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UNIVERSAL HUMIDITY CHART

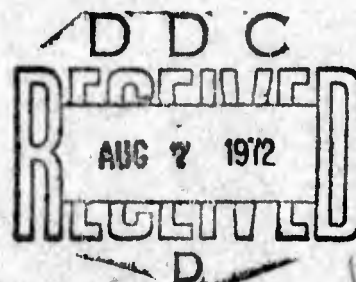## P.G. SEXTON

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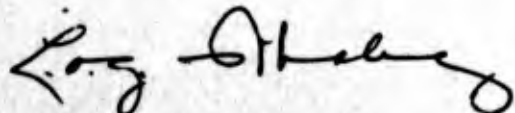# SYSTEMS NAVAL COASTAL LABORATORY

ABSTRACT

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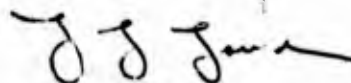
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Humidity charts suitable for use with gas mixtures of various compositions and for various pressures are rare in the literature. Present charts specifically for use with gas mixtures used in saturation diving require the use of separate charts and interpolation for pressures which are intermediate to those specifically presented. The Universal Humidity Chart in the report is a single chart allowing humidity and energy calculations for any mixture of monatomic and diatomic gases at pressures from 1 atmosphere to any pressure that might conceivable be encountered in saturation diving. The simplification is made possible by a judicious choice of units for humidity.

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KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Humidity						
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Dew Point						
Test Chambers						
IDENTIFIERS:						
Psychrometric Chart						
Hyperbaric Environment						
Saturation Diving						
Breathing Gas Mixture						
Heliox						
Universal Humidity Chart						

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NOMENCLATURE

C_p	Constant pressure specific heat - Btu/lbm°R
H	Enthalpy - Btu
M	Mass - lbm
P	Pressure - lb_f/ft^2 absolute
$\overline{P}$	Pressure - atmospheres absolute
$P_{subscript}$	Partial pressure in a mixture
P_{sat}	Vapor pressure of saturated water vapor at dry bulb temperature
Q	Heat - Btu
$\dot{Q}$	Heat rate - Btu/min
R	Gas constant - ft lbf/lbm°F
RH	Relative humidity
t	Dry bulb temperature - °F
T	Dry bulb temperature - °R
t_{dp}	Dew point temperature - °F
T_{dp}	Dew point temperature - °R
V	Total mixture volume
y	Volume fraction
ϕ	Relative humidity
ρ	Mass density - lbm/ft^3

Subscripts

a	Diatomic gas
b	Monatomic gas
g	Saturated vapor
i	i^{th} component
v	Water vapor

INTRODUCTION

As saturation diving has progressed from its initial experimental stages to its present state in which operational dives are now being performed, the need for basic engineering data presented in usable form has grown to be more widespread.

Undersea habitats, personnel transfer capsules, decompression chambers, and other hyperbaric facilities have become numerous, more sophisticated, and larger in size. The design of life support equipment such as scuba gear has become more complex with a concurrent increase in attention to the physiological aspects of, for example, temperature and humidity control of the divers' breathing gas mix and environmental atmosphere.

Although no new basic knowledge is necessary for analyzing equipment to be used for conditioning of hyperbaric atmospheres, a need has arisen for techniques allowing the designer to make computations without going through the tedious calculations customarily undertaken. It is the purpose of this report to present information on humid atmospheres in a form which will aid in such computations.

Humidity charts suitable for use with gas mixtures of various compositions and pressures have been rare in the literature. The Navy Diving-Gas Manual (Reference 1) presents the only known set of humidity charts specifically for use with breathing gas mixtures used in saturation diving. There are three charts to cover the range of pressures from 14.7 to 600 psia. They are presented in units not customarily associated with humidity calculations.

The Universal Humidity Chart (Figure 1) is a single chart allowing humidity calculations for any breathing gas mixture (any mixture of diatomic and monatomic gases) at 1 atmosphere upward to any pressure that might conceivably be encountered in saturation diving. The units used will be familiar to persons normally engaged in calculations of environmental conditioning.

UNIVERSAL HUMIDITY CHART
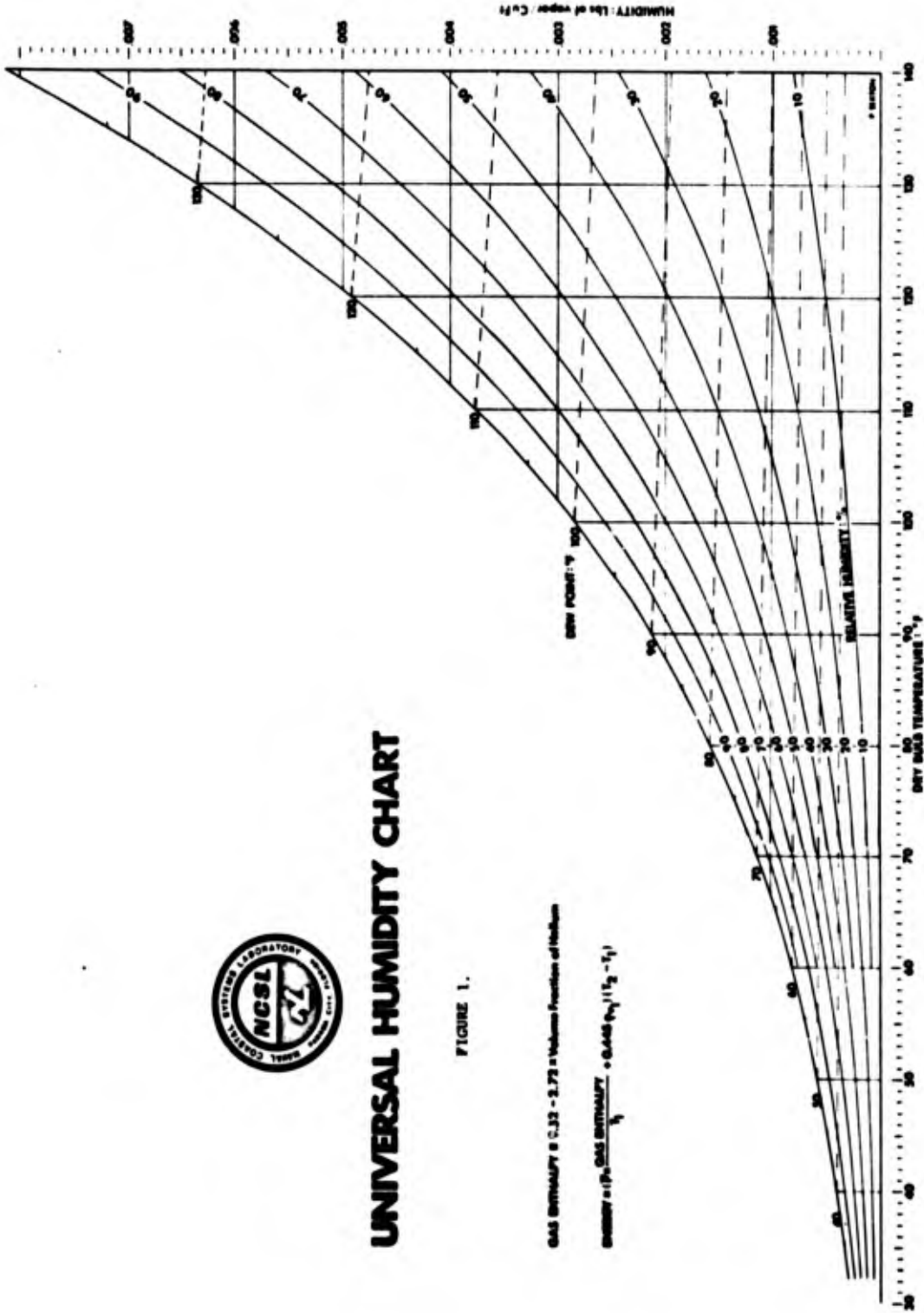
FIGURE 1.

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3.1   3.2

DEVELOPMENT OF THE CHART

The simplicity and universality of the chart (Figure 1) result from a judicious choice of units for the ordinate. The normal choice of units for the ordinate of a psychrometric chart is "mass of water vapor/mass of dry air." For use in normal heating and air conditioning calculations, such a scale provides the basis for simplicity in computation. When pressures are widely variable, however, such units are impossible to use because the density of the carrying gas (air in the case of a psychrometric chart) is also widely variable. Consideration of this difficulty led to the choice of units for the ordinate of the Universal Humidity Chart that would lend itself to being independent of the density of the carrying gas. The chosen unit was "mass of water vapor/cubic foot of mixture." The ordinate is then nothing more nor less than the mass density of the water vapor present in the mixture. Since the abscissa of the chart is dry bulb temperature, the saturation line (100% RH) is simply a plot of the density of saturated water vapor (ρ_g in Reference 2 nomenclature) as a function of temperature. Values used to plot this line were taken from *Steam Tables* (Reference 2).

Equations (1) and (2) are the equations for the lines of constant value of relative humidity and dew point temperature shown in Figure 1. It should be noted that in both cases the purpose of the derivation is to produce an equation for water vapor density as a function of dry bulb temperature with the property in question as a parameter. Mathematically,

$$\rho_v = f(t, \zeta)$$

in which ζ is the property in question. It should also be noted that the resulting equations will not be explicit in t. As an example, Equation (2) was derived for lines of constant relative humidity; ϕ is clearly the parameter, but the function involves t implicitly. That is, ρ_g is a function of t, the function being in tabular form in *Steam Tables* rather than in equation form.

Having derived the equations, it becomes a simple matter to insert the desired values of the parameters and then plot the curves of ρ_v as a function of t.

RELATIVE HUMIDITY

Lines of constant relative humidity were drawn assuming that water vapor behaves as an ideal gas. Such an assumption is well established and is customarily made in the development of psychrometric charts and introduces little error (Reference 3).

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The equation for a line of constant relative humidity results almost directly from its standard definition

$$\phi = \frac{P_v}{P_{sat}} .$$ (1)

The assumption of ideal gas behavior for the water vapor allows

$$P_v = \rho_v R_v T,$$

so that

$$\phi = \frac{\rho_v R_v T}{P_{sat}} .$$

But the same assumption for water vapor in the saturated state allows

$$P_{sat} = \rho_g R_v T ,$$

and thus

$$\phi = \frac{\rho_v R_v T}{\rho_g R_v T} .$$

A rearrangement yields

$$\rho_v = \phi \rho_g.$$ (2)

As previously stated, lines of constant relative humidity can now be drawn by (1) selecting the desired value of ϕ and (2) using tabulated values of ρ_g versus t, plot ρ_v as a function of t.

DEW POINT TEMPERATURE

The dew point temperature of a mixture of gas and water vapor is defined as that temperature at which condensation will occur when the mixture is cooled at a constant pressure. Thus, until condensation occurs in a mixture, the partial pressure of the water vapor is unchanged. A line of constant dew point temperature is then also a line of constant partial pressure of water vapor. In addition, the value of the water vapor partial pressure is that value corresponding to the saturation pressure at the dew point temperature of the mixture.

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Hence for a constant dew point temperature

$$P_v = \text{constant} = P_{sat} @ t_{dp} . \tag{3}$$

Employing the ideal gas relations again,

$$P_v = \rho_v R_v T$$

and

$$P_{sat} @ t_{dp} = (\rho_g @ t_{dp}) R_v T_{dp} .$$

Therefore,

$$\rho_v R_v T = (\rho_g @ t_{dp}) R_v T_{dp}$$

or

$$\rho_v = (\rho_g @ t_{dp}) \frac{T_{dp}}{T} . \tag{4}$$

Equation (4) shows that lines of constant dew point temperature on the Universal Humidity Chart (Figure 1) are not horizontal as on a standard psychrometric chart, but slope slightly downward with increasing temperature.

ENERGY CALCULATIONS

Standard psychrometric charts include lines of constant mixture enthalpy for use in energy calculations. The fact that the Universal Humidity Chart is specifically designed to apply to a wide variety of mixed gases over a wide range of pressures precludes the inclusion of such lines. Rather, a simplified technique for energy calculations was developed and is presented as an equation on the chart. The use of the equation is straightforward and in cases of moderate to high hyperbaric pressures will give accurate results even if water vapor content is ignored. A later discussion will show limits of error.

It is convenient to divide the development of the energy calculation equation into three parts. The first discussion will be concerned with the dry carrier gas, the second with the contained moisture, and the third with total energy calculation.

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ENERGY FOR THE DRY CARRIER GAS

The equations developed here all rely on the assumption that the carrier gas is composed of only diatomic and monatomic gases. Since the chart has been developed primarily for use with mixtures for saturation diving where the overwhelming majority of dry gas is a mixture of helium (or neon), oxygen, and nitrogen, this assumption is believed to impose little or no restrictions. Although mixes will be encountered which contain carbon dioxide and other nonsimple gases, the percentages thereof are necessarily small in a life supporting atmosphere.

Remember that each gas in a mixture of gases behaves as if it occupies the total mixture volume at the mixture temperature. Thus, its equation of state is

$$P_1 V = M_1 R_1 T . \tag{5}$$

Remember also that the constant pressure specific heat of any diatomic gas, or mixture thereof, is related (to a close approximation)* to its gas constant by the equation

$$C_{p_a} = 0.0045 \ R_a ** . \tag{6}$$

Similarly for a monatomic gas (or a mixture of monatomic gases)

$$C_{p_b} = 0.00324 \ R_b ** . \tag{7}$$

Finally, remember that a gas heated (or cooled) at constant pressure requires energy given by

$$Q = H_2 - H_1 . \tag{8}$$

Now consider the constant pressure heating of a mixture of diatomic and monatomic gases from T_1 to T_2:

---

*Clearly these relations hold only over a small temperature range, but the Universal Humidity Chart (Figure 1) is similarly limited.

**For a discussion of these approximations, see Reference 4.

$$Q = H_2 - H_1 = M_a C_{p_a} (T_2 - T_1) + M_b C_{p_b} (T_2 - T_1)$$

$$= (T_2 - T_1) (M_a C_{p_a} + M_b C_{p_b}) .$$

Using Equations (6) and (7)

$$Q = (T_2 - T_1) (0.0045 \, M_a R_a + 0.00324 \, M_b R_b) .$$

Rearranging slightly,

$$Q = (\frac{T_2}{T_1} - 1) (0.0045 \, M_a R_a T_1 + 0.00324 \, M_b R_b T_1) ,$$

and using Equation (5)

$$Q = (\frac{T_2}{T_1} - 1) (0.0045 \, P_a V_1 + 0.00324 \, P_b V_1) .$$

Thus, the energy required per unit original volume is

$$\frac{Q}{V_1} = (\frac{T_2}{T_1} - 1) (0.0045 \, P_a + 0.00324 \, P_b) .$$

It is convenient (as will later develop) to divide the preceding by the total mixture pressure

$$\frac{Q}{PV_1} = (\frac{T_2}{T_1} - 1) (0.0045 \, \frac{P_a}{P} + 0.00324 \, \frac{P_b}{P}) .$$

The pressure ratios may now be replaced by the corresponding volume fractions to yield

$$\frac{Q}{PV_1} = (\frac{T_2}{T_1} - 1) (0.0045 \, y_a + 0.00324 \, y_b) .$$

Since all dry gas components have been assumed to be either diatomic or monatomic

$$y_a + y_b = 1,$$

and the substitution $y_a = 1 - y_b$ may be made to yield

$$\frac{Q}{PV_1} = (\frac{T_2}{T_1} - 1) (0.0045 - 0.00126 \, y_b) . \tag{9}$$

When using the humidity chart, it is more convenient to deal with pressures in atmospheres. The constants in Equation (9) must then be adjusted to yield

$$\frac{Q}{PV_1} = (\frac{T_2}{T_1} - 1) (9.52 - 2.72 \, y_b).$$ (10)

Equation (10) may be used directly to calculate energy required to heat or cool dry gas mixtures of diatomic and monatomic gases. The right-hand side is evaluated knowing the initial and final temperatures, and the volume fraction of the monatomic gas. The resulting number need only be multiplied by the total pressure in atmospheres and the initial volume (or initial volume flow rate) to obtain the energy (or the energy rate) required.

ENERGY FOR THE WATER VAPOR

Equation (10) will be shown later to be sufficient for calculating energies required for even humid gas mixtures under a variety of conditions with little error. Since, however, water vapor is present (and for completeness) the equation for energy required to heat or cool the water vapor is presented.

Equation (8) could be used for water vapor, enthalpy being evaluated directly from the *Steam Tables* (Reference 2). Over the relatively small temperature range and at the low partial pressures in the Universal Humidity Chart, however, it is sufficiently accurate to deal with the water vapor as an ideal gas and write

$$Q_v = M_v C_{p_v} (T_2 - T_1) .$$

Using an average value for C_{p_v} and dividing by the initial volume

$$\frac{Q_v}{V_1} = \frac{M_v}{V_1} 0.445(T_2 - T_1) ,$$

or

$$\frac{Q_v}{V_1} = 0.445 \, \rho_{v_1} (T_2 - T_1) .$$ (11)

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ENERGY FOR THE MOIST GAS MIXTURE

For the Universal Humidity Chart, the monatomic gas will be taken to be helium. For simplicity of presentation on the chart a new quantity is arbitrarily defined:

Gas enthalpy ≡ 9.52 - 2.72 x volume fraction of helium*.

Comparison with Equation (10) shows that the energy per unit initial volume required to heat or cool the dry gas could be written in terms of "gas enthalpy" as

$$\frac{Q}{V_1} = \overline{P} \times \frac{\text{gas enthalpy}}{T_1} (T_2 - T_1) .$$

Adding this quantity and that given by Equation (11) yields the energy for a moist gas

$$\frac{Q + Q_v}{V_1} = (\overline{P} \times \frac{\text{gas enthalpy}}{T_1} + 0.445 \rho_{v_1}) (T_2 - T_1) . \qquad (12)$$

This equation is presented on the Universal Humidity Chart. Examples of its use are given in a later section.

ERRORS DUE TO NEGLECTING WATER VAPOR

Investigation of Equation (12) will show that the energy term due to water vapor could be quite small compared with that due to the dry carrier gas. The percent error due to neglecting water vapor is given by

$$\% \text{ error} = \frac{0.445 \rho_{v_1}}{\overline{P} \times \frac{\text{gas enthalpy}}{T_1} + 0.445 \rho_{v_1}} \times 100 . \qquad (13)$$

Equation (13) has been used to plot Figure 2 which shows the total pressure for which the water vapor term may be ignored as a function of initial gas temperature for given allowable errors. The figure has been

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*As is clear from Equation (10), the general case includes the possibility of any monatomic gas, not just helium.
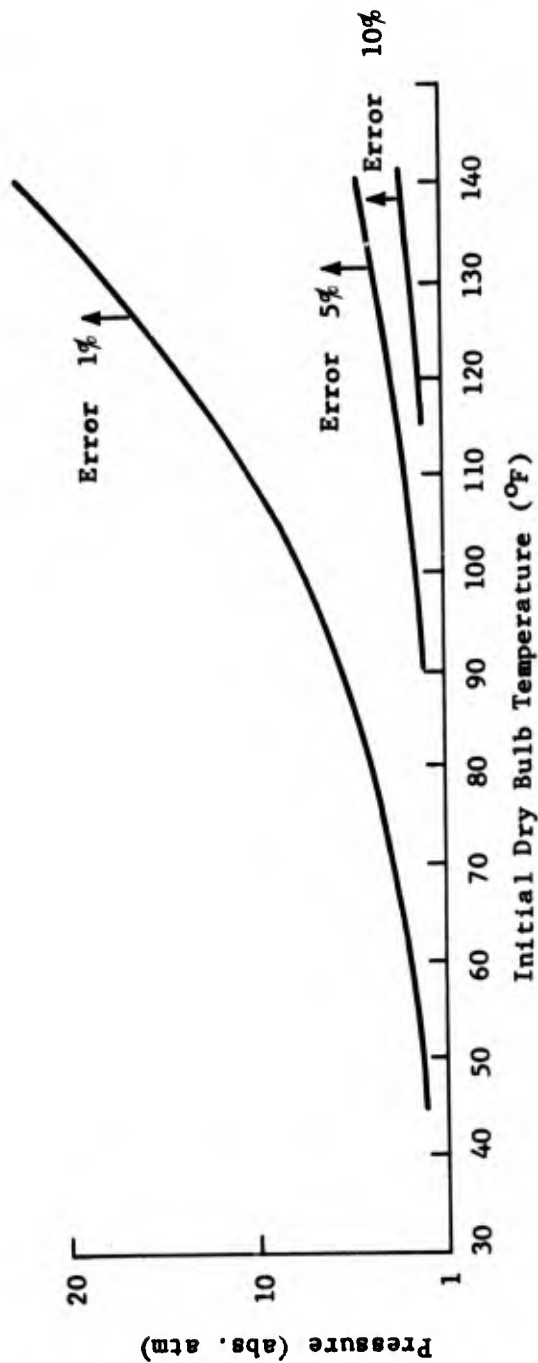
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FIGURE 2. MAXIMUM ERROR DUE TO IGNORING WATER VAPOR IN ENERGY
CALCULATIONS AT VARIOUS INITIAL TEMPERATURES
AND VARIOUS TOTAL MIXTURE PRESSURES

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computed assuming 100 percent relative humidity and no monatomic gas.
This is by far the worst case. The error is directly proportional to
relative humidity. As an example, note that less than 1 percent error
will occur if one is calculating energies for a gas mixture at 5 atmos-
pheres and an initial temperature of 88°F. At 50 percent relative
humidity, less than 1 percent error would occur at half that pressure
(2.5 atmospheres).

OMISSIONS FROM THE CHART

WET BULB TEMPERATURE

Standard psychrometric charts include lines of constant wet bulb
temperature. Such lines are not included on the Universal Humidity
Chart. There are two major reasons for the omission: first, in hyper-
baric atmospheres the slope of the lines of constant wet bulb tempera-
ture is dependent on pressure. The higher the pressure, the more
nearly vertical are the lines. Physically, this means that extremely
accurate measurements of wet bulb temperatures would be required to
obtain accurate readings of relative humidity; and second, there is as
yet no analysis suitable to predicting these lines with any degree of
accuracy. Although analyses have been presented in the literature,
their accuracy is as yet unproven.

SPECIFIC VOLUME

The other information customarily included on standard psychromet-
ric charts is specific volume. Clearly, since composition of the
carrier gas may vary over wide ranges, it would not be feasible to
include such information in the present chart.

EXAMPLES OF USE OF THE CHART

The Universal Humidity Chart is used in a manner very similar to
that for a standard psychrometric chart. The major difference is the
choice of units for the ordinate. Since horizontal lines on the chart
represent constant water vapor density rather than constant mass frac-
tion of water vapor, lines representing simple heating and cooling must
follow lines of constant dew point temperature. (It will be recalled
that lines of constant dew point temperature are coincident with lines

of constant mass fraction of water vapor.) The following examples
illustrate the use of the chart in some simple problems.

DETERMINATION OF RELATIVE HUMIDITY

One of the more common problems is that of determining the rela-
tive humidity and moisture content of a hyperbaric atmosphere having
measured the dry bulb temperature and the dew point temperature.

Figure 3 illustrates this determination in a case where the dry
bulb temperature is 90°F and the dew point temperature 70°F. The state
point is located at the intersection of lines representing those values.
The state is seen to be at a relative humidity of 52 percent with a
moisture content of 0.0011 pounds/cubic foot. Note that this result
is independent of total pressure.

Permutations of this type of problem are obvious. For example,
one might require the dew point temperature necessary to give 52 percent
relative humidity at 90°F dry bulb temperature. The answer is clearly
70°F dew point temperature.

SIMPLE HEATING

Another common situation is one in which a hyperbaric atmosphere
of known initial condition is to be heated to a known final temperature.
It is desired to determine the final condition and the energy required.

For illustration, suppose that a habitat atmosphere at a seawater
depth of 200 feet is to be heated from an initial state of 50°F and
100 percent relative humidity to a final dry bulb temperature of 80°F.

Figure 4 shows the initial state (1), the path followed, and the
final state (2). Since the process is one of constant gas and water
vapor composition, the path is coincident with a line of constant dew
point temperature, in this case 50°F. The final state is seen to be
at 35 percent relative humidity. It should be noted that the path is
independent of total pressure.

To calculate the energy involved one must know the gas composition.
Table 1 is included for reference and convenience in determining compo-
sition. The volume fractions of the various dry constituents are tabu-
lated as a function of seawater depth for a commonly occurring situation
in which the enclosure (habitat) is initially pressurized with air to
1.43 atmospheres (to produce an oxygen partial pressure of 30 percent
sea level equivalent). The remaining pressurization is accomplished
with pure helium. Values for volume fractions when pure heliox is used
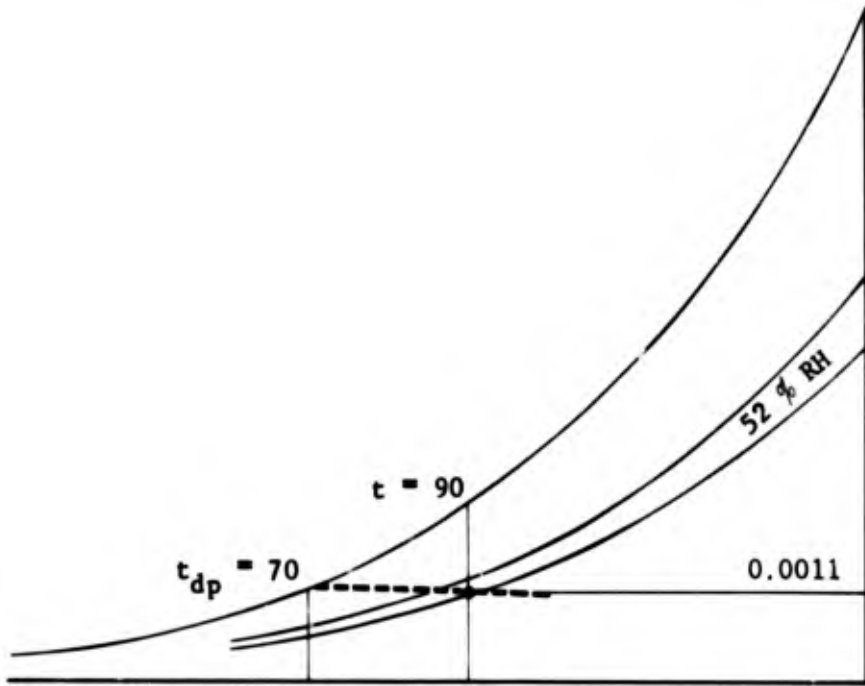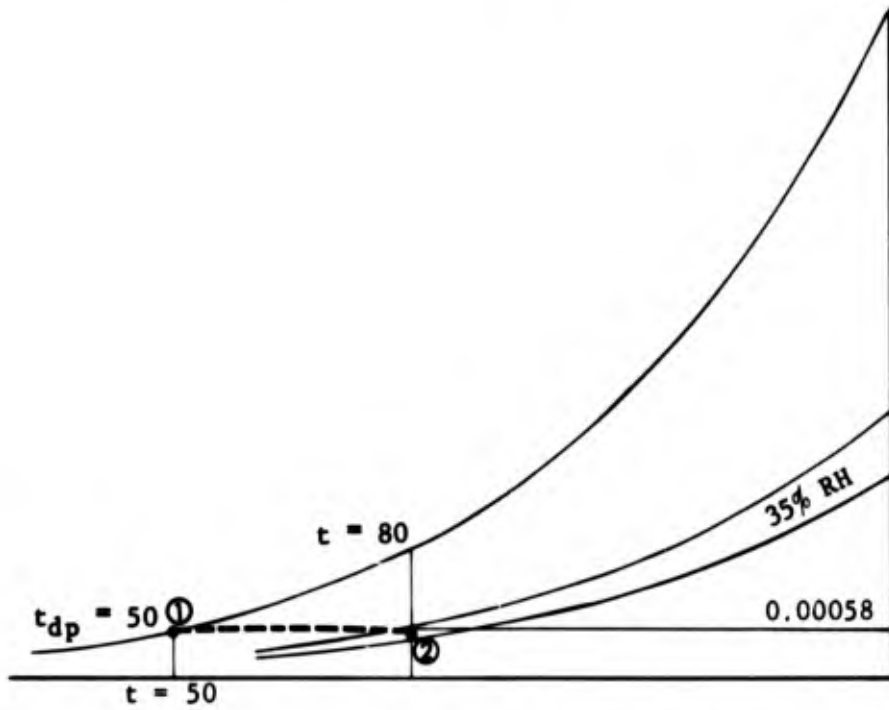
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FIGURE 3. ILLUSTRATION OF A HUMIDITY PROBLEM

FIGURE 4. ILLUSTRATION OF A HEATING PROBLEM

TABLE 1

REFERENCE PRESSURES AND HELIUM VOLUME FRACTIONS FOR VARIOUS SEAWATER DEPTHS AND COMPOSITIONS

Seawater Depth (Ft)	Pressure (Abs. Atm)	Oxygen Vol (%)	Helium	
			Chamber Diving* Vol (%)	Pure Heliox Vol (%)
100	4.03	7.43	64.50	92.57
200	7.05	4.24	79.70	95.76
300	10.08	2.97	85.80	97.03
400	13.11	2.28	89.09	97.72
500	16.13	1.85	91.13	98.15
600	19.15	1.56	92.53	98.44
700	22.18	1.34	93.55	98.66
800	25.21	1.18	94.33	98.82
900	28.24	1.05	94.90	98.95
1000	31.26	0.95	95.43	99.05
1100	34.29	0.86	95.84	99.14
1200	37.32	0.79	96.17	99.21
1300	40.34	0.73	96.46	99.27
1400	43.37	0.68	96.71	99.32
1500	46.39	0.64	96.92	99.36
1600	49.42	0.60	97.11	99.40
1700	52.45	0.56	97.27	99.44
1800	55.47	0.53	97.42	99.47
1900	58.50	0.50	97.56	99.50
2000	61.53	0.48	97.68	99.52
2100	64.55	0.45	97.78	99.55
2200	67.58	0.43	97.88	99.57
2252.2	69.00	0.42	97.93	99.58

*Chamber diving is defined as the situation in which nitrogen partial pressure (due to residual nitrogen from initial air pressurization) is constant at 858 mm Hg.

are also tabulated for the same oxygen partial pressure. For other compositions the user of the chart must compute the volume fractions.

In this example, Table 1 shows the helium fraction to be 79.70 percent and the total pressure to be 7.05 atmospheres. Using the equations presented on the chart:

$$\text{Gas enthalpy} = 9.52 - 2.72 \times 0.7970$$

$$= 7.35$$

$$\text{Energy} = \left(7.05 \times \frac{7.35}{510} + 0.445 \times 0.00058\right)(540 - 510)$$

$$= 3.06 \text{ Btu/cubic foot .}$$

Remember that the energy quantity calculated is on the basis of original volume. Thus, if the heat rate required to warm 100 cfm of gas beginning at state (1) was required, the calculation would be:

$$\dot{Q} = 3.06 \, \frac{\text{Btu}}{\text{ft}^3} \times 100 \, \text{ft}^3/\text{min}$$

$$= 306 \text{ Btu/min .}$$

Reference to Figure 2 prior to the calculations would have shown that less than 1 percent error would have occurred by ignoring the water vapor.

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