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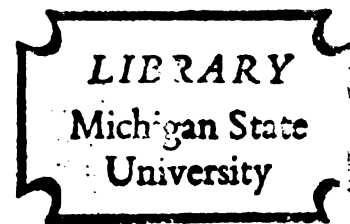
A FORTRAN PSYCHROMETRIC MODEL

Thesis for the Degree of M. S.
MICHIGAN STATE UNIVERSITY
LLOYD EUGENE LEREW
1972



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ABSTRACT

A FORTRAN PSYCHROMETRIC MODEL

BY

LLOYD EUGENE LEREW

Psychrometric properties are basic to many agricultural systems. A psychrometric model is therefore required for computer simulation and analysis of such systems.

A collection of theoretical and empirical psychrometric equations have been programmed as a set of efficient and interconnected FORTRAN sub-programs.

Dry-bulb, wet-bulb and dew-point temperature, absolute and relative humidity, vapor and saturated vapor pressure, latent heat, enthalpy, and specific volume are included in the model. Given any two of these properties (if they are independent), it is possible to find the remaining properties with the model.

Specific instructions for the use of the model are given for a number of pairs of independent starting properties.

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A FORTRAN PSYCHROMETRIC MODEL

BY

LLOYD EUGENE LEREW

A THESIS

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PREFACE

The thesis, A Fortran Psychrometric Model, written by Lloyd E. Lerew represents only a small part of his research efforts over the past two years. Following is a complete list of the projects to which Lloyd E. Lerew has either contributed significantly or has been its sole researcher:

1. Grain Drying

Bakker-Arkema, F. W., T. W. Evans, and L. E. Lerew (1970) Michigan State Grain Drying Models. ASAE Paper No. 70-832.

Bakker-Arkema, F. W. and L. E. Lerew (1970) Single particle cooling and thin-layer drying simulation. In Proceedings of the Institute for Simulation of Cooling and Drying Beds of Agricultural Products, Agricultural Engineering Department, Michigan State University, East Lansing, Michigan.

Bakker-Arkema, F. W., R. J. Patterson, and L. E. Lerew (1971) Multiple-zone drying in stationary and moving bed dryers. ASAE Paper No. 71-302.

Bakker-Arkema, F. W., L. E. Lerew, and R. J. Anderson (1972) Better quality grain through the use of concurrent flow grain drying with counterflow cooling. In Proceeding of Grain Damage Symposium, Ohio State University, Columbus, Ohio.

Bakker-Arkema, F. W., L. E. Lerew, and S. F. DeBoer (1972) Grain dryer simulation. Research Report - Michigan Agricultural Experiment Station, Michigan State University, East Lansing, Michigan.

Bakker-Arkema, F. W., M. G. Roth, and L. E. Lerew (1972). Gleichzeitig Wärme-und Stoff-Austausch in einem getreidetrockner mit gegenstrom. Landtechnische Forschung (accepted for publication).

Brooker, D. B., L. E. Lerew, and F. W. Bakker-Arkema (1971) Drying by alternating heated and unheated air: a mathematical analysis. ASAE Paper No. 71-307.

Lerew, L. E. (1970) Comparison of thin-layer drying equations for corn. Unpublished Report.

2. Potatoes

Lerew, L. E. (1972) Energy and time requirements for heating potatoes after storage. In Proceedings of the Midwest Potato Storage Workshop, Cooperative Extension Service, Michigan State University, East Lansing, Michigan.

Rosenau, J. R., F. W. Bakker-Arkema, and L. E. Lerew (1970) Cooling of a bed of potatoes (or apples, tomatoes, sugarbeets, onions): a realistic model. In Proceedings of the Institute for Simulation of Cooling and Drying Beds of Agricultural Products, Agricultural Engineering Department, Michigan State University, East Lansing, Michigan.

3. Other

Bakker-Arkema, F. W. and L. E. Lerew (1972) Heat exchangers, computer analysis. IFT Convention, Minneapolis, Minnesota.

Lerew, L. E. (1972) Toward more effective use of the CDC 6500 (how to get the 6500 before it gets you). To be published, Department of Agricultural Engineering, Michigan State University, East Lansing, Michigan.

Lerew, L. E., F. W. Bakker-Arkema, and G. H. Bulgrien (1972) User's guide to SGRAF6 and SPLOT6: printer and Calcomp plot packages. Unpublished report.

It was the intention of the guidance committee to include in this thesis all the papers of which Lloyd E. Lerew had been the author or a co-author. Unfortunately current administration procedures within the Colleges of Engineering and of Agriculture and Natural Resources at Michigan State University did not allow this.

F. W. Bakker-Arkema
Chairman Guidance Committee
of L. E. Lerew and Major
Professor.

TABLE OF CONTENTS

	Page
INTRODUCTION	1
BASIC PSYCHROMETRIC EQUATIONS	2
FORMULATION OF THE MODEL	6
USE OF THE MODEL	15
ZEROIN	17
USER CONSIDERATIONS	20
MODEL VALIDATION	21
RECOMMENDATIONS FOR FURTHER STUDY	22
SUMMARY	23
BIBLIOGRAPHY	24
APPENDIX A: Original References	27
APPENDIX B: Model Listing	28
APPENDIX C: Suggested Calling Sequence With DB Known	34
APPENDIX D: Suggested Calling Sequence To Find DB	37
APPENDIX E: Validation Program	38
APPENDIX F: Results Of Validation Program	41

LIST OF TABLES

	Page
Mnemonic Codes Used in the FORTRAN Psychrometric Model	10
Psychrometric Properties by Independent Groups	10
Relationships Given by the Equations	11
Pairs of Properties Which Require Two-Dimensional Search	11
Pairs of Beginning Properties for the Psychrometric Model . . .	12
Function Subprograms in the Model	13

LIST OF SYMBOLS

T	Dry-bulb temperature, R
T_{wb}	Wet-bulb temperature, R
T_{dp}	Dew-point temperature, R
P_v	Vapor pressure, psi
P_s	Saturation vapor pressure at T , psi
P_{swb}	Saturation vapor pressure at T_{wb} , psi
H	Humidity ratio, lb water per lb dry air
H'	Humidity ratio at saturation at T_{wb} , lb water per lb dry air
h_{fg}	Latent heat of vaporization of water at saturation, Btu per lb
h'_{fg}	Latent heat of vaporization of water at T_{wb} , Btu per lb
h''_{fg}	Latent heat of vaporization of water at T_{dp} , Btu per lb
h_{ig}	Heat of sublimation of ice, Btu per lb
h'_{ig}	Heat of sublimation of ice at T_{wb} , Btu per lb
h''_{ig}	Heat of sublimation of ice at T_{dp} , Btu per lb
h	Enthalpy of air-vapor mixture, Btu per lb dry air
rh	Relative humidity, decimal
V_{sa}	Air specific volume, ft ³ per lb dry air

INTRODUCTION

Psychrometrics is basic to research and design of many agricultural processing, storage and environmental systems applications. A number of professional organizations have published psychrometric charts and tables to be used as standards for their industries (ASHRAE, 1963; ASAE, 1971).

Charts and tables are not well suited to the application of computer aided design and simulation. The recent increase in the use of computer techniques has created the need for a standard computer model of the psychrometric chart.

The psychrometric model presented here is based on a combination of theoretical and empirical equations. Ten thermodynamic properties are considered. In all but five cases, it is possible to find the eight remaining properties when given two independent properties which uniquely describe a state point of a dry air--water vapor mixture.

The model has been designed to be easily implemented as well as easily modified. Several novice programmers have already successfully applied portions of the model (Farmer, 1971; Schluckbier, 1972). Equations for additional properties or more accurate equations can be easily added. Portions of the model have been used in the simulation of grain dryers (Bakker-Arkema et al., 1972).

BASIC PSYCHROMETRIC EQUATIONS

Brooker (1967, 1970) has compiled and tested a number of equations for psychrometric properties. Appendix A contains the original references given by Brooker for the equations used here. All error limits presented here are taken from Brooker (1970).

The following assumptions were made by Brooker (1970):

- (1) The properties of steam are properly described by Kennan and Keyes (1936).
- (2) Air-water vapor mixtures can be treated as a mixture of ideal gases.

The saturation line can be described by

$$\ln P_s = 23.3924 - \frac{11286.6489}{T} - 0.46057 \ln T \quad (1)$$

$$459.69 \leq T \leq 491.69$$

and by

$$\ln(P_s/R) = \frac{A + BT + CT^2 + DT^3 + ET^4}{FT - GT^2} \quad (2)$$

$$491.69 \leq T \leq 959.69$$

where

R = 0.3206182232000000 D 04	D = 0.2153211916363544 D -04
A = -0.2740552583614256 D 05	E = -0.4620266568199822 D -08
B = 0.5418960763289505 D 02	F = 0.2416127209874000 D 01
C = -0.4513703841126545 D -01	G = 0.1215465167060546 D -02

The form of equation (1) results from the integration of the Clausius-Clapeyron equation. Coefficients were obtained by fitting the equation to the data of Keenan and Keyes for a temperature range of 0 to 32 F. The deviation from Keenan and Keyes for a temperature range of -20 to 32 F is as follows:

$$0.00002 \leq P_{\text{error}} \leq 0.00069$$

$$0.2993 \leq \% \text{ error} \leq 0.8501$$

Equation (2) is empirical. The deviation from Keenan and Keyes data is shown below for a few data points where the error was large when compared to the error at other temperatures.

At 32 F	Absolute error = 0.0002 psia	Percent error = 0.228
At 40 F	Absolute error = 0.0001 psia	Percent error = 0.081
At 470 F	Absolute error = 0.5027 psia	Percent error = 0.097

Latent heats are found by the following empirical equations:

$$h_{ig} = 1220.844 - 0.05077 (T - 459.69) \quad (3)$$

$$459.69 \leq T \leq 491.69$$

$$h_{fg} = 1075.8965 - 0.56983 (T - 459.69) \quad (4)$$

$$491.69 \leq T \leq 609.69$$

$$h_{fg} = (1354673.214 - 0.9125275587 T^2)^{1/2} \quad (5)$$

$$609.69 \leq T \leq 959.69$$

Equation (3) can be used for temperatures as low as -20 F with an absolute error in h_{ig} of 0.66 Btu per lb. For a temperature range of 0 to 32 F, the error range is as follows:

$$0.0209 \leq h_{\text{error}} \leq 0.1932$$

$$0.0017 \leq \% \text{ error} \leq 0.0158$$

Error limits for equations (4) and (5) from 32 to 480 F are as follows:

$$0.00 \leq h_{\text{error}} \leq 1.47$$

$$0.00 \leq \% \text{ error} \leq 0.20$$

From 480 to 500 F, the absolute error increases to 3.2 Btu/lb. At 500 F, the percent error is 0.45.

The wet-bulb line is described by

$$P_{swb} - P_v = B (T_{wb} - T) \quad (6)$$

where

$$B = \frac{0.2405 (P_{swb} - P_{atm}) (1 + 0.15577 P_v / P_{atm})}{0.62194 h'_{fg}}$$

$$459.69 \leq T \leq 959.69$$

Equation (6) was derived on the assumption that $(H' - H)$ lb of water vapor is combined with one lb of dry air and H lb of water vapor is combined with one lb of dry air and H lb of water vapor by an adiabatic process at wet bulb temperature. The derivation is shown by Brooker (1967).

For temperatures below 32 F values of h'_{ig} are used in equation (6) rather than h'_{fg} .

There is no way to express the accuracy of equation (6) except to use the equation and then check the answer against some known standard. Examples are given by Brooker (1967).

The equation for absolute humidity is

$$H = \frac{0.6219 P_v}{P_{atm} - P_v} \quad (7)$$

$$459.69 \leq T \leq 959.69$$

This equation is based directly on the definition of H and assumes that dry air and water vapor are ideal gases.

Specific volume is found by the equation

$$v_{sa} = \frac{53.35 T}{144 (P_{atm} - P_v)} \quad (8)$$

$$459.69 \leq T \leq 959.69$$

Equation (8) is the ideal gas law and needs no explanation.

Enthalpy is best described as

Enthalpy = Enthalpy of air + Enthalpy of water (or ice) at dew point temperature + Enthalpy of evaporation (or sublimation) at dew-point temperature + Enthalpy added to the water vapor (superheat) after evaporization.

The results in the equations

$$h = 0.2405 (T_{db} - 459.69) - H [143.35 + 0.485(491.69 - T_{dp})] + h'_{ig} H + 0.448 H (T_{db} - T_{dp})$$

$$459.69 \leq T_{dp} \leq 491.69 \quad (9)$$

and

$$h = 0.2405 (T_{db} - 459.69) + H (T_{dp} - 491.69) + h'_{fg} H + 0.448 H (T_{db} - T_{dp})$$

$$491.69 \leq T_{dp} \leq 671.69$$

The value of specific heat for water vapor is considered to be 0.448 Btu per lb per F in equations (9) and (10). This value is appropriate for dew-point temperatures of 70 F or less. If for some reason the dew-point temperature is higher, the specific heat of the vapor should be considered a function of temperature and increased.

Relative humidity is defined as

$$rh = \frac{P_v}{P_s} \quad (11)$$

Equations (1) through (11) constitute the complete set on which the psychrometric model is based.

FORMULATION OF THE MODEL

In order to simplify the notation, the mnemonic codes listed in Table 1 were developed.

A number of the ten properties shown in Table 1 are not independent. To uniquely describe a point on the psychrometric chart, two independent properties must be given. Table 2 lists dependent properties together by groups; two properties not in the same group in Table 2 do describe a point uniquely.

A complete model of the psychrometric chart should be capable of finding the remaining eight properties regardless of which pair of independent properties are given. If relationships are known such that given any property within a group all other properties within that group can be found, all that remains to completely model the chart is to specify the relationships among groups.

Equations (1) through (5) represent relationships between DB and the other properties of group I. Equation (6) is a relationship among groups I, II, and III (DB, PV, and WB respectively). A relationship between members of group II is given by equation (7). Equation (8) deals with groups I, II, and V, equations (9) and (10) with I, II, and III, and equation (11) with groups I, II, and IV. This is summarized in Table 3.

The form of the equations makes explicit solution for some of the properties impossible or quite difficult. Equation (2), for example, is difficult to solve for DB, the dry bulb temperature, and equation (6) can not be solved explicitly for WB. The use of a search technique helps to overcome these difficulties.

Careful examination of equations (1) through (11) reveals that relationships between groups III and IV, groups III and V, or groups IV and V with any other group are non-existent. This means that, given properties from any two of these groups, the relationships to explicitly solve for the remaining properties are missing.

The equations which express relationships among groups are all keyed to groups I and II (see Table 3). With the aid of a two-dimensional search, it is possible to find group I and group II properties when only group III, IV, or V properties are given. Table 4 lists the possible pairs of properties which would require a two-dimensional search.

TABLE 1. Mnemonic Codes Used in the FORTRAN Psychrometric Model

<u>Code</u>	<u>Property</u>	<u>Units</u>
DB	dry bulb temperature	R
DP	dew point temperature	R
EN	enthalpy	Btu/lb dry air
HA	absolute humidity	lb water/lb dry air
HL	latent heat of vaporization (sublimation)	Btu/lb water
PS	saturation vapor pressure	psia
PV	vapor pressure	psia
RH	relative humidity	decimal
S	search or special	
VS	specific volume of dry air	ft ³ /lb
WB	wet bulb temperature	R

TABLE 2. Psychrometric Properties by Independent Groups

<u>Group</u>	<u>Properties</u>
I	DB, HL, PS
II	DP, HA, PV
III	EN, WB
IV	RH
V	VS

TABLE 3. Relationships Given by the Equations

<u>Equation Number</u>	<u>Relationship</u>
1	I
2	I
3	I
4	I
5	I
6	I, II, III
7	II
8	I, II, V
9	I, II, III
10	I, II, III
11	I, II, IV

TABLE 4. Pairs of Properties which Require a Two-Dimensional Search

EN and RH

WB and RH

EN and VS

WB and VS

RH and VS

TABLE 5. Pairs of Beginning Properties for the Psychrometric Model

P = Possible to find remaining properties starting with these two.

N = Two dimensional search necessary to find remaining properties starting with these two.

I = Infeasible; this pair does not uniquely describe a point on the psychrometric chart

	DB	DP	EN	HA	HL	PS	PV	RH	VS	WB
DB		P	P	P	I	I	P	P	P	P
DP			P	I	P	P	I	P	P	P
EN				P	P	P	P	N	N	I
HA					P	P	I	P	P	P
HL						I	P	P	P	P
PS							P	P	P	P
PV								P	P	P
RH									N	N
VS										N
WB										

TABLE 6. Function Subprograms in the Model

<u>Name</u>	<u>Statement</u>	<u>Equation Number</u>
DBPSS#	$0 = PS - PSDB (DB)$	1
DPDBENS#	$0 = .2405*(DB-459.69) - EN + HA*HLDB(DP) +$ $.448*HA*(DB-DP) - HA*(143.35 + .485*(491.69 - DP))$ <p>for $DP < 491.69$</p>	9
	$0 = .2405*(DB-459.69) - EN + HA*HLDB(DP) +$ $.448*HA*(DB-DP) + HA*(DP - 491.69)$ <p>for $DP \geq 491.69$</p>	10
DPHAS#	$0 = PVHA(HA) - PSDB(DP)$	
ENDBDP	$= [.2405*(DB-459.69) + HLDB(DP)*HA + .448*HA*(DB-DP)] - [HA*(143.35 + .485*(491.69 - DP))]$ <p>for $DP < 491.69$</p>	9
	$= [.2405*(DB-459.69) + HLDB(DP)*HA + .448*HA*(DB-DP)] + HA*(DP - 491.69)$ <p>for $DP \geq 491.69$</p>	10
HADBRH	$= HAPV(RH*PSDB(DB))$	11
HADP	$= HAPV(PSDB(DP))$	11
HAPV	$= .6219*PV / (PATM - PV)$	7
HLDB	$= 1220.844 - .05077*(DB-459.69)$ <p>for $DB < 491.69$</p>	3
	$= 1075.8965 - .56983*(DB-459.69)$ <p>for $491.69 \leq DB < 609.69$</p>	4

	$= \text{SQRT}(1354673.214 - 0.912575587 * \text{DB}^2)$ for $\text{DB} \geq 609.69$	5
PSDB	$= \text{EXP}[23.3924 - 11286.6489 / \text{DB} - .46057 * \text{ALOG}(\text{DB})]$ for $\text{DB} < 491.69$	1
	$= R * \text{EXP}[(A + B * \text{DB} + C * \text{DB}^2 + D * \text{DB}^3 + E * \text{DB}^4) / (F * \text{DB} - G * \text{DB}^2)]$ where R, A, B, C, D, E, F, G are constants (Brooker, 1970)	2
PVDBVS	$= \text{PATM} - 53.35 * \text{DB} / \text{VS} / 144$	8
PVDBWB	$= \{ \text{PSDB}(\text{WB}) * [.62194 * \text{HLDB}(\text{WB}) * \text{PATM}] - [.2405 * (\text{PSDB}(\text{WB}) - \text{PATM}) * (\text{WB} - \text{DB})] * \text{PATM} \} / \{ [.62194 * \text{HLDB}(\text{WB}) * \text{PATM}] + [.15577 * [.2405 * (\text{PSDB}(\text{WB}) - \text{PATM}) * (\text{WB} - \text{DB})] \}$	6
PVHA	$= \text{HP} * \text{PATM} / (.6219 + \text{HA})$	7
DBHA	$= \text{PVHA}(\text{HA}) / \text{PSDB}(\text{DB})$	11
RHPSPV	$= \text{PV} / \text{PS}$	11
VSDBHA	$= 53.35 * \text{DB} * (.6219 + \text{HA}) / 144. / .6219 / \text{PATM}$	8
WDBBHAS#	$0 = \text{TWB} - \text{DB} - (\text{PSDB}(\text{WB}) - \text{PVHA}(\text{HA})) / [.2405 * (\text{PSDB}(\text{TWB}) - \text{PATM}) * (1. + .15577 * \text{PVHA}(\text{HA}) / \text{PATM})] * (.62194 * \text{HLDB}(\text{WB}))$	6

These equations are solved via SUBROUTINE ZEROIN.

Since the occurrence of a situation which would provide only one of the pairs of properties listed in Table 4 is considered to be very unlikely, a two-dimensional search is not included with this model. A number of such routines are available (Rosenbrock, 1966; Powell, 1964) and can be implemented easily if the need arises.

Table 5 depicts forty-five combinations of the ten properties taken two at a time, and shows which are infeasible due to dependence, which would require the use of a two dimensional search, and which are possible with this model. Note that of the thirty-eight physically possible starting pairs, thirty-three can be used without the aid of a two-dimensional search.

The model contains nineteen function subprograms and one subroutine (a zero finding technique discussed later) and required less than 1300 octal memory positions. Several of the function subprograms are used internally only and need not concern the user. Those with which the user is concerned have been named using the codes of Table 1 and a mnemonic scheme. The first two letters are the code of the property that is sought; the second two and third two (if present) are the codes of the properties of which the first is a function. If the first is a function of two values, they are listed in alphabetical order.

Examples:

RHDBHA - relative humidity as a function of dry bulb temp and absolute humidity (humidity ratio).

PVHA - vapor pressure as a function of humidity ratio.

If the property which is being sought is a temperature (dry-bulb, wet-bulb, or dew-point), the equations require the search routine for a solution; and the user will have to supply additional parameters

(discussed later). An "S" is added to the names of these routines to help remind the user to supply the additional values.

Table 6 lists the sixteen function names which are accessible to the user and the principle statement along with the number of the equation from which it was developed. Most of the developments are straightforward. The zero finding search technique (subroutine ZEROIN) is used to solve equations of difficult form or, as in the case in DPHAS, to solve for a property common to two equations.

The computer programs are listed in Appendix B.

USE OF THE MODEL

The sixteen functions in Table 6 plus the search technique enable the user to find the eight remaining properties given DB and any other independent property. In addition, it is possible to find DB given one property from group II and one property from groups III, IV or V. Appendices C and D contain lists of suggested function calls and the order of calls and the order of calls to accomplish this.

Use of the non-search functions (those without an S attached) is simple and best illustrated by examples:

- i) If TABS = absolute dry bulb temperature and R = relative humidity (decimal)* and it is desired to find the humidity ratio H, the following FORTRAN statement would be used

H = HADBRH(TABS,R))

- ii) If the vapor pressure VAP is desired, the following might be used

VAP = PVHA(HADBRH(TABS,R))

This is simply a nested call similar to $X = \text{EXP}(\text{SIN}(Y))$ for $x = e^{\sin(y)}$. Use of the search functions (those with an S appended) is only slightly more difficult. The general form is:

FNAME(PAR1,PAR2,GUESS1,GUESS2,EPSLON)

where

FNAME = the function name (DBPS, WBDBHAS, etc.)
PAR1,PAR2 = first and second (if applicable) parameters
 specified by the two letter codes in the
 function name.
GUESS1 = a low estimate of the answer
GUESS2 = a high estimate of the answer
EPSLON = allowable tolerance in the result

The values of GUESS1, GUESS2, and EPSLON should be chosen with care as they greatly affect the time required for the zero-finding search

* Note that all temperatures are in degrees Rankine and that the relative humidity is in decimal form.

technique to arrive at a solution. In general, it should be remembered that input psychrometric quantities are seldom accurate to more than 2 or 3 decimal places and hence an EPSLON of .01 or .001 should be sufficient. The search routine guarantees convergence (usually better than linear, Dekker, 1967), but small EPSLONS require more time. If the values of GUESS1 and GUESS2 are chosen such that both are above or both are below the correct answer, an appropriate error message is printed but computation continues.

Example:

If the following are known

TDB = dry bulb temperature, R

TDP = dew point temperature, R

and the wet bulb temperature is needed, Appendix C says that the absolute humidity must first be found from HADP and then the wet bulb can be found from WBDBHAS. Therefore the calls could take the form

HAVS=HADP(TDP)

TWB=WBDBHAS(TDB,HABS,TDP,TDB,.01)

or

TWB=WBDBHAS(TDB,HADP(TDP,HADP(TDP),TDP,TDB,.01)

if the absolute humidity is not desired separately.

Note the use of TDP and TDB as GUESS1 and GUESS2.

ZEROIN

ZEROIN is the root finding search technique included in the psychometric mode. Although used by some of the functions in the model, this subroutine remains completely independent of them and can thus be freely used for other purposes.

ZEROIN is based on an algorithm presented by Dekker (1967) which is a mixture of linear interpolation, extrapolation and bisection. Convergence to a small interval in which a zero exists is guaranteed. No derivatives are used.

ZEROIN must be given a function for which a zero exists on an interval J, end points A and B of this interval and EPS the largest acceptable final interval. ZEROIN then works with three points A, B, and C on the interval and the function values at these points FA, FB, and FC. Point B is the most recent iterate, point A the previous one and point C the "contrapoint" or the last one satisfying $\text{SIGN}(FB) \neq \text{SIGN}(FC)$. Initially, point B is taken as the end point of J which results in the smallest absolute value of the function; points A and C are taken as the opposite end point. Interpolation or extrapolation is performed between A and B yielding a provisional value I for the next iterate according to the formula:

$$I = \frac{-(B-A) FB}{FB-FA} + B$$

If this division results in a divide fault or overflow, bisection is used to determine I by the equation:

$$I = M = \frac{B+C}{2}$$

Computation continues using the newly calculated value. If no problem exists with the division, I and M are checked to determine which is closer to B. I is then assigned this value.

Having determined a suitable value for I, the difference between B and I is compared to EPS. If EPS is larger, I is re-evaluated as:

$$I = \text{SIGN} (C-B) \times \text{EPS} + B$$

If EPS is smaller, the following reassignments are made in preparation for the next step:

$$A=B \quad B=I \quad FA=FB \quad FB=\text{the function evaluated at } I.$$

One further check is necessary before beginning the following step. If $\text{SIGN } FB = \text{SIGN } FC$, C is reassigned to A and FC is reassigned the value of FA.

When $|C - B| \leq 2 \times \text{EPS}$ the termination procedure is initiated. ZEROIN takes the mid-point value between B and C, assigns it to A and evaluates the function at this point, FA. The final values returned are A and B or C (whichever one has a function evaluation different in sign from FA).

A call to ZEROIN takes the form:

CALL ZEROIN (A,B,EPS,FUNC)

where A and B = the end points of the interval containing a zero

EPS = the largest acceptable final interval
containing a zero

FUNC = the name of the user supplied function
subprogram containing the function for
which a zero is to be found.

Note that FUNC must be typed EXTERNAL in the calling routine.

ZEROIN returns in A and B the endpoints of the final interval of length less than EPS. Either A or B or their average can be used as the zero.

ZEROIN checks the function values of the initial interval end points. If the function values have the same sign, ZEROIN sets the value of ICHK in the labeled common area ICHECK to one. Calculations then continue as this indicates that multiple roots or no roots occur within the given interval.

In the case of multiple roots one of them will be found. In the case of no roots ZEROIN will converge to the point where the absolute value of the function is a minimum, whether this occurs at an end point or arbitrary value within the interval.

Subroutine ZEROIN can easily be used to form additional functions from the sixteen given. For example, suppose that dew-point temperatures DP and wet-bulb temperatures WB are known in some cases and relative humidity RH and DP are known in other cases and that in both cases the dry-bulb temperature DB is to be found. Appendix D shows that in the first case absolute humidity and then vapor pressure should be found so that PVDBWB can be used with ZEROIN to solve for DB. This might be programmed as

```
FUNCTION DB1(T)
COMMON/BLOCK/PV,WB
DB1 = PV-PVDBWB(T,WB)
RETURN
END
```

where T is a dummy variable representing the various values for DB tried by ZEROIN.

Appendix D also shows that in the second case the absolute humidity should be found and that RHDBHA should be solved for DB using ZEROIN.

This might be as follows:

```
FUNCTION DB2(T)
COMMON/BLOCK2/RH,HA
DB2 = RH-RHDBHA(T,HA)
RETURN
END
```

The calling routine might be

```

PROGRAM SAMPLE(INPUT,etc.)
COMMON/PRESS/PATM
COMMON/BLOCK1/PV,WB
COMMON/BLOCK2/RH,HA
EXTERNAL DB1
EXTERNAL DB2
.
.
.
statements to assign values
to PATM, EPS EST1, EST2 and
determine whether DP and WB
or DP and RH are given
.
.
.
when DP and WB are given
CALL ZEROIN(EST1,EST2,EPS,DB1)
DB = (EST1+EST2)/2.
.
.
.
when DP and RH are given
CALL ZEROIN(EST1,EST2,EPS,DB2)
DB=(EST1+EST2)/2.
.
.
.
END

```

Note the labeled common area PRESS. This must be specified in all programs which use the model and a value for atmospheric pressure in psia must be assigned to PATM.

USER CONSIDERATIONS

The following should help the user avoid possible errors and locate problems that do arise:

1. These routines are said to give accurate results from 440 to 960 R (-20 to 500 F). Accuracy within this region is generally better than can be read from a psychrometric chart.
2. The values returned from these functions for a temperature of 491.69 R (32 F) are those for water vapor mixtures at that temperature. Lower temperatures will cause the heat of fusion to be included where appropriate.
3. All temperatures must be in degrees Rankine.
4. All relative humidities must be decimal.
5. A MODE 0 error (on CDC 6000 series computers) indicates that the EXTERNAL card has been omitted.
6. The following names are used by this package (in addition to the functions listed in Table 6) and should not be used in the user's program

DPL1
DPL2
DBL
WBL
SPECIAL

7. The following statement must appear in the user's program

COMMON/PRESS/PATM

and a value must be assigned to PATM.

MODEL VALIDATION

No attempt was made to check the error limits reported by Brooker (1970) for individual equations. Instead, a validation program was written (Appendix E) which computes all remaining properties given DB and HA. These computed properties were then used, one at a time, with the given DB to recompute all remaining properties. The resulting output is in table form for easy comparison of all computed values.

Appendix F contains a number of results from the validation program. The values of DB and HA were chosen so that comparison with the psychrometric chart would be easy. Only a few points show variation to the accuracy printed and this is never more than one or two in the least significant digit.

Comparison of the computed values with the chart shows the model to be at least as accurate as the chart.

RECOMMENDATIONS FOR FURTHER STUDY

Although the inclusion of a two-dimensional search enables this model to completely describe the psychrometric chart, it is not recommended as a standard. Differences in computer hardware and software preclude this.

Ideally, a model of the psychrometric chart should need neither a one-dimensional nor two-dimensional search. Work should be done to derive theoretical or empirical relationships among more of the properties.

A true standard would need to specify accuracy and number of significant digits to be carried through the calculations.

In addition, the effect of changes in atmospheric pressure may not be properly reflected by this model. More experimental data at various pressures is needed.

SUMMARY

This package of subprograms was written to facilitate the use of psychrometric parameters and the processing of psychrometric data. The included Tables and examples are intended to assist the user in the application of these routines and are not to be considered the only possibilities. Much thought was, however, put into the lists of suggested calls and calling orders and it is believed that they are the most efficient.

The routines have been thoroughly tested. They gave excellent results when compared to the thermodynamic values read from the standard psychrometric charts.

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BIBLIOGRAPHY

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APPENDICES

APPENDIX A

Original References

References for equations given by Brooker (1970).

<u>Equation Number</u>	<u>Reference</u>
1	Brooker (1967)
2	Smith, et al. (1934)
3	Brooker (1967)
4	<u>Ibid.</u>
5	Brooker (1970)
6	Brunt (1941)
7	Brooker (1970)
8	<u>Ibid.</u>
9	<u>Ibid.</u>
10	<u>Ibid.</u>
11	

APPENDIX B: Model Listing

```

C*****          P S Y C H R O M E T R I C   M O D E L          *****
C*****                                L.E. LEREW, PROGRAMMER          *****
C*****
C*****
C*****
C*****
C***** DESCRIPTION          *****
C*****      GROUP OF HIGHLY INTERACTIVE FUNCTION SUBPROGRAMS BASED *****
C*****      ON EQUATIONS BY BROOKER (1967,1970) AND A ROOT FINDING SUB- *****
C*****      ROUTINE BASED ON AN ALGORITHM BY DEKKER (1967) USED TO FIND *****
C*****      AND CONVERT PSYCHROMETRIC PROPERTIES *****
C*****
C***** FUNCTION SUBPROGRAMS CONTAINED *****
C*****      DBPSS *****
C*****      DBL (USED INTERNALLY ONLY) *****
C*****      DPOBENS *****
C*****      DPHAS *****
C*****      DPL1 (USED INTERNALLY ONLY) *****
C*****      DPL2 (USED INTERNALLY ONLY) *****
C*****      ENDBJP *****
C*****      HADBRH *****
C*****      HADP *****
C*****      HAPV *****
C*****      HLOB *****
C*****      PSDB *****
C*****      PVHA *****
C*****      PVD8VS *****
C*****      PV03WB *****
C*****      RHPS2V (ENTRY--RHOBHA) *****
C*****      VSDB4A *****
C*****      W8DB4AS *****
C*****      W3L (USED INTERNALLY ONLY) *****
C*****
C***** SUBROUTINES CONTAINED *****
C*****      ZEROIN *****
C*****
      FUNCTION DBPSS(PS,G1,G2,EPS)
      COMMON /SPECIAL/PV,TB,XTRA
      COMMON/ICHECK/ICLK
      EXTERNAL DBL
      A=G1 $ B=G2 $ XTRA=PS
      CALL ZEROIN (A,B,EPS,DBL)
      DBPSS=(A+B)/2.
      IF(ICLK.EQ.1) PRINT 210,G1,G2,DBPSS
210 FORMAT(1H0,130(1HS)/10X54HW A R N I N G--NO OR MULTIPLE ROOTS DETE
      1CTED BY ZEROIN/30X33HCALLED FROM DBPSS . GUESSES ARE,G21.14,4H A
      2N0,G22.14/30X17HRETURNED VALUE IS,G21.14)
      RETURN
      END

      FUNCTION DBL(T)
      COMMON /SPECIAL/PV,TB,PS
      DBL=PS-PSDB(T)
      RETURN
      END

```



```

FUNCTION DPD3ENS(DB,EN,G1,G2,EPS)
COMMON /SPECIAL/PV,TB,XTRA
COMMON/ICHECK/ICHK
EXTERNAL DPL2
A=G1 $ B=G2
XTRA=.2405*(DB-459.69)-EN
TB=DB
CALL ZEROIN (A,B,EPS,DPL2)
DPOBENS=(A+B)/2.
IF(ICHK.EQ.1) PRINT 210,G1,G2,DPOBENS
210 FORMAT(1H0,13J(1HS)/10X54HW A R N I N G--NO OR MULTIPLE ROOTS DETE
1CTED BY ZEROIN/30X33H CALLED FROM DPOBENS. GUESSES ARE,G21.14,4H A
2ND,G22.14/30X17H RETURNED VALUE IS,G21.14)
RETURN
END

```

```

FUNCTION OPHAS(HA,G1,G2,EPS)
COMMON /SPECIAL/PV,DB,XTRA
COMMON/ICHECK/ICHK
EXTERNAL DPL1
PV=PVHA(HA)
A=G1 $ B=G2
CALL ZEROIN (A,B,EPS,DPL1)
OPHAS=(A+B)/2.
IF(ICHK.EQ.1) PRINT 210,G1,G2,OPHAS
210 FORMAT(1H0,13J(1HS)/10X54HW A R N I N G--NO OR MULTIPLE ROOTS DETE
1CTED BY ZEROIN/30X33H CALLED FROM OPHAS . GUESSES ARE,G21.14,4H A
2ND,G22.14/30X17H RETURNED VALUE IS,G21.14)
RETURN
END

```

```

FUNCTION DPL1(TDP)
COMMON /SPECIAL/PV,DB,XTRA
DPL1=PV-PSDB(TDP)
RETURN
END

```

```

FUNCTION DPL2 (TDP)
COMMON /SPECIAL/PV,DB,XTRA
HA=HAOP(TDP)
T2=HA*HLOB(TDP)+.448*HA*(DB-TDP)
IF(TDP-491.69) 1,2,2
1 DPL2=XTRA+T2 -HA*(143.35+.485*(491.69-TDP))
RETURN
2 DPL2=XTRA+T2+HA*(TDP-491.69)
RETURN
END

```

```

FUNCTION ENDBDP (DB,DP)
COMMON/PRESS/ PATH
HA=HADP(DP)
T1=.2405*(DB-459.69)+HLDB(DP)*HA+.448*HA*(DB-DP)
IF(DP-491.69) 1,2,2
1 ENDBDP=T1-HA*(143.35+.485*(491.69-DP))
RETURN
2 ENDBDP=T1+HA*(DP-491.69)
RETURN
END

```

```

FUNCTION HADBRH(DB,RH)
HADBRH=HAPV(RH*PSDB(DB))
RETURN
END

```

```

FUNCTION HADP(DP)
HADP=HAPV(PSDB(DP))
RETURN
END

```

```

FUNCTION HAPV(PV)
COMMON/PRESS/PATH
HAPV=.6219*PV/(PATM-PV)
RETURN
END

```

```

FUNCTION HLDB (DB)
IF(DB-491.69) 1,2,2
1 HLDB=1220.844-.05077*(DB-459.69)
RETURN
2 IF(DB-609.69) 3,4,4
3 HLDB=1075.8965-.56983*(DB-459.69)
RETURN
4 HLDB=SQRT(1354673.214-.9125275587*DB*DB)
RETURN
END

```



```

FUNCTION PSD8 (DB)
  DATA R,A,B,C,D,E,F,G/.3206182232E04,-.274055258361426E05,.54189607
  A6328951E02,-.451370384112655E-1,.215321191636354E-4,-.462026656819
  B982E-8,.2416127209874E01,.121546516706055E-2/
  IF(DB-491.69) 1,2,2
1  PSD8=EXP(23.3924-11286.6489/DB-.46057*ALOG(DB))
  RETURN
2  PSD8=R*EXP((A+DB*(B+DB*(C+DB*(D+DB*E)))))/(DB*(F-G*DB)))
  RETURN
END

```

```

FUNCTION PVHA (HA)
  COMMON/PRESS/PATM
  PVHA=HA*PATM/(.6219+HA)
  RETURN
END

```

```

FUNCTION PVD8VS(DB,VS)
  COMMON/PRESS/PATM
  PVD8VS=PATM-53.35*DB/VS/144.
  RETURN
END

```

```

FUNCTION PVD8WB(DB,WB)
  COMMON/PRESS/PATM
  A=PSD8(WB) $ B=.62194*HLOB(WB)*PATM $ C=.2405*(A-PATM)*(WB-DB)
  PVD8WB=(A*B-C*PATM)/(B+.15577*C)
  RETURN
END

```

```

FUNCTION RHPSPV(D1,D2)
  A=D1 $ B=D2 $ GO TO 1
  ENTRY RHDBHA
  A=PSD8(D1) $ B=PVHA(D2)
1  RHPSPV=B/A
  RETURN
END

```



```

FUNCTION VSD3HA (DB,HA)
COMMON /PRESS/PATH
VSOBHA=53.35*DB*(.6219+HA)/144./+.6219/PATH
RETURN
END

```

```

FUNCTION WBD3HAS(DB,HA,G1,G2,EPS)
COMMON /SPECIAL/PV,TB,XTRA
COMMON/ICHECK/ICLK
EXTERNAL WBL
A=G1 $ B=G2
TB=DB
PV=PVHA(HA)
CALL ZEROIN (A,B,EPS,WBL)
WBD3HAS=(A+B)/2.
IF(ICLK.EQ.1) PRINT 210,G1,G2,WBD3HAS
210 FORMAT(1H0,13J(1HS)/10X54HW A R N I N G--NO OR MULTIPLE ROOTS DETE
1CTED BY ZEROIN/30X33HCALLED FROM WBD3HAS. GUESSES ARE,G21.14,4H A
2ND,G22.14/30X17HRETURNED VALUE IS,G21.14)
RETURN
END

```

```

FUNCTION WBL(TWB)
COMMON /PRESS/PATH
COMMON /SPECIAL/PV,DB,XTRA
PW3=PSDB(TWB)
WBL=TWB-DB-(PW3-PV)/(.2405*(PW3-PATH)*(1.+.15577*PV/PATH))*(.62194
1*HLDB(TWB))
RETURN
END

```



```

SUBROUTINE ZEROIN(A,B,EPS,FUNC)
C*****
C*****          C A U T I O N
C*****  THE FOLLOWING ARE INTRINSIC LIBRARY FUNCTIONS ON THE CDC 6500
C*****  AND MAY HAVE TO BE CHANGED FOR OTHER MACHINES
C*****
C*****  LEGVAR - CHECKS CHARACTERISTIC OF ARGUMENT AND RETURNS 0 FOR
C*****             NORMAL.  USED HERE AS A DIVIDE FAULT CHECK
C*****  SIGN   - TRANSFERS SIGN OF SECOND ARGUMENT TO FIRST ARGUMENT
C*****
COMMON/ICHECK/ICLK
REAL I,M
ICLK=0
FA=FUNC(A) $ FB=FUNC(B) $ FC=FA $ C=A
IF(SIGN(1.,FB).NE.SIGN(1.,FC)) GO TO 1
ICLK=1
1 IF(ABS(FC)-ABS(FB)) 2,3,3
2 C=B $ B=A $ A=C $ FC=FB $ FB=FA $ FA=FC
3 IF(ABS(C-B)-2.*EPS) 12,12,4
4 I=(B-A)*FB/(FB-FA) $ J=LEGVAR(I) $ M=(C+B)/2. $ IF(J=0) 7,5,7
5 I=-I+B $ CHINT=(B-I)*(M-I) $ IF(CHINT) 8,8,7
7 I=M
8 IF(ABS(B-I)-EPS) 9,10,10
9 I=SIGN(1.,(C-B))*EPS+B
10 A=B $ B=I $ FA=FB $ FB=FUNC(B)
   IF(SIGN(1.,FB)-SIGN(1.,FC)) 1,11,1
11 C=A $ FC=FA $ GO TO 1
12 A=(C+B)/2. $ FA=FUNC(A)
   IF(SIGN(1.,FA).EQ.SIGN(1.,FB)) B=C
RETURN
END

```


APPENDIX C

Suggested Calling Sequence with DB Known

GIVEN DB* AND

HA	To Find	RH	Use	RHDBHA
		PV		PVHA
		VS		VSDBHA
		EN		DPHAS then ENDBDP
		WB		WBDBHAS
		DP		DPHAS
RH		HA		HADBRH
		PV		HADBRH then PVHA
		VS		HADBRH then VSDBHA
		EN		HADBRH then DPHAS then ENDBDP
		WB		HADBRH then WBDBHAS
		DP		HADBRH then DPHAS
PV		HA		HAPV
		RH		PSDB then RHPSPV or HAPV then RHDBHA
		VS		HAPV then VSDBHA
		EN		HAPV then DPHAS then ENDBDP
		WB		HAPV then WBDBHAS
		DP		HAPV then DPHAS
VS		HA		PVDBVS then HAPV

VS	To Find	RH	Use	PVDBVS and PSDB then RHPSPV or PVDBVS then HAPV then RHDBHA
		PV		PVDBVS
		EN		PVDBVS then HAPV then DPHAS then ENDBDP
		WB		PVDBVS then HAPV then WDBHAS
		DP		PVDBVS then HAPV then DPHAS
EN		HA		DPDBENS then HADP
		RH		DPDBENS then HADP then RHDBHA
		PV		DPDBENS then PSDB (using DP as argument)
		VS		DPDBENS then HADP then VSDBHA
		WB		DPDBENS then HADP then WDBHAS
		DP		DPDBENS
WB		HA		PVDBWB then HAPV
		RH		PVDBWB and PSDB then RHPSPV or PVDBWB then HAPV then RHDBHA
		PV		PVDBWB
		VS		PVDBWB then HAPV then VSDBHA
		EN		PVDBWB then HAPV then DPHAS then ENDBDP or PVDBWB then DBPSS (using PV as argument, resulting in DP) then ENDBDP
DP		HA		HADP
		RH		HADP then RHDBHA
		PV		PSDB (using DP as argument)

DP	To Find	VS	Use	HADP then VSDBHA
		EN		ENDBDP
		WB		HADP then WDBHAS

*Note: PS and HL can be found any time that DB is known by using PSDB and HLDB.

APPENDIX D

Suggested Calling Sequence to Find DB

TO FIND DB

Given	HA	And	RH	Use	HADBRH and ZEROIN
			VS		PVHA then PVDBVS and ZEROIN
			EN		DPHAS then ENDBDP and ZEROIN
			WB		PVHA then PVDEWB and ZEROIN
	RH		PV		HAPV then HADBRH and ZEROIN
			DP		HADP then RHDBHA and ZEROIN
	PV		VS		PVDBVS and ZEROIN
			EN		HAPV then DPHAS then ENDBDP and ZEROIN
			WB		PVDEWB and ZEROIN
	VS		DP		HADP then PVHA then PVDBVS and ZEROIN
	EB		DP		ENDBDP and ZEROIN
	WB		DP		HADP then PVHA then PVDEWB and ZEROIN
	PS				DBPSS
	HL				HLDB and ZEROIN

APPENDIX E

Validation Program

The following program was written for the sole purpose of testing the psychrometric package. The general scheme of the program is as follows:

1. Read in a dry-bulb temperature, humidity ratio and low estimate (for those routines using the search).
2. Solve for those properties which are temperature dependent only, i.e. PS and HL, and print them.
3. Using the routines and calling order suggested in Appendix C, find all other properties from DB and HA. Save these values for later use and print them.
4. Using Appendix C and the RH found in number 3, resolve for all other properties and print them.
5. Same as number 4 using PV found in number 3.
6. Same as number 4 using WB found in number 3.
7. Same as number 4 using DP found in number 3.
8. Same as number 4 using VS found in number 3.
9. Same as number 4 using EN found in number 3.
10. Go back to 1 and read more data and repeat.

This program uses all routines at least once and prints the results in tabular form for comparison (Appendix F). If the routines are working properly, all values should be approximately the same for a given data sheet.

```

PROGRAM PSYC4VL (INPUT,OUTPUT,TAPE60=INPUT)
COMMON /PRESS/PATH
DATA PATH/14.696/
C ****      INPUT TEMP AND HUMIDITY
1 READ(60,200) T,H,GSLOW
IF (EOF(60)) 99,2
2 DB=T+459.69
PS=PSDB(DB)
HL=HLDB(DB)
GSLOW=GSLOW+459.69
PRINT 210,T,PS,HL
C ****      FIND REMAINING VALUES FROM T AND H, PRINT, AND SAVE
RHSV=RHDBHA(DB,H)
PVSF=PVHA(H)
WBSV=WBDHBAS(DB,H,GSLOW,DB,.0001)
DPSV=DPHAS(H,GSLOW,WBSV,.0001)
VSSV=VSDBHA(DB,H)
ENSV=ENDBDF(DB,DPSV)
WBPR=WBSV-459.69
DPPR=DPSV-459.69
PRINT 211,H,H,RHSV,PVSF,WBPR,DPPR,VSSV,ENSV
C ****      FIND VALUES USING T AND RH- SAVED AND PRINT
H=HADBRH(DB,RHSV)
PV=PVHA(H)
WB=WBDHBAS(DB,H,GSLOW,DB,.0001)
DP=DPHAS(H,GSLOW,WB,.0001)
VS=VSDBHA(DB,H)
EN=ENDBDF(DB,DP)
WBPR=WB-459.69
DPPR=DP-459.69
PRINT 212,RHSV,H,RHSV,PV,WBPR,DPPR,VS,EN
C ****      FIND VALUES USING T AND PV- SAVED AND PRINT
H=HAPV(PVSF)
RH=RHDBHA(DB,H)
WB=WBDHBAS(DB,H,GSLOW,DB,.0001)
DP=DPHAS(H,GSLOW,WB,.0001)
VS=VSDBHA(DB,H)
EN=ENDBDF(DB,DP)
WBPR=WB-459.69
DPPR=DP-459.69
PRINT 213,PVSF,H,RH,PVSF,WBPR,DPPR,VS,EN
C ****      FIND VALUES USING T AND WB- SAVED AND PRINT
PV=PVDBWB(DB,WBSV)
H=HAPV(PV)
RH=RHPSPV(PS,PV)
DP=DPASS(PV,GSLOW,WBSV,.0001)
VS=VSDBHA(DB,H)
EN=ENDBDF(DB,DP)
WBPR=WBSV-459.69
DPPR=DP-459.69
PRINT 214,WBPR,H,RH,PV,WBPR,DPPR,VS,EN
C ****      FIND VALUES USING T AND DP- SAVED AND PRINT
H=HADP(DPSV)
RH=RHDBHA(DB,H)
PV=PVHA(H)
WB=WBDHBAS(DB,H,DPSV,DB,.0001)
VS=VSDBHA(DB,H)
EN=ENDBDF(DB,DPSV)
WBPR=WB-459.69
DPPR=DPSV-459.69

```



```

      PRINT 215,OPPR,H,RH,PV,WBPR,OPPR,VS,EN
C ****      FIND VALUES USING T AND VS-SEALED AND PRINT
      PV=PVOBVS(OB,VSSV)
      H=HAPV(PV)
      RH=RHOBHA(OB,H)
      WB=WBOBHAS(OB,H,GSLOW,OB,.0001)
      DP=OPHAS(H,GSLOW,WB,.0001)
      EN=ENUBOP(OB,DP)
      WBPR=WB-459.69
      OPPR=DP-459.69
      PRINT 216,VSSV,H,RH,PV,WBPR,OPPR,VSSV,EN
C ****      FIND VALUES USING T AND EN-SEALED AND PRINT
      DP=DFOBENS(OB,ENSV,GSLOW,OB,.0001)
      H=HAOP(OP)
      RH=RHOBHA(OB,H)
      PV=PVHA(H)
      WB=WBOBHAS(OB,H,GSLOW,OB,.0001)
      VS=VSOBHA(OB,H)
      WBPR=WB-459.69
      OPPR=DP-459.69
      PRINT 217,ENSV,H,RH,PV,WBPR,OPPR,VS,ENSV
      GO TO 1
99 CONTINUE
200 FORMAT(3F10.0)
210 FORMAT(1H1,10X,22HORY BULB TEMPERATURE =F7.2,6H DEG F/10X17HSAT VA
1POR PRESS =F9.4,4H PSI/10X37HLAT HEAT VAPORIZATION (SUBLIMATION) =
2F8.2,7H BTU/LB/////36X8HCOMPUTED//18X2HHA7X2HRH7X2HPV7X2HWB7X2HOP7
3X2HVS7X2HEN/5X5HGIVEN)
211 FORMAT(1H02X4HHA =F7.5,I9,F9.5,F9.4,F9.2,F9.2,F9.3,F9.2)
212 FORMAT(1H02X4HRH =F7.5,F9.5,I9,F9.4,F9.2,F9.2,F9.3,F9.2)
213 FORMAT(1H02X4HPV =F7.4,F9.5,F9.5,I9,F9.2,F9.2,F9.3,F9.2)
214 FORMAT(1H02X4HWB =F7.2,F9.5,F9.5,F9.4,I9,F9.2,F9.3,F9.2)
215 FORMAT(1H02X4HOP =F7.2,F9.5,F9.5,F9.4,F9.2,I9,F9.3,F9.2)
216 FORMAT(1H02X4HVS =F7.3,F9.5,F9.5,F9.4,F9.2,F9.2,I9,F9.2)
217 FORMAT(1H02X4HEN =F7.2,F9.5,F9.5,F9.4,F9.2,F9.2,F9.3,I9)
      END

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APPENDIX F: Results Of Validation Program

DRY BULB TEMPERATURE = 200.00 DEG F
 SAT VAPOR PRESS = 11.5253 PSI
 LAT HEAT VAPORIZATION (SUBLIMATION) = 978.54 BTU/LB

GIVEN	COMPUTED						
	HA	RH	PV	WB	DP	VS	EN
HA = .02000	X	.03973	.4579	100.94	76.91	17.166	70.74
RH = .03973	.02000	X	.4579	100.94	76.91	17.166	70.74
PV = .4579	.02000	.03973	X	100.94	76.91	17.166	70.74
WB = 100.94	.02000	.03973	.4579	X	76.91	17.166	70.74
DP = 76.91	.02000	.03973	.4579	100.94	X	17.166	70.74
VS = 17.166	.02000	.03973	.4579	100.94	76.91	X	70.74
EN = 70.74	.02000	.03973	.4579	100.94	76.91	17.166	X

DRY BULB TEMPERATURE = 100.00 DEG F
 SAT VAPOR PRESS = .9492 PSI
 LAT HEAT VAPORIZATION (SUBLIMATION) = 1018.91 BTU/LB

GIVEN	COMPUTED						
	HA	RH	PV	WB	DP	VS	EN
HA = .01500	X	.36465	.3461	77.48	68.60	14.450	40.36
RH = .36465	.01500	X	.3461	77.48	68.60	14.450	40.36
PV = .3461	.01500	.36465	X	77.48	68.60	14.450	40.36
WB = 77.48	.01500	.36465	.3461	X	68.60	14.450	40.36
DP = 68.60	.01500	.36465	.3461	77.48	X	14.450	40.36
VS = 14.450	.01500	.36465	.3461	77.48	68.60	X	40.36
EN = 40.36	.01500	.36465	.3461	77.48	68.60	14.450	X

DRY BULB TEMPERATURE = 70.00 DEG F
 SAT VAPOR PRESS = .3631 PSI
 LAT HEAT VAPORIZATION (SUBLIMATION) = 1036.01 BTU/LB

GIVEN	COMPUTED						
	HA	RH	PV	WB	DP	VS	EN
HA = .00800	X	.51408	.1866	58.89	51.26	13.525	25.43
RH = .51408	.00800	X	.1866	58.89	51.26	13.525	25.43
PV = .1866	.00800	.51408	X	58.89	51.26	13.525	25.43
WB = 58.89	.00800	.51408	.1866	X	51.26	13.525	25.43
DP = 51.26	.00800	.51408	.1866	58.89	X	13.525	25.43
VS = 13.525	.00800	.51408	.1866	58.89	51.26	X	25.43
EN = 25.43	.00800	.51408	.1866	58.89	51.26	13.525	X

DRY BULB TEMPERATURE = 70.00 DEG F
 SAT VAPOR PRESS = .3531 PSI
 LAT HEAT VAPORIZATION (SUBLIMATION) = 1036.01 BTU/LB

GIVEN	COMPUTED						
	HA	RH	PV	WB	DP	VS	EN
HA = .00300	X	.19432	.0706	49.97	26.93	13.418	20.11
RH = .19432	.00300	X	.0706	49.97	26.93	13.418	20.11
PV = .0706	.00300	.19432	X	49.97	26.93	13.418	20.11
WB = 49.97	.00300	.19432	.0706	X	26.93	13.418	20.11
DP = 26.93	.00300	.19432	.0706	49.97	X	13.418	20.11
VS = 13.418	.00300	.19432	.0706	49.97	26.93	X	20.11
EN = 20.11	.00300	.19432	.0706	49.97	26.93	13.418	X

DRY BULB TEMPERATURE = 32.00 DEG F
 SAT VAPOR PRESS = .0087 PSI
 LAT HEAT VAPORIZATION (SUBLIMATION) = 1057.66 BTU/LB

GIVEN	COMPUTED						
	HA	RH	PV	WB	DP	VS	EN
HA = .00300	X	.79503	.0706	29.82	26.93	12.455	10.92
RH = .79503	.00300	X	.0706	29.82	26.93	12.455	10.92
PV = .0706	.00300	.79503	X	29.82	26.93	12.455	10.92
WB = 29.82	.00300	.79503	.0706	X	26.93	12.455	10.92
DP = 26.93	.00300	.79503	.0706	29.82	X	12.455	10.92
VS = 12.455	.00300	.79503	.0706	29.82	26.93	X	10.92
EN = 10.92	.00300	.79503	.0706	29.82	26.93	12.455	X

DRY BULB TEMPERATURE = 0.00 DEG F
 SAT VAPOR PRESS = .0186 PSI
 LAT HEAT VAPORIZATION (SUBLIMATION) = 1220.84 BTU/LB

GIVEN	COMPUTED						
	HA	RH	PV	WB	DP	VS	EN
HA = .00050	X	.63428	.0118	-1.22	-8.52	11.598	.53
RH = .63428	.00050	X	.0118	-1.22	-8.52	11.598	.53
PV = .0118	.00050	.63428	X	-1.22	-8.52	11.598	.53
WB = -1.22	.00050	.63428	.0118	X	-8.52	11.598	.53
DP = -8.52	.00050	.63428	.0118	-1.22	X	11.598	.53
VS = 11.598	.00050	.63428	.0118	-1.22	-8.52	X	.53
EN = .53	.00050	.63428	.0118	-1.22	-8.52	11.598	X

DRY BULB TEMPERATURE = -20.00 DEG F
 SAT VAPOR PRESS = .062 PSI
 LAT HEAT VAPORIZATION (SUBLIMATION) = 1221.86 BTU/LB

GIVEN	COMPUTED						
	HA	RH	PV	WB	DP	VS	EN
HA = .00010	X	.37995	.0024	-20.77	-36.25	11.086	-4.70
RH = .37995	.00010	X	.0024	-20.77	-36.25	11.086	-4.70
PV = .0024	.00010	.37995	X	-20.77	-36.25	11.086	-4.70
WB = -20.77	.00010	.37995	.0024	X	-36.25	11.086	-4.70
DP = -36.25	.00010	.37995	.0024	-20.77	X	11.086	-4.70
VS = 11.086	.00010	.37995	.0024	-20.77	-36.25	X	-4.70
EN = -4.70	.00010	.37995	.0024	-20.77	-36.25	11.086	X

