls of the cabinet. The vaporization chamber VC does not carry andy appreciable weight, nor does it support any substantial pressure. It does not either occupy much space above the contained equipment. A unitary closed cabinet is thus provided which carries a top section entirely sealed from the outside, and in which a heat transfer feature has been embodied as simply as possible, while only slightly changing the configuration and the overall dimensions of the cabinet without requiring the addition of any substantial part or weight, and that can easily be accommodated with a standard cabinet.

The present invention may be carried out in different forms shown in Figure 1. Figure 2 shows a typical top section for a cabinet according to the present invention. Figure 2 shows how typically the cabinet top according to the present invention is mounted on the upper part of the cabinet. The cabinet 20 is provided with flanges 21 along the upper part of the vertical metal plates on four sides of the enclosure in which electrical components of the enclosed apparatus are mounted. The top section 22 is in the form of a sealed vaporizarion chamer, containing working fluid which by gravity rests on the lower surface 23. The upper surface 24 of the top section 22 exhibits creases at 25 for the puprose described heretofore. Preferably, but not necessarily, creases at 26 are also provided in the metal sheet forming the lower surface 23. The heat sink, or evaporator, is constituted by the lower metal sheet 23, the heat dissipator, or condensor is found at 24 with the upper metal sheet of the top section 22. A platform 27 is provided which can be mounted easily laterally of the top section on a supporting plate 32. On the platform are mounted pressure and temperature gauges 28, 29 which are in communication with the vaporization chamber through an access port 30, provided with a peripheral point 31 which can be sealed tight between the supporting plate 32 by bolts and screws 33.

It is possible to build vaporization chamber VC as a separate unit all sealed off in advance, and to build separately the equipment vessel AR with all parts mounted inside as another unit. The two units are then assembled, mounted and joined integrally in order to form the cabinet according to the present invention.

Normally heat from the equipment vessel to the vaporization chamber is transferred to the heat sink by radiation, conduction, and convection. Provision can be made, not necessarily, for an electric fan within the equipment vessel AR, in order to force circulation of the air enclosed in the cabinet toward and along the surface of the heat sink (5, 6, 7, 8) in order to increase heat exchange with the vaporization chamber.

It is also possible to include within the equipment vessel one or more additional vaporization chambers, each azsociated with specific electrical components or parts of greater concern. These additional chambers would abandon heat from their heat dissipator surfaces into the air space inside the equipment enclosure. In this fashion cascaded cooling may take place from down with the equipment vessel AR up to the main heat sink surface (5, 6, 7, 8) of the main vaporization chamber VC according to the present invention.

CLAIMS

1. A cabinet for electrical equipment comprising an enclosure having side walls and bottom surfaces, a partition defining two compartments one on top of the other, the lower compartment containing electrical equipment and the top compartment being a sealed compartment forming a vaporization chamber defined between said partition as a heat sink and a heat dissipator serving as the top surface of said cabinet.

2. The cabinet of claim 1, with said vaporization chamber containing liquid resting by gravity on said partition and having a vaporization temperature above 80°F and below 120°F.

3. The cabinet of claim2, with said liquid being trichlorotrifluoroethane.

4. The cabinet of claim 2, with said top surface being recessed from a horizontal plane defined by the highest points of the sidewalls of said cabinet.

5. The cabinet of claim 4 with said top surface having a plurality of planar surfaces inclined downward, the form factors of which promote the return of the condensate to the liquid on said partition.

6. The cabinet of claim 5 with said top surface being made of metal sheet, and said planar surfaces being formed by folding of said metal sheet.

7. A cabinet for electrical equipment comprising a bottom wall, four vertical side walls, an amovable top section adapted to be mounted directly on said side walls to form a closed housing therewith, and means attached at least to said side walls for supporting the electrical equipment inside said closed housing; with said top section consisting of a vaporization chamber.

8. The cabinet of claim 7 with said top section having an upper metallic plate, a lower metallic plate and four side plates, said upper, lower and side plates being integrally united to form a sealed chamber containing liquid trichloro-trifluoroethane resting by gravity on said lower surface.

9. The cabinet of claim 8 with said lower plate being a heat sink for said cabinet, and with said higher plate being a heat dissipator for said vaporization chamber.

10. The cabinet of claim 9 with said upper plate having a plurality of planar surfaces inclined downward, the form factors of which promote the return of the con-

densate from vapor evolving from said liquid.

11. The cabinet of claim 10 with said lower, upper and side plates having a minimal thickness.

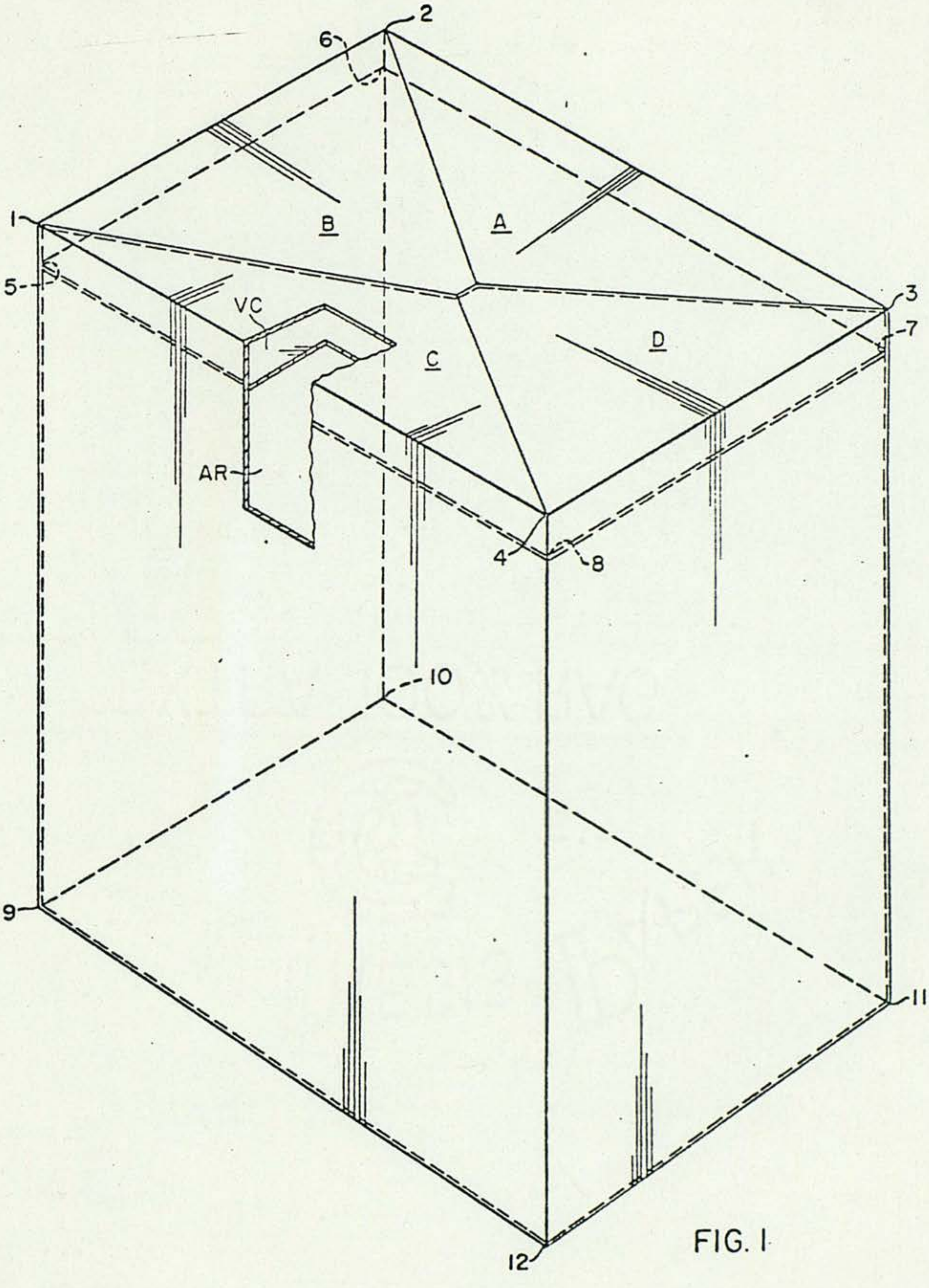


FIG. 1

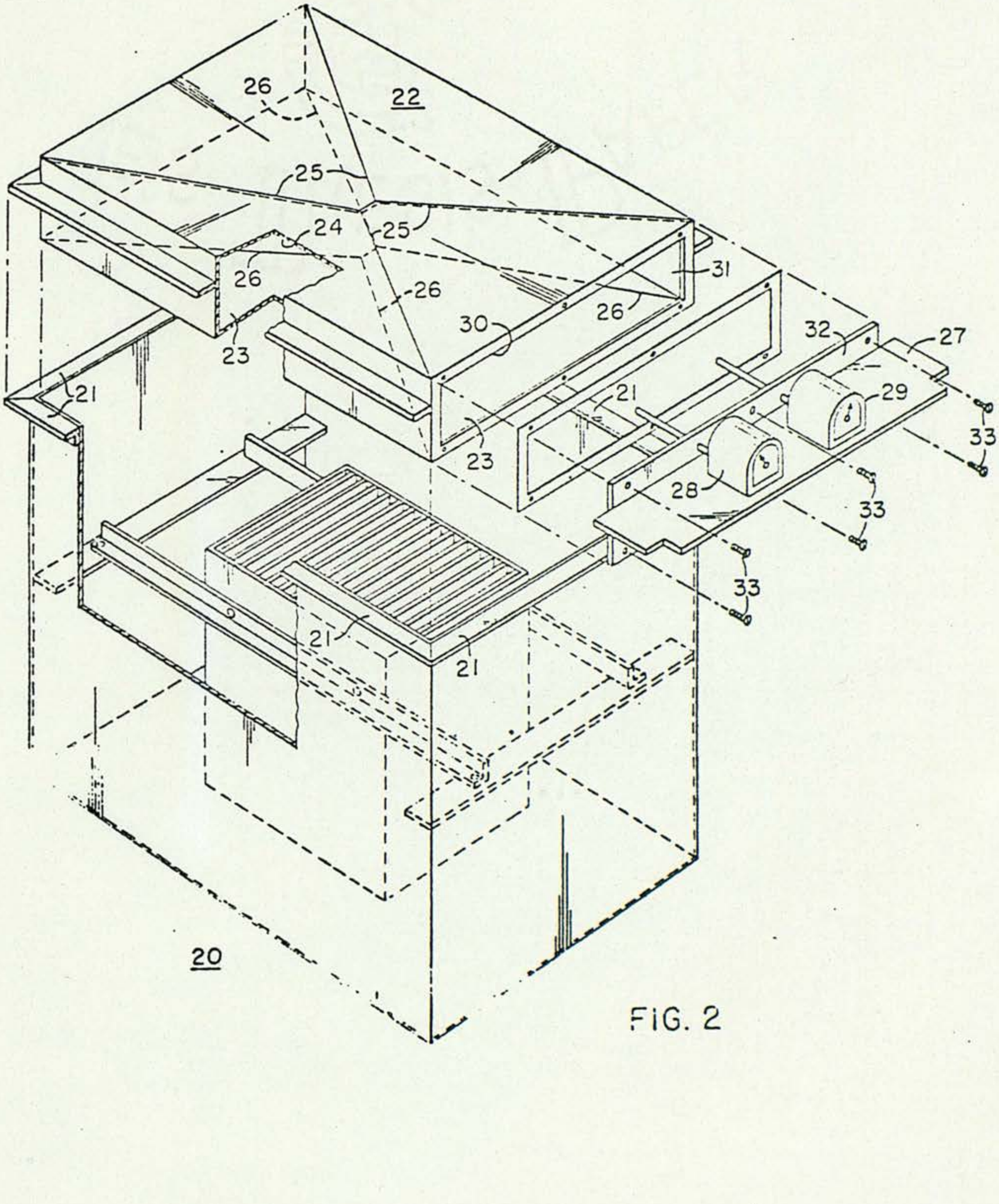


FIG. 2

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