How to Use Hand-Held Computers to Evaluate Wood Drying

Howard N. Rosen and Darrell S. Martin
HOW TO USE HAND-HELD COMPUTERS TO EVALUATE WOOD DRYING

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A gap exists between the theory and practice of industrial wood processing. Wood drying is one area where sophisticated theory and mathematical models have been developed and now need to be put into practice. Hand-held computers are one way of doing it. They have the advantage over larger models of being easily portable and inexpensive, yet they are capable of sophisticated programming.

Although several companies sell hand-held computers with 1 to 8K memory (Goldfarb and Griffin 1982), few programs have been available for the wood products industry. Drying is a time-consuming and expensive step in the processing of wood. Several mathematical models have been developed recently to assist drying operators in developing schedules, evaluating final drying times, and determining basic properties of wood exposed to a particular drying environment. This paper describes several basic drying programs developed for a hand-held computer.

PROGRAMS

Five separate programs written in BASIC have been developed for a Sharp1 PC 1500 pocket computer (weighing less than 1 lb) with a 3.5K random access memory (RAM). These programs are combined into a program package called DRYPAC (see tabulation below):

Programs Developed in DRYPAC

<table>
<thead>
<tr>
<th>Program</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>EMC</td>
<td>Determines equilibrium moisture content, humidity, or wet-bulb temperature from basic psychrometric relationships.</td>
</tr>
<tr>
<td>FIT-CURVE</td>
<td>Determines parameters a and b by fitting Equations (18) and (19) to a data set of three points.</td>
</tr>
<tr>
<td>FIT-CURVE-A</td>
<td>Determines approximate a and b when FIT-CURVE does not converge.</td>
</tr>
<tr>
<td>DRY-CURVE-1</td>
<td>Determines and plots a drying curve and tabulates moisture content versus time for ten time increments.</td>
</tr>
<tr>
<td>DRY-CURVE-2</td>
<td>Determines and plots relative moisture content versus time; tabulates these values as well as relative drying rates for ten time increments.</td>
</tr>
</tbody>
</table>

Programs are stored on audio cassette tapes and fed into the computer from a tape recorder. Once inside the computer memory, the program is initiated by pressing the RUN button. Only one of the five programs can occupy RAM at a given time.

Output appears on a dot graphic liquid crystal display area directly on the computer or on a four-color X-Y plotting Sharp CE-150 printer which is a separate unit. The computer, interface, and printer weight less than 3 lbs and are easily carried to any part of the wood processing plant (fig. 1).

The programs can be used on any small computer using the BASIC programming language having 3.5K RAM, but generally would have to be modified for input/output format and plotting commands. Most hand-held computers such as the Radio Shack TRS80 PC-2 or the Panasonic HHC could take a modified program.

Figure 1--Hand-held computers can be easily carried to perform complex calculations in any part of the processing plant.

1Use of trade names does not constitute endorsement of the products by the USDA Forest Service.
Program EMC

To evaluate a drying curve, equilibrium moisture content, EMC, must be determined from the conditions in the kiln. The EMC at atmospheric pressure is a function of dry-bulb temperature and either relative humidity or wet-bulb temperature. Also, Program EMC provides the user with EMC over a range of dry-bulb temperatures from 32 to 400°F, which is more extensive than most published tables. Program EMC calculates enthalpy and either relative humidity (RH), if wet-bulb temperature (TWB) is given, or TWB, if RH is given (fig. 1a and list 1a in Appendix B). Humidity calculations are made from basic psychometric relationships (Appendix A) (Elliott 1983).

The program will ask for dry-bulb temperature ("TDB = ?") and relative humidity "RH = ?"). If RH is not known, any negative number can be input, i.e. "-1," and the program will ask for wet-bulb temperature ("TWB = ?"). Temperatures should be input to 0.1°F and RH to 0.1 percent. The program requires less than 3 minutes to run in most situations.

Output illustrated by three separate outputs (table 1), will include the input data as well as either RH or TWB, EMC to 0.1 percent, and enthalpy to 0.1 Btu/lb dry air. If an improper RH is input to the program, the message "INVALID HUMIDITY" will be the output.

Program FIT-CURVE

If data of moisture content at various drying times are given, Program FIT-CURVE will determine two parameters, a and b (will list as A and B for clarity of copy), which describe and can be used to calculate basic properties of the curve (fig. 2a and list 2a in Appendix B). Moisture content data (initial moisture content, equilibrium moisture content, and moisture content at three selected times) must be entered into the program. The three moisture contents at selected times must be converted to relative moisture content, E, by Equation (12) and then must meet the following criteria: one at a short time (Eo, t0) where E > 0.90, one when approximately half the water is removed from the wood (Em, tm) where 0.45 < E < 0.55, and one at a long time (EL, tL) where E < 0.15 (fig. 2).

Also, the range of time data should be in units such that the maximum time is no greater than 100, but optimally near 10. For example, if E = 0.04 at 3000 minutes, the program will run more efficiently if the minutes were converted to 50 hours.

The program will ask for initial moisture content ("IMC = "), equilibrium moisture content ("EMC = "), and data points ("TS = ", "MCS = ", "TM = ", "MCM = ", "TL = ", "MCL = "). Moisture contents should be input to 0.1 percent and times to three decimal places or less. Output consists of values for A, B, and D (criterion for fit; D < 0.01 is a good fit).

Sample input of data show convergence of a and b in 4 minutes with a very close fit (table 2--Input and Output 1). In many cases for highly nonlinear functions, the program will not converge. Thus, a message "TRY ALTERNATE" will be output after approximately 10 minutes as in table 2--Input and Output 2. A solution with the data of Input 2 can be approximated with Program FIT-CURVE-A.

Program FIT-CURVE-A

If the Program FIT-CURVE does not converge to value of a and b, this program will provide values (fig. 3a and list 3a in Appendix B). The program requires the same input format and will provide the same output format (except that the criterion for fit is DA rather than D) as Program FIT-CURVE. The Pro-
Table 2.—Sample Input and Output from Program FIT-CURVE and FIT-CURVE-A

<table>
<thead>
<tr>
<th>FIT-CURVE</th>
<th>Input 1</th>
<th>Input 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>“IMC =”</td>
<td>105.0</td>
<td>“EMC =”</td>
</tr>
<tr>
<td>“TS =”</td>
<td>0.04</td>
<td>“MCS =”</td>
</tr>
<tr>
<td>“TM =”</td>
<td>0.30</td>
<td>“MCM =”</td>
</tr>
<tr>
<td>“TL =”</td>
<td>1.50</td>
<td>“MCL =”</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Output 1</th>
<th>Output 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>“A =”</td>
<td>2.036</td>
</tr>
<tr>
<td>“B =”</td>
<td>0.914</td>
</tr>
<tr>
<td>“D =”</td>
<td>0.002</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>FIT-CURVE-A</th>
<th>Input 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Same as Input 2)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Output 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>“A =”</td>
</tr>
<tr>
<td>“B =”</td>
</tr>
<tr>
<td>“DA =”</td>
</tr>
</tbody>
</table>

Program FIT-CURVE-A will not give as close a fit as FIT-CURVE and requires 10 minutes computing time but is adequate in many instances (table 2—Input and Output 3).

**Program DRY-CURVE-1**

This program generates a drying curve of moisture content versus time (fig. 4a and list 4a in Appendix B). The program will ask for parameter values (“A = ?”, “B = ?”), initial and equilibrium moisture contents (“IMC = ?”, “EMC = ?”) and units of time (“TIME UNITS = ?”). Units of time must fill four spaces, such as DAYS, HRS., MIN., SEC., etc. Output consists of a drying curve in moisture content (MC) in percent versus time (T), a table of the same information with data to two decimal places, and a listing of A, B, and EMC (fig. 3). The program provides results in 3 to 5 minutes depending on the values of the parameters.

**Program DRY-CURVE-2**

This program is similar to DRY-CURVE-1, only the program is intended for more basic work (fig. 5a and list 5a in Appendix B). Input requires only parameter values (“A = ?”, “B = ?”). Output provides a plot of relative moisture content, E versus drying time, a table of dry time (T), E, and relative drying rate (RDR) in scientific rotation to three significant digits calculated from Equation (13) (fig. 4). Researchers should find this program useful to determine initial drying rates and characteristic drying curves.

**General**

DRYPAC is most applicable when drying is being done at constant conditions of temperature and humidity, so that EMC is constant during the entire drying time. Constant conditions are not normally maintained in commercial drying operations. In many cases, drying curves for varying conditions can be fit with the analysis of DRYPAC by assuming EMC is equal to that at the final drying conditions.

**SUMMARY AND OUTLOOK**

The program package DRYPAC can be helpful to wood processors and researchers in fitting drying data, predicting drying times, and evaluating basic parameters for efficient kiln operation. The programs are readily adaptable to hand-held computers and can be saved on cassette tape.

The development of DRYPAC allows for expansion and alteration as computer technology advances. Two possible programs to add are an economic analysis program and a program to predict drying times based on wood characteristics and kiln conditions. Microcomputer hardware technology is progressing at such a rapid pace that details of the programs might be

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Figure 3.—Example output of moisture content versus time plot and tabular values from Program DRY-CURVE-1.

Figure 4.—Example output of relative moisture content versus time plot and tabular values from Program DRY-CURVE-2.
done more efficiently in the near future. For example, hand-held computers now have 16K RAM plug-in units which could store the entire DRYPAC package. The wood industry must be alert to the expanding microcomputer technology and use this technology to produce the best quality wood product in the most efficient manner.

LITERATURE CITED

APPENDIX A

\[ h = 0.01 \text{ RH} \]  

\[ X_s = \left[ \frac{a_s a_h h}{1 + a_s a_h h + 1 - a_h h} \right]^{1800} a_3 \]  

where:

\[ a_s = 3.730 + 0.003642 T_{db} - 0.0000154 T_{db}^2 \]
\[ a_h = 0.6740 + 0.001053 T_{wb} - 0.000001714 T_{wb}^2 \]
\[ a_3 = 216.9 + 0.01961 T_{db} + 0.00572 T_{db}^2 \]

Relative humidity can be determined from wet- and dry-bulb temperatures using the following psychrometric relationships (Elliott 1983):

\[ Y_s = \frac{(1093 - 0.556 T_{wb}) Y_{s,wb} - 0.240 (T_{db} - T_{wb})}{1093 + 0.444 T_{db} - T_{wb}} \]

Also,

\[ Y_s = \frac{0.622 p_s}{14.7 - p_s} \]

\[ p_v = 0.000145 \exp \left(-5800/T' + 1.391 - 0.04864 \right) \]
\[ T' = 0.4176 \times 10^4 T^2 - 0.1445 \times 10^{-7} T^6 + 6.546 \ln(T') \]  

Absolute humidity can then be determined by evaluating Equations (4) and (5) at the wet-bulb temperature and plugging in the value of \( Y_{s,wb} \) into Equation

Subscripts

db . dry bulb  
e . equilibrium  
f . final  
i . initial  
L . long time  
M . middle time  
s . saturation  
S . short time  
w . wet bulb

THEORY
Program EMC

The equilibrium moisture content, \( X_s \), must be determined from relative humidity, RH, and dry-bulb temperature, \( T_{db} \) (Simpson and Rosen 1981).
Further
\[ p = \frac{14.7Y}{0.622 + Y} \] (7)

Knowing \( p, p_{s,db} \) can be evaluated from Equation (5) to obtain:
\[ \text{RH} = 100 \left( \frac{p}{p_{s,db}} \right) \] (8)

Enthalpy, \( H \), in Btu/lb dry air can be evaluated from the following relationship:
\[ H = 0.240(1 + 8.33 \times 10^{-5} T_{db}) T_{db} + Y[1061 + 0.444(1 + 4.464 \times 10^{-4} T_{db}) T_{db}] \] (9)

The program is straightforward when \( T_{db} \) and \( T_{wb} \) are given. Equation (3) is evaluated for absolute humidity, \( Y \), which can then be substituted into Equation (7) to determine the vapor pressure of water in the humid air. The saturation vapor pressure of water at the dry-bulb temperature, \( p_{s,db} \), can be obtained from Equation (5) and, thus, relative humidity calculated from Equation (8).

When RH is given, a programmed iterative Newton method solves Equation (3) for \( T_{wb} \). The mathematics are similar to the solution when \( T_{wb} \) is given. In this case, \( Y_{wb} \) in Equation (3) is a complex function of \( T_{wb} \) and is unknown. Thus, a numerical technique is required to solve for \( T_{wb} \). This iterative procedure becomes unstable near a \( T_{wb} \) of 212°F; thus, several safeguards are placed in the program to ensure a reasonable value of \( T_{wb} \) as \( T_{wb} \) approaches 212°F. If \( T_{wb} \) is determined to be greater than 211.5°F, the value is set at 211.5°F for calculations of enthalpy. For most practical kiln operations, conditions will not go above 211.5°F \( T_{wb} \). The program also ensures that a proper RH is input; e.g. that RH cannot go above 22 percent at 300°F \( T_{db} \) and atmospheric pressure. Enthalpy is calculated from Equation (9).

**Program FIT-CURVE**

Drying curves for wood products are defined in terms of a rate factor, \( a \), and bend factor, \( b \) (Rosen 1980, 1982):

- **Drying curve**
  \[ E = 1 - \dot{E}_s \int_{0}^{t} \exp(-at^{1/b}) dt \] (10)

  where
  \[ \dot{E}_s = \frac{a^{b}}{b\Gamma(b)} \] (11)
  \[ E = \frac{X - X_{s}}{X_{i} - X_{s}} \] (12)

Relative drying rate
\[ \frac{dE}{dt} = \dot{E} = \dot{E}_s \exp(-at^{1/b}) \] (13)

The series solution to Equation (10) is:
\[ E = 1 - \dot{E}_s t \sum_{n=0}^{\infty} \frac{(-1)^{n}a^{n}t^{n/b}}{(n/b + 1)n!} \] (14)

An approximate solution to Equation (10) is:
\[ E = 1 - \frac{\sigma^{b}}{b\Gamma(b)} (1 - \frac{b\sigma}{b + 1}); \sigma = 0.5 \] (short times) (15)
\[ E = \frac{\sigma^{b-1}\exp(-\sigma)(\sigma + b - 1)}{\Gamma(b)} \] (long times) (16)

where
\[ \sigma = at^{1/b} \] (17)

The program substitutes input values of \( E_s, t_s \) and \( E_L, t_L \) into Equations (15) and (16).

- **Exponent for \( E_s \)**
  \[ E_s = 1 - \frac{a^{t_{s}}}{b\Gamma(b)} (1 - \frac{b\Gamma(b)}{b + 1}) \] (18)

- **Exponent for \( E_L \)**
  \[ E_L = (at^{1/b})^{b-2} \exp(-at^{1/b})(at^{1/b} + b - 1)/\Gamma(b) \] (19)

Equations (18) and (19) are solved for \( a \) and \( b \) by a two-dimensional Newton-Raphson Method (Stark 1970). The gamma function of \( b \) is solved by a series expansion (Davis 1963).

Initial values of \( a \) and \( b \) must be carefully selected because of instabilities in the Newton-Raphson Method with these highly nonlinear functions. Also, Equations (18) and (19) can converge to two sets of answers depending on the initial guess of \( a \) and \( b \)--one set with \( b < 1.0 \) and one set with \( b \geq 1.0 \). Techniques have been developed to generate good initial guesses for \( a \) and \( b \) and to have a method for picking the best final values for a given set of data.

The value of \( b \) is the most critical since this value determines the degree of nonlinearity of Equation (10). From past experience (Rosen 1982), values of \( b \) fall in the range of 0.2 to 4.0. Thus, the numerical solution uses a stepwise searching technique starting with a value of \( b = 0.15 \) and incrementing \( b \) by selected amounts until a solution is found or until \( b = 4.0 \). Once each \( b \) is given, \( a \) is estimated from Equation (11):
\[ \dot{E}_s = \text{initial slope of drying curve} = \frac{1.0 - E_s}{t_s} \] (20)
When two solutions are found for Equations (18) and (19), a comparison is made to determine the best solution of the two. Values of $E_m$ and $t_m$ from the data and those calculated by Equation (14) are substituted into the following equation:

$$D = \sqrt{(\Delta E_m^2 + 2\Delta E_L^2)/3}$$  \hspace{1cm} (22)

where $\Delta E_m = E_m$ (calculated) $- E_m$ (data)
$\Delta E_L = E_L$ (calculated) $- E_L$ (data)

Equation (22) gives added numerical emphasis to the end of the drying, where small absolute differences in $E$ can make a bigger difference in $t$ than in earlier drying stages. The values of $a$ and $b$ corresponding to the lowest value of $D$ are the optimal values.

Program FIT-CURVE-A

The program is similar to FIT-CURVE, but uses a direct calculation rather than the Newton-Raphson Method. The function $DA$ is minimized over a range of $b$'s from 0.05 to 4.1; where this range is divided into 24 increments of increasing size as the value of $b$ increases. Greater numerical emphases on $\Delta$ $E$'s are given on the middle and end of drying.

$$DA = \sqrt{(0.5 \Delta E_s^2 + \Delta E_m^2 + 2\Delta E_L^2)/3.5}$$  \hspace{1cm} (23)

where $\Delta E_s = E_s$ (calculated) $- E_s$ (data)

Program DRY CURVE-1

The program uses values of $a$, $b$, $X_i$, and $X_e$ to generate a drying curve. The program must first estimate the final time to dry slightly above $X_e$ so that the time axis of the graph can be determined.

$$t_f = (\frac{1.5 + 2b}{a})^b$$  \hspace{1cm} (24)

Final time is then divided into ten increments, such that the four increments are closer together than the remaining six. $E$'s are calculated for each $t$ by Equation (14) and transformed to moisture content by Equation (12).

Program DRY-CURVE-2

Only drying parameters $a$ and $b$ need to generate the drying curve of $E$ versus $t$ by Equation (14).

Relative drying rates, $\dot{E}$, are also calculated at each $t$ by Equation (13).
Figure 1a.—Logic diagram for Program EMC.
6:COLOR 0:INPUT "TDB=?";TD:INPUT "RH=?";RH
25:TW=0:R1=RH:IF RH>OGOTO 30
27:INPUT "TW=?";TW
30:PRINT " GIVEN:"
31:COLOR 1:PRINT USING "##########.";"TDB =";TDB
32:IF RH>0:PRINT "RH =";RH
33:IF RH<0:PRINT "TW =";TW
34:PRINT " 
35:COLOR 0:PRINT " RESULTS:"
36:COLOR 3:PRINT " 
40:T=TD:GOSUB 600
41:PD=PS
45:N=0:IF RH>OGOTO 250
50:T=TW
55:GOSUB 600
60:PW=PS:Y=2:Y=Y3
72:IF Y<0:LET Y=0
75:P=(14.7*Y)/(.622+Y):IF N<OGOTO 90
80:R=PW/PD*100
85:PRINT "RH = ";RH
90:K1=.373+.03642*TD-.0001547*TD*TD
95:K2=.674+.001053*TD-.000001714*TD*TD
100:W=216.9+.01961*TD+.00572*TD*TD
105:H1=RH/100
110:EM=(K1*K2*H1)/(1+K1*K2*H1)+K2*H1/(1-K2*H1)*1800/W
115:PRINT "EM =";EM
120:H=2.*((1+8.333*6*TD)*TD
125:HB=Y*(1061+.443*(1+4.464*6*TD)*TD)
130:H=HA+HB
135:PRINT USING "#####.");"ENTHALPY =";H
190:END
250:PRINT "RH*PD/100
255:Y=(P*.622)/(14.7-P)
280:TA=TD-20
285:T=TA:GOSUB 600
286:N=N+1
290:PS=PS:F1=Y-Y3
300:TB=TA-.005
305:T=TB:GOSUB 600
310:PS=F0=Y-Y3
360:DR=(F1-F0)/.005
365:TW=TA-(F1/DR))
367:IF TW<212GOTO 375
368:TA=211
373:GOTO 395
375:DF=ABS (TW-TA)
385:IF DF<.05GOTO 450
390:TA=TW
395:IF N<15GOTO 500
400:GOTO 285
450:PRINT "TW =";TW
460:GOTO 50
500:PRINT "TW > 211.5"
510:TW=212:GOTO 50
600:T1=T+T+(T+459.6)/1.8
610:PS=EXP (-5800/T+1.391-0.04864*T+0.4176E-4*T*T-.1445E-
7*(T-3)+6.546*LN T)
620:PS=PS*.999945
625:IF Ti=TDMOTO 670
627:IF PS<14.69GOTO 670
630:Y2=(.622*PS)/(14.7-PS)
635:Y3=((1093-.556*Ti)*Y2-.240*(TD-T1))/(1093+.443*TD-T1)
670:RETURN

List 1a.--Program for EMC.
Figure 2a. Logic diagram for Program FIT-CURVE.
5: INPUT "IMC=";J: INPUT "EMC=";B:A=J-B
10: INPUT "TS=";T1: INPUT "MCS=";E1: INPUT "TM=";T2:E1=(E1-B)/A
11: INPUT "MCM=";E2:E2=(E2-B)/A: INPUT "TL=";T3: INPUT "MCL=";E3:
   B2=.1;E3=(E3-B)/A;J=10
17: B2=B2+.05:N=0:COLOR 0
18: IF B2>.5LET B2=B2+.10
19: IF B2>1.2LET B2=B2+.4
21: B=B2
22: A=((1-E1)/(T1)*B+G)*A
23: if B2>4GOTO 269
25: BO=B" GO=G" AO=A
27: BI=BO+.005" AI=AO+.005 • B=B1 "GOSUB 600
55: G=GM" A=AO" B=BO" G=GO" GOSUB 500
70: FA=DO: A=AO: B=BO: G=GO" M=GM: GOSUB 500
85: FC=DO: A=AO: B=BO: G=GO" M=GM: GOSUB 500
100: G=GM" A=AO" B=BO" G=GO" GOSUB 500
115: EZ=FE=FB/.005: EZ=FE=FB/.005
125: X=GMFZ=GM" R=GMG=GM" GOSUB 500
130: A1=(GMGA+R+GMGA-FB)/XR-EXAO+GMGA-FB)/R(X)
131: IF A1<0.005GOTO 17
140: B1=(GMGA+R+GMGA-FB)/XR-EXAO+GMGA-FB)/R(X)
141: IF B1<.1GOTO 17
142: IF B1>14GOTO 17
143: IF N>25GOTO 280
155: IF A0>.001THEN GOTO 25
215: EZ=(A-B)/(B+G): T=T2: GOSUB 700: EZ=(E-E2)^2
230: T=T3: GOSUB 700: D=((GMFZ-EXA+1)/3)^0.5: IF D+JGOTO 17
255: J=D; B3=B: A3=A: IF B2>3GOTO 270
259: IF B2<1LET B2=1: GOTO 17
269: IF A3<JGOTO 280
270: LPRINT USING "###.###"; A=""; A3: LPRINT "B ="; B3: LPRINT "":
   COLOR 3: LPRINT "D ="; J: END
280: LPRINT "TRY ALTERNATE"; END
500: D=((A+3-(1/B))-(B-2))*(EXP(-A+3-(1/B)))*((A+3-(1/B)
   +B-1)/G)*E3
555: M=1-E1-(T1*A-B)/(B+G)+(A^B+1)*T1-((B+1)/B)/(B+G): RETURN
600: M=1: X=B
625: IF B<1GOTO 645
630: M=M*(B-1): B=B-1: GOTO 625
645: G=B+.5772156*(B-2)+(E-2)*(.655878)*B^-3+(-.042003)*B^-4+
   (.1665386)*B^-5
650: G=G*(-.0421977)*(B-6)+(-.009622)*(B-7)+(.00719)*(B-8)+
   (.001165)*(B-9)
655: G=M/(G+D+(-.0002152)*(B-10)): B=X: RETURN
700: X:=0: G:=0: N:=0: R=1
705: GOTO 765
710: N=N+1: R=R*N
765: X=X+(1-N)+B-N+T-((N/B)/(N/B+1))/R:D=ABS (X-G)
780: IF D=0.000001GOTO 790
782: G=X: GOTO 710
790: E=1-(EZ*T*X): RETURN

List 2a.--Program for FIT-CURVE.
Convert X's to E's by Eq. 12

Initialize

\[ b = 0.05 \]
\[ J = 10 \]

Calculate a from slope and Eq. 21

Is a > 20 or < 0.001?

NO

YES

Increment b

Is b > 4.1?

NO

Calculate DA by Eq. 23

Is DA < J

NO

YES

\[ a = a_{\text{new}} \]
\[ b = b_{\text{new}} \]
\[ J = DA \]

Print a, b, DA

END

Figure 3a.--Logic diagram for Program FIT-CURVE-A.
List 3a.--Program for FIT-CURVE-A.
Input: \( a, b, X_i, X_e, \) time units

Calculate \( \Gamma(b) \) then \( \dot{E}_i \) from Eq. 11

Calculate \( t_f \) from Eq. 24

Draw and label graph axes and column headings

\( I = 0 \)

\( I = I + 1 \)

Is \( I > 10? \)

YES

END

NO

Calculate time increments with scale factors

Print \( t(i) \) & \( X(i) \) in table

Calculate \( E(i) \) by Eq. 14

Plot \( X(i) \) at \( t(i) \)

Calculate \( X(i) \) by Eq. 12

Figure 4a.--Logic diagram for Program DRY-CURVE-1.
Program for DRY-CURVE-1.

List 4a.
Input: a, b, time units

Calculate \( \Gamma(b) \), then \( \dot{E}_f \) from Eq. 11

Calculate \( t_f \) from Eq. 24

Draw and label graph axes and column headings

\( I = 0 \)

\( I = I + 1 \)

Is \( I > 10 \)?

YES \( \longrightarrow \) END

NO

Calculate time increments with scale factors

Print \( t(i), E(i) \)

Calculate \( \dot{E}(i) \) by Eq. 13

Calculate \( E(i) \) by Eq. 14

Plot \( \dot{X}(i) \) at \( t(i) \)

Calculate \( X(i) \) by Eq. 12

Print \( t(i), E(i), \dot{E}(i) \)

in table

Figure 5a.--Logic diagram for Program DRY-CURVE-2.
10: INPUT "A=?"; A
15: INPUT "B=?"; B
17: S=1.5*B
19: INPUT "TIME UNITS=?"; A$
20: T=1
22: X=B
25: IF B=1GOTO 45
30: T=T*(B-1)
35: B=B-1
40: GOTO 25
45: G=8+.5772156*(B-2)*(-.655878)*(B-3)+
(-.042003)*(B-4)+(.1665386)*(B-5)
50: D=(-.0421977)*(B-6)+(-.0096222)*(B-7)+
(.007219)*(B-8)+(-.001165)*(B-9)
55: H=(-.0002152)*(B-10)
60: G=(G+D+H)
65: H=(-.0002152)*(B-10)
70: E=1-(EO*T)^2
75: F=(S/A)-B
80: G=0
85: H=0
90: GRAPH
95: CSIZE 1
100: COLOR 1
105: LPRINT "RELATIVE MOISTURE, E"
110: GLCURSOR (30,-31):SORGN
115: FOR I=ITO 4
120: H=H-64
125: G=0
130: GRAPH
140: NEXT I
145: GLCURSOR (-30,-108)
150: ROATATE 1
155: LPRINT "TIME "; A$
160: LINE (0,0)-(210,0)
165: LINE (0,0)-(90,264)
170: LINE (-10,-322)-(210,-322)
175: LINE (160,-400)-(160,-280)
180: LINE (-10,-360)-(210,-360)
185: GLCURSOR (163,-282)
200: LPRINT "T("; A$; ") E RDR"
205: FOR I=1TO 5
210: G=6+35:D=I*.2
215: GLCURSOR (6,28)
220: LPRINT USING "##.##"; D
225: LPRINT "-
230: NEXT I
235: LINE (-10,-26)
240: IF F<=2LET MU=0.25
245: FOR I=1TO 4
250: MU=INT (F/4+1)
255: FOR I=1TO 4
260: LINE (-10,-26)
265: LPRINT "-
270: NEXT I
275: LINE (-10,-26)
280: IF F<=2LET MU=0.5
285: LPRINT "-
290: END

List 5a.--Program for DRY-CURVE-2.
APPENDIX C — EXAMPLE PROBLEM

The drying of ¼-inch-thick pine sapwood at 234°F dry-bulb temperature and 210°F wet-bulb temperature in a laboratory dryer will serve as an example to demonstrate the use of computer package DRYPAC (Kollmann and Schneider 1961). First, \( T_{db} \) and \( T_{wb} \) are input to Program EMC to obtain an \( X_e \) of 5.9 percent (fig. 6a). Values of \( X_i, X_e, X_s, t_i, X_M, t_M, X_L, \) and \( t_L \) are then input to Program FIT-CURVE which converge to a value of \( a \) and \( b \) in less than 3 minutes with a value of \( D \) of only 0.007, indicating a good fit to the three data points. Finally, \( X_i, X_e, a, \) and \( b \) are input to Program DRY-CURVE-1 for a complete predicted curve, which closely fits all the data points (fig. 6a).

A practical question which can be answered by this example, is “How long would be required to dry this wood to 15 percent moisture content?” From figure 6a, 5.7 hours is necessary.

\[
\begin{align*}
X_s &= 110 \\
t_s &= 0.27 \\
X_M &= 60 \\
t_M &= 2.00 \\
X_L &= 10 \\
t_L &= 6.93
\end{align*}
\]

\( a = 0.194 \)
\( b = 0.732 \)
\( D = 0.007 \)
\( T_{db} = 234°F \)
\( T_{wb} = 210°F \)
\( EMC = 5.9\% \)

**Figure 6a.**—Plot of moisture content versus time for drying pine sapwood (Kollmann and Schneider 1961). The solid line is the predicted curve and the solid circles are the input data points for Program DRY-CURVE-1.
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Techniques have been developed to evaluate and generate wood drying curves with hand-held computers (3-5K memory). Predictions of time to dry to a specific moisture content, drying rates, and other characteristics of wood drying curves can be made. The paper describes the development of programs and illustrates their use.

KEY WORDS: Drying rate, numerical analysis, models, psychrometric relationships, moisture content.