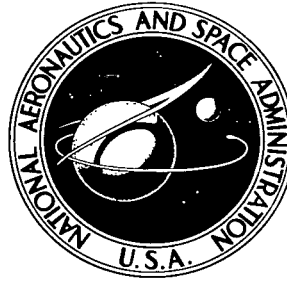


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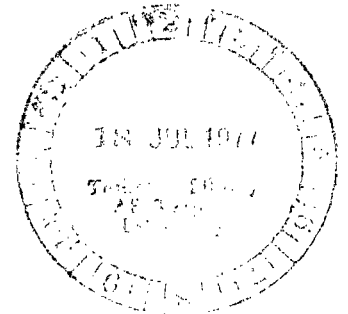
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**GASPLOT - A COMPUTER GRAPHICS PROGRAM
THAT DRAWS A VARIETY OF THERMOPHYSICAL
PROPERTY CHARTS**

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16. Abstract <p>This report describes a FORTRAN V computer program, written for the UNIVAC 1100 series, that draws a variety of precision thermophysical property charts on the Calcomp plotter. In addition to the program (GASPLOT), which requires (15 160)₁₀ storages, a thermophysical properties routine (such as GASP, which requires (9900)₁₀ storages) is needed to produce plots. The program is designed so that any two of the state variables (P, ρ, T), the derived variables (H, S, C_p, C_v, C, γ), or the transport variables (λ, η, σ) may be plotted as the ordinate-abscissa pair with as many as five parametric variables. The parameters may be temperature, pressure, density, enthalpy, and entropy. Each parameter may have as many as 49 values, and the range of the variables is limited only by the thermophysical properties routine.</p>					
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GASPLOT - A COMPUTER GRAPHICS PROGRAM THAT DRAWS A VARIETY OF THERMOPHYSICAL PROPERTY CHARTS

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SUMMARY

This report describes a FORTRAN V computer program, written for the UNIVAC 1100 series, that draws a variety of precision thermophysical property charts on the Calcomp plotter. The program, GASPLOT, is currently associated with but not limited to the subprogram GASP, which computes the thermophysical properties for 10 fluids: helium, methane, neon, nitrogen, carbon monoxide, oxygen, argon, carbon dioxide, fluorine, and parahydrogen. In addition to GASPLOT (which requires (15 160)₁₀ storages), a thermophysical properties routine (such as GASP, which requires (9900)₁₀ storages) plus the Calcomp software package are all that is needed to produce a thermophysical chart.

The program is designed so that any two of the state variables pressure, density, and temperature (P, ρ, T), the derived variables enthalpy, entropy, specific heats, sonic velocity, and isentropic expansion coefficient ($H, S, C_p, C_v, C, \gamma$), or the transport variables thermal conductivity, viscosity, and surface tension (λ, η, σ) may be plotted as the ordinate-abscissa pair with as many as five parametric variables. The parameters may be temperature, pressure, density, enthalpy, and entropy. Each parameter may have as many as 49 values, and the range of the variables is limited only by the thermophysical properties routine.

INTRODUCTION

Thermodynamic charts are important tools to the systems engineer. With the aid of charts such as temperature against entropy, preliminary designs, components, and general systems can be rapidly evaluated. However, many charts are quite complex and difficult to construct, and very often the resolution is poor. Obtaining new charts is costly and usually requires long lead times - neither of which benefits preliminary analysis.

A solution to this problem is a computer graphics program that will not only draw the type of thermodynamic chart required by the engineer, but also enlarge any segment of this chart to achieve the desired resolution. This report describes such a program, called GASPLOT, that produces a variety of thermophysical property charts of the desired resolution on the Calcomp plotter. GASPLOT is currently associated with but not limited to the subprogram GASP (ref. 1), which computes the thermophysical properties for 10 pure fluids: helium, methane, neon, nitrogen, carbon monoxide, oxygen, argon, carbon dioxide, fluorine, and parahydrogen.

The three main sections of this report cover (1) comments on the design of the program, (2) operation of the program, and (3) description of the program subroutines. The first section discusses some of the decisions that had to be made when designing the program. The second section explains the operation of the program, with sample problems used as illustrations. The third section describes the program, including selected design features, subroutines, and labeling. There are five appendixes. Appendix A explains the interpolation routines and appendix B the subprogram GASP. Appendix C describes the modification procedure for adapting GASPLOT for other thermophysical property packages and for other charts not built into the program. Appendix D presents a procedure for producing figures with grey-grid background. Appendix E defines the symbols used.

COMMENTS ON THE DESIGN OF PROGRAM GASPLOT

Designing a thermophysical properties graphics package requires some knowledge of the nature of the surfaces to be constructed. A thermodynamic surface for pure component fluids can be expressed as an implicit function in many ways. Two of the most common are the varial form, which is in terms of the measured variables (P, V, T),

$$P - P(V, T) = 0 \tag{1}$$

or the fundamental form, which is in terms of the energy variables (Ψ , V, T),

$$\Psi - \Psi(V, T) = 0 \tag{2}$$

Planes tangent to such surfaces, combined with planes passing normal to the coordinate axes, lead to descriptions of a family of thermodynamic surfaces; enthalpy, entropy, and sonic velocity are a few such examples, where entropy can be written as

$$S - S(V, T) = S_0 \tag{3}$$

Similarly, the transport properties for a pure component fluid that involve fluid dynamics as well as statics or thermodynamics may be expressed as

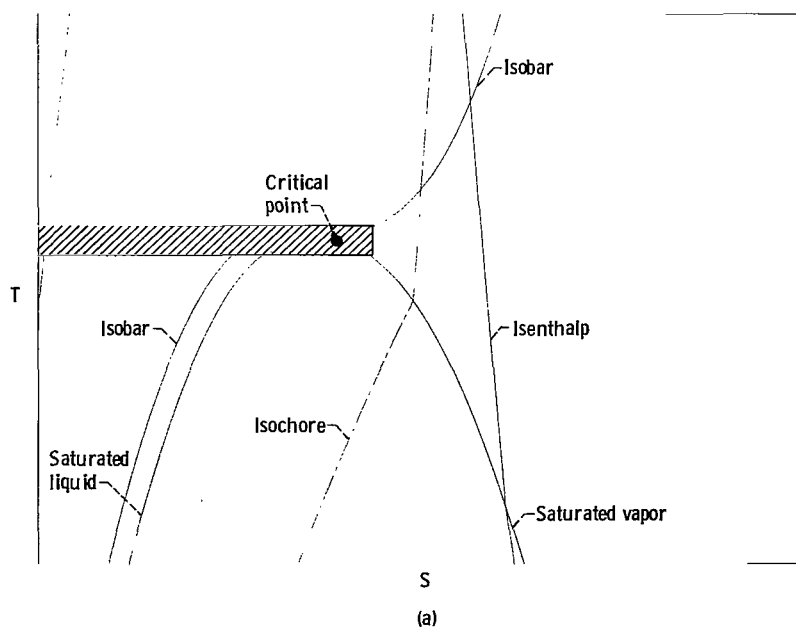
$$\Lambda - \Lambda(V, T) = 0 \quad (4)$$

Each of the surfaces described by equations (1) to (4) changes abruptly along phase transition boundaries and, of course, in the region near the thermodynamic critical point. At the critical point, some fluid properties possess singularities. The description of such properties is currently beyond the scopes of GASP and GASPLIT.

As GASPLIT is currently limited to one independent and one dependent variable, we will always be seeking a projection of the surface onto a plane. Since isoparametric lines are most often required in the projection, a number of decisions had to be made so that these lines could be properly described. Some of the decisions were

- (1) How to determine the number of points and their spacing so that the interpolation package used by GASPLIT will accurately represent the line segment of the parameter being drawn
- (2) How to treat the critical region, where data are not always reliable and singularities exist
- (3) How to describe isoparametric lines in the two-phase region and also to locate a point or points of intersection on the saturation locus

These decisions and others are most easily explained when associated with a specific example. Here we have chosen to use a temperature-entropy sketch because of its familiarity.



POINT SPACING AND LINE SEGMENTS

As all thermophysical property surfaces have large gradients near the critical point, it was recognized that many points would be required in this region. However, away from the critical point and the phase boundaries, most thermophysical property surfaces are well behaved and have small gradients, which would require only a small number of points to describe. Even though there is an optimum point-spacing technique for each variable, it was decided to use 86 points of a geometric sequence as the most representative for every line segment to be drawn. Thus, line segments are generally drawn from regions of large gradients (fine point spacing), such as the critical region, to regions of small gradients (large point spacing), such as the vapor region of the fluid.

NEAR-CRITICAL REGION

As discussed earlier, the thermodynamic critical region is a most difficult region both to compute from the standpoint of thermophysical properties and to plot in a representative manner. Therefore, a small region near the critical point will be excluded. This excluded region is the crosshatched portion in the temperature-entropy sketch (a). Data points, for the line segments, are computed starting at the boundaries of the crosshatched region and then are drawn away from this region.

SATURATION DATA

While not obvious from sketch a, the routines that GASPLOT uses to obtain the thermophysical properties are limited at the liquid-vapor transition boundaries; that is, no data are calculated in the so-called two-phase region but only on the saturation locus. Therefore, it was decided to compute all the saturation properties and to make them available to the program for the following reasons:

- (1) To find, through interpolation, the point or points of intersection on the saturation locus for an isoparametric line
- (2) To provide data for the calculation of data points for the isoparametric lines in the two-phase region
- (3) And to enable the program to draw the proper saturation curve if it falls within the chart boundaries.

TWO-PHASE REGION

This region is bounded by the saturation locus, the near-critical exclusion region, and the lower limits of the thermophysical properties program, usually the triple point. All variations in thermophysical properties in this region are assumed to behave in a linear manner, such that

$$\alpha = X\alpha_V + (1 - X)\alpha_L \quad (5)$$

where $0 \leq X \leq 1$. Thus, to plot line segments within the two-phase region, choose the parameter to be held constant such as enthalpy H in the temperature-entropy sketch a, increment the independent variable temperature T over the saturation data tables, and then solve for the dependent variable entropy S .

$$X = \frac{H - H_L}{H_V - H_L} \quad (6)$$

$$S = XS_V + (1 - X)S_L \quad (7)$$

Not shown in sketch a, isenthalps can intersect the saturation loci at two points. These points are determined by interpolating the array of saturation values. These points plus the points obtained from solving equations (6) and (7) make up the data for the line segment in the two-phase region.

LIQUID AND VAPOR REGIONS

When generating data points for line segments in the liquid and vapor regions, a single geometric progression from the critical point to the extreme limits of the program was not satisfactory. It was therefore necessary to further subdivide the isoparametric lines into a number of line segments. The specific line segments associated with each parameter are discussed in the section Constant-Parameter Subroutines.

FLOW OF THE PROGRAM

The flow of the program (fig. 1) is such that it first reads the NAMELIST statement called /DATA/. These cards contain all the pertinent data necessary for the program to produce a plot. Control is then sent to subroutines CHART, BOUND, and GETGAS.

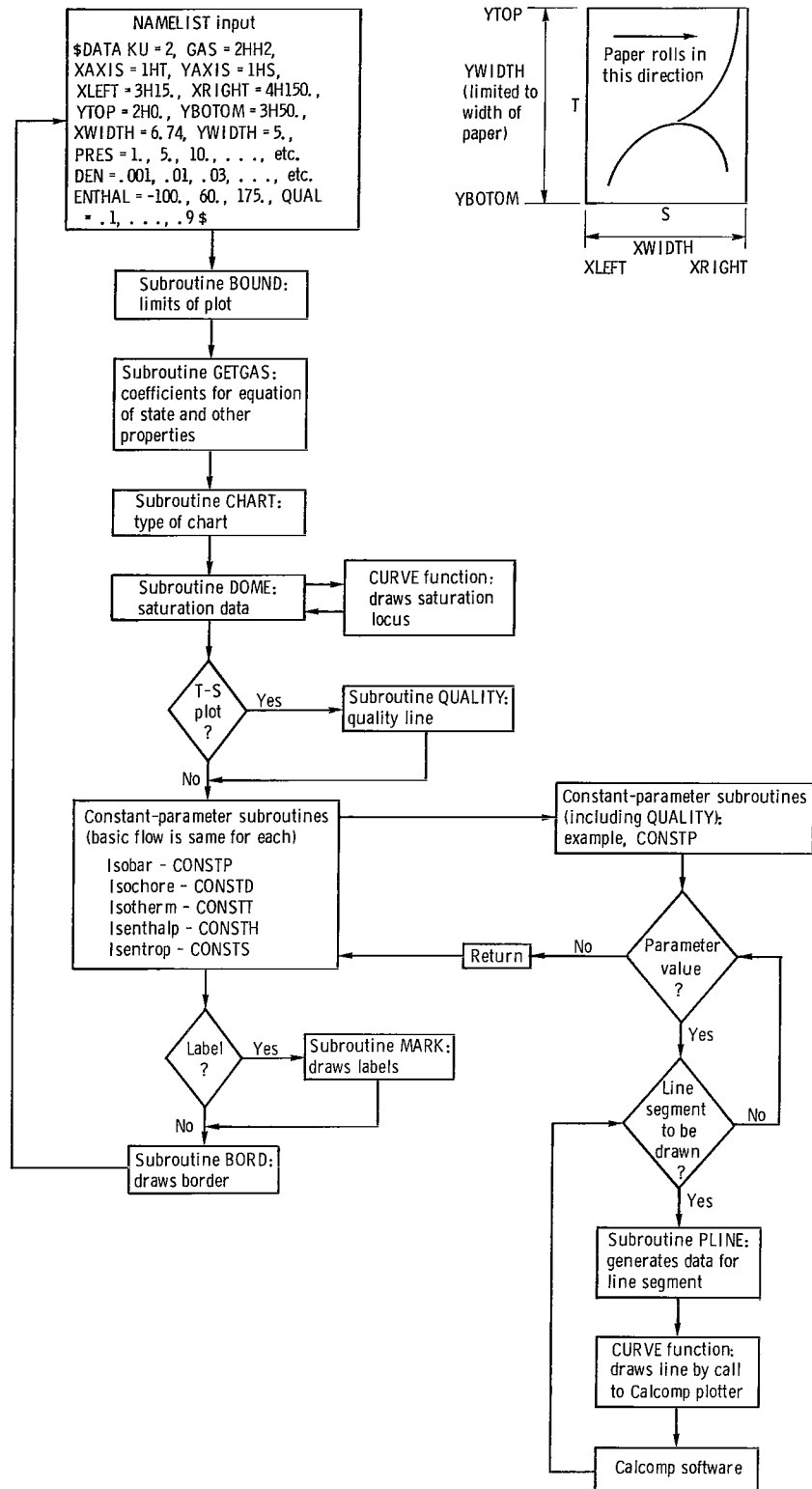


Figure 1. - Compact flow chart for program GASPLOT.

These subroutines then make use of those data read in that are necessary to perform their functions. Namely, CHART needs the symbols representing the x and y axes, BOUND uses the limits of the plot requested, and GETGAS uses the Hollerith code representing the gas to be used. Subroutine DOME is then called, and the saturation data pertaining to the x and y axes are generated. If these data fall within the limits of the plot, the logical function CURVE will draw this curve. Control then moves to the constant-parameter subroutines. These routines obtain from GASP all data necessary for generating a constant-parameter curve and again the logical function CURVE draws only that portion of the constant-parameter line that is within the limits of the plot requested. Finally, the calls to the subroutines that do the labeling are made, and then control is returned to the read statement to see if another plot is requested.

OPERATION OF THE PROGRAM

The purpose of this section is twofold: (1) to demonstrate, by using sample problems, the use of the program and (2) to show, through illustrations, the nature of the output.

DATA INPUT

The GASPLOT program accepts all input through the NAMELIST statement called /DATA/. The FORTRAN symbols for the NAMELIST input are listed and defined in table I. When entering values for the symbols on the NAMELIST cards, the following should be considered:

(1) For DEN, ENTHAL, ENTRO, PRES, and DEGREE, a maximum of 49 values is allowed for each variable, and the values must be in the units indicated by the unit specification number KU (table II).

(2) For every chart request, the program switches LABEL to TRUE, RECIP to FALSE, and YLOG10 and XLOG10 to FALSE and sets XWIDTH and YWIDTH equal to 10.

(3) The Hollerith codes that should be used for GAS, XAXIS, and YAXIS are shown in tables III and IV.

(4) The units for XLEFT, XRIGHT, YTOP, and YBOTOM should be in agreement with the KU number as shown in table II.

(5) The limits for the parameter values for each gas (for the subprogram GASP) are indicated in table V.

SAMPLE PROBLEMS WITH OUTPUT

The following sample problems will be considered:

- (1) Temperature against entropy (T against S)
- (2) Enlargement of the vapor side of figure 2 (T against S)
- (3) Enthalpy against entropy (H against S)
- (4) Temperature against specific heat at constant pressure (T against C_p)
- (5) Pressure against volume (P against V ($V \equiv 1/D$))
- (6) Temperature against conductivity (T against K)
- (7) Enthalpy against $\log P$

Each figure (2 to 8) has a corresponding figure with grey-grid background (figs. 10 to 16).

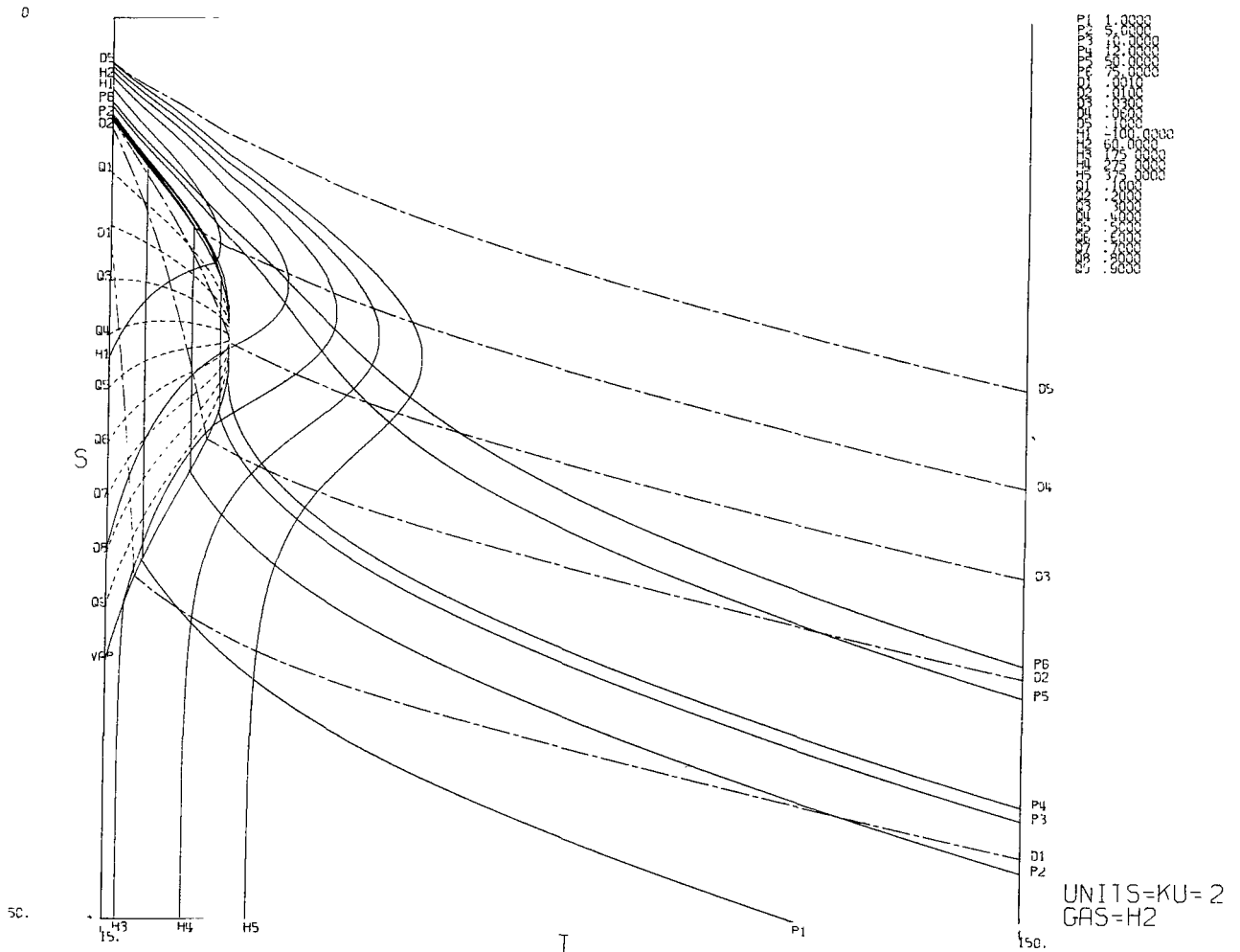


Figure 2. - Temperature T against entropy S for fluid hydrogen.

Problem 1 - Temperature against Entropy

The NAMELIST input described here contains the proper information that will enable the program to draw a temperature-entropy chart:

```
$DATA KU=2, GAS=2HH2, XAXIS=1HT, YAXIS=1HS,  
XLEFT=3H15. , XRIGHT=4H150. ,  
YTOP=2H0. , YBOTOM=3H50. ,  
PRES=1. , 5. , 10. , 12. , 50. , 75. ,  
DEN=. 001, . 01, . 03, . 06, . 1,  
ENTHAL=-100. , 60. , 175. , 275. , 375. ,  
QUAL=. 1, . 2, . 3, . 4, . 5, . 6, . 7, . 8, . 9. $
```

where

KU=2	units specification (table II)
GAS=2HH2	Hollerith code to specify that gas is hydrogen
XAXIS=1HT	Hollerith code to specify that parameter for x-axis is temperature
YAXIS=1HS	Hollerith code to specify that parameter for y-axis is entropy
XLEFT=3H15.	temperature of 15 K for x-axis at coordinate (0, 0)
XRIGHT=4H150.	temperature of 150 K for x-axis at coordinate (XWIDTH, 0)
YTOP=2H0.	entropy of zero for y-axis at coordinate (0, YWIDTH)
YBOTOM=3H50.	entropy of 50 for y-axis at coordinate (0, 0)
PRES	pressure parameters
DEN	density parameters
ENTHAL	enthalpy parameters
QUAL	quality numbers

See figure 2 for the plot produced.

Problem 2 - Enlargement of Vapor Side of Figure 2

NAMELIST input for problem 2 is the same as for problem 1 except that

```
XLEFT=3H25. , XRIGHT=2H50. , YTOP=3H15. , YBOTOM=3H45.
```

See figure 3 for the plot produced.

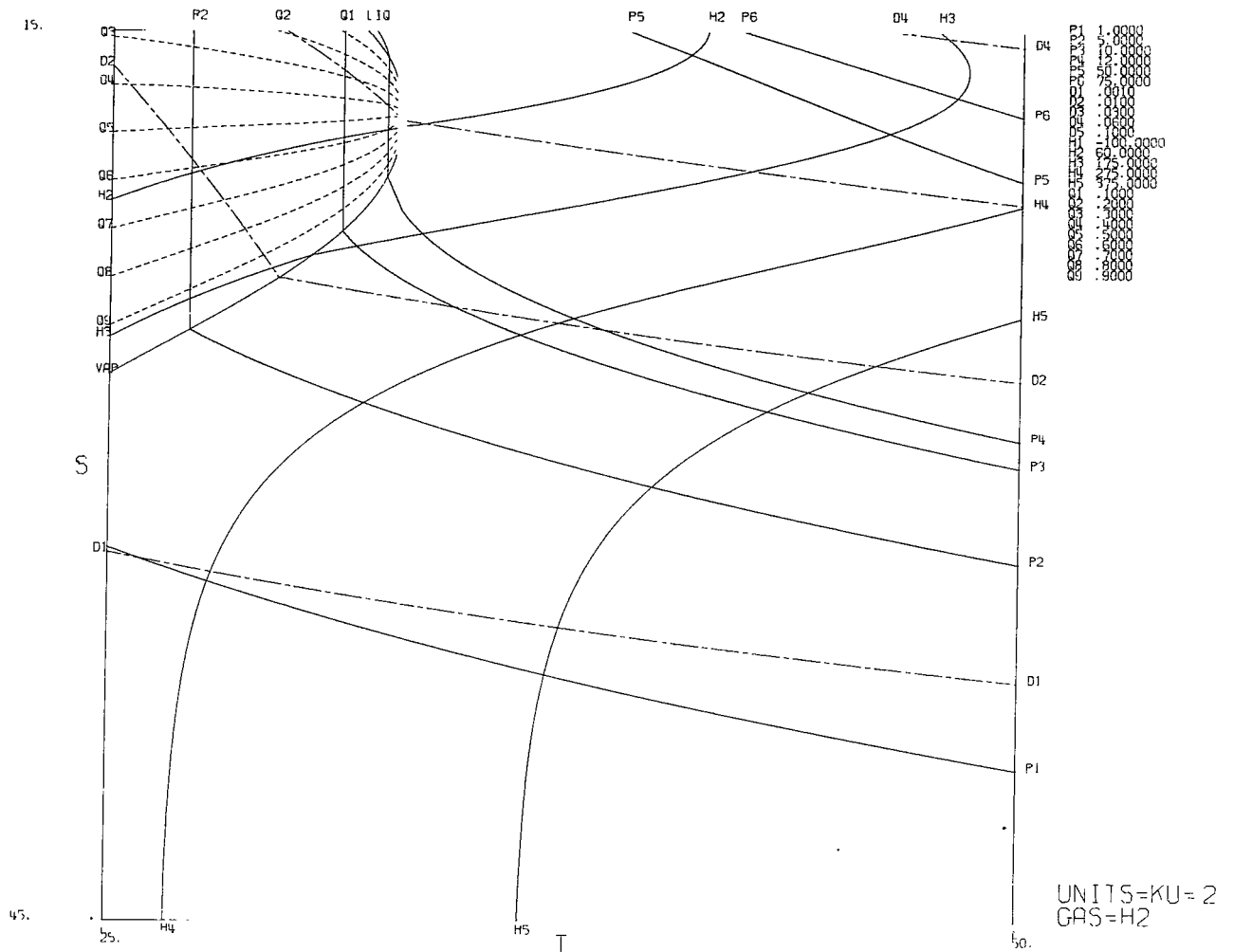


Figure 3. - Temperature T against entropy S for fluid hydrogen (enlargement of vapor side of fig. 2).

Problem 3 - Enthalpy against Entropy

The NAMELIST input for problem 3 is as follows:

```

$DATA KU=1, GAS=2HO2, XAXIS=1HS, YAXIS=1HH,
XLEFT=2H1. , XRIGHT=2H6. , YTOP=4H700. , YBOTOM=5H100. ,
PRES=1. , 5. , 10. , 15. , 25. , 50. , 100. ,
DEN=. 01, . 05, . 1, . 2, . 3, . 4, . 6, 1. ,
DEGREE=75. , 100. , 150. , 200. , 300. , 500. $

```

where DEGREE denotes temperature parameters. See figure 4 for plot produced.

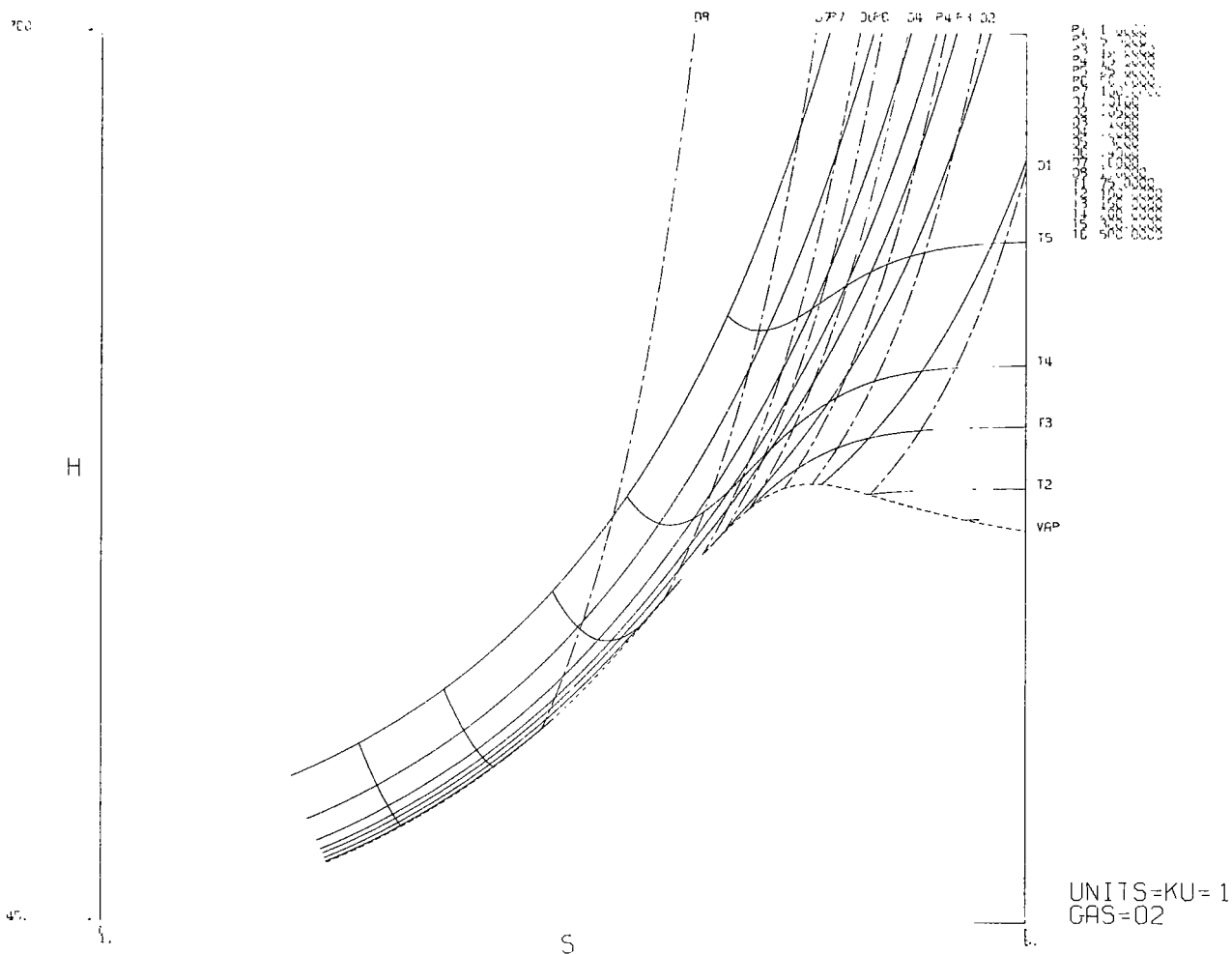


Figure 4. - Entropy S against enthalpy H for fluid oxygen.

Problem 4 - Temperature against Specific Heat at Constant Pressure

The NAMELIST input for problem 4 is as follows:

```

$DATA KU=1, GAS=2HN2, XAXIS=1HT, YAXIS=2HCP,
XLEFT=3H90, XRIGHT=4H210., YTOP=3H10., YBOTOM=2H0.,
PRES=1., 3., 5., 6., 7., 10. $
  
```

See figure 5 for plot produced.

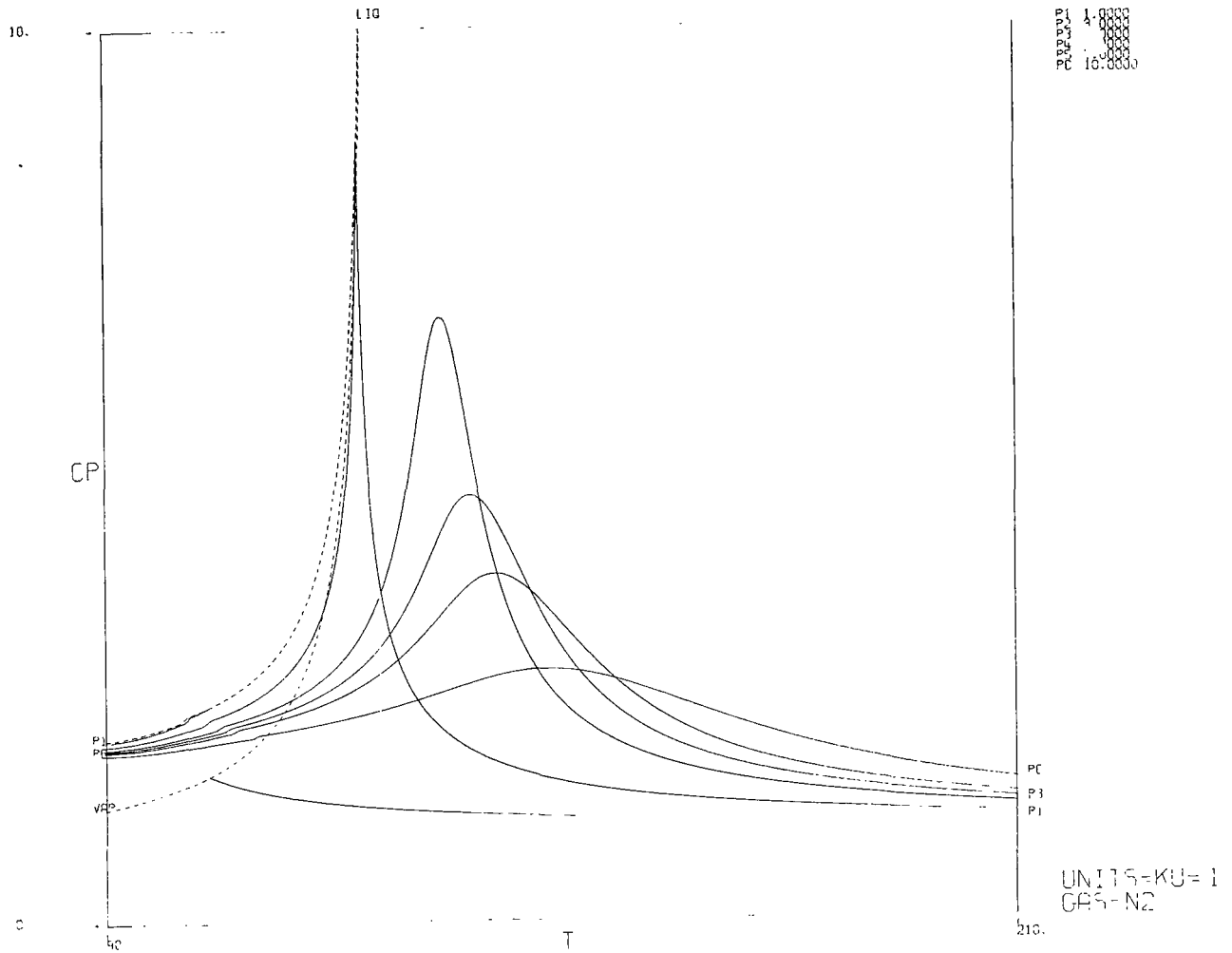


Figure 5. - Temperature T against specific heat at constant pressure C_p for fluid nitrogen.

Problem 5 - Pressure against Volume ($V \equiv (1/D)$)

The NAMELIST input for problem 5 is as follows:

```

$DATA KU =1, GAS=2HAR, XAXIS=1HP, YAXIS=1HD,
RECIP=. TRUE. , YTOP=3H10, YBOTTOM=2H0. ,
XLEFT=2H0. , XRIGHT=3H20. ,
DEGREE=125. , 160. , 200. , 300. , 500. $

```

where `RECIP=. TRUE.` plots the reciprocal of the y-axis. See figure 6 for plot produced.

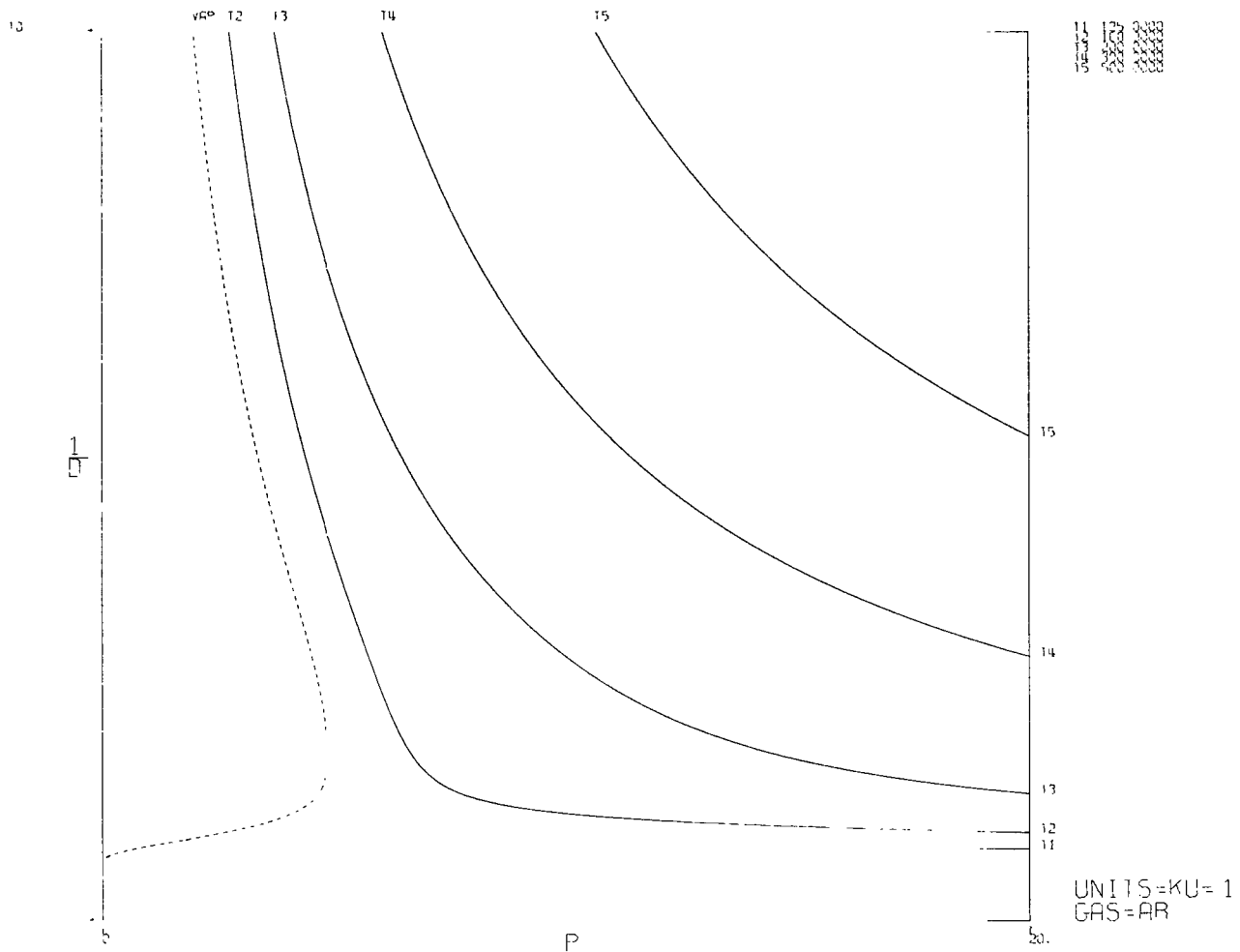


Figure 6. - Pressure P against volume $(V = 1/D)$ for fluid argon.

Problem 6 - Temperature against Conductivity

The NAMELIST input for problem 6 is as follows:

```

$DATA KU=1, GAS=3HCO2, XAXIS=1HT, YAXIS=1HK,
XLEFT=4H220., XRIGHT=4H420., YTOP=5H.0013,
YBOTOM=5H.0003,
PRES=5., 8., 10., 15., 20. $

```

See figure 7 for plot produced.

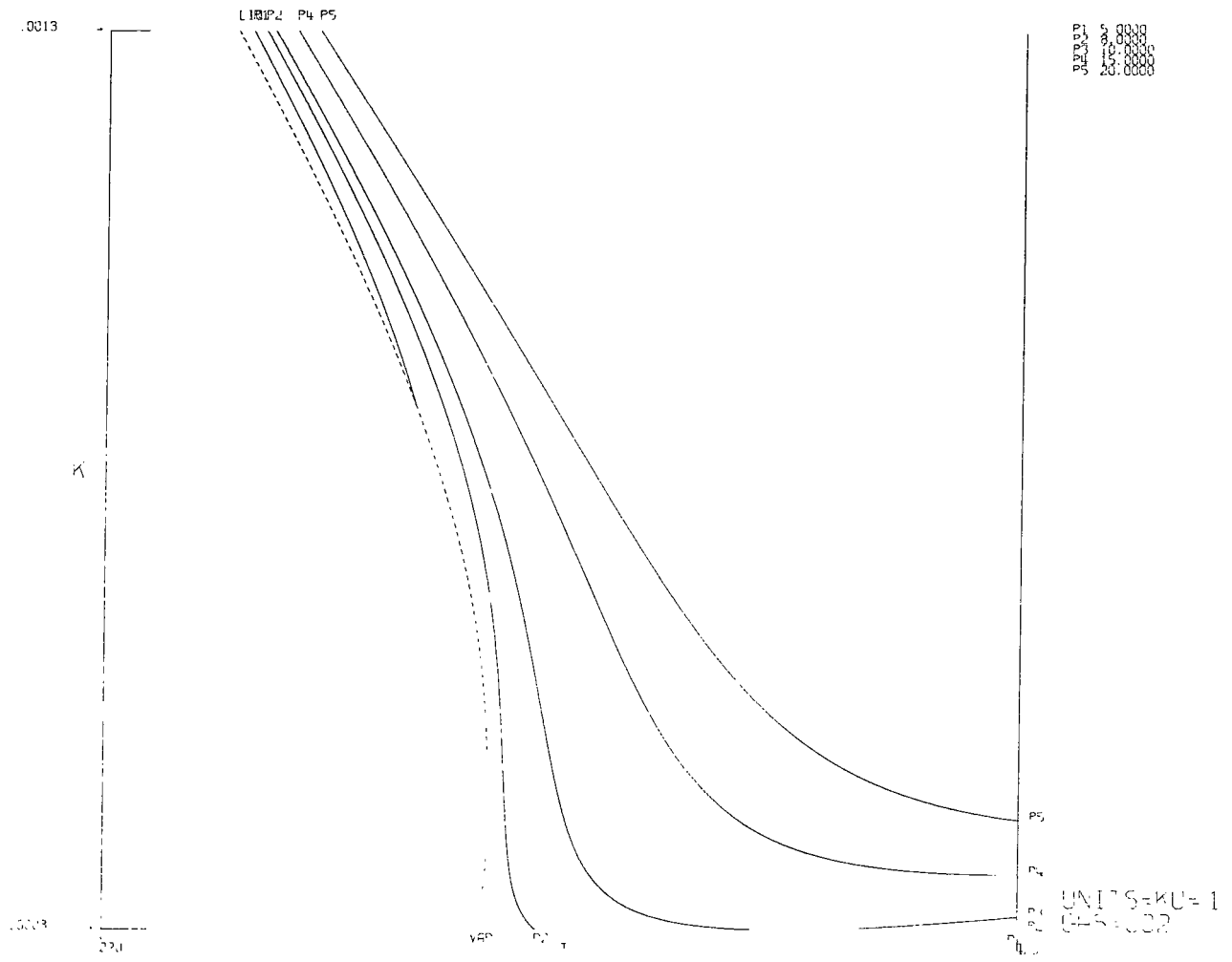


Figure 7. - Temperature T against conductivity K for fluid carbon dioxide.

Problem 7 - Enthalpy against Log of Pressure

The NAMELIST input for problem 7 is as follows:

```

$DATA KU=3, GAS=3HCH4, XAXIS=1HH, YAXIS=1HP
XLEFT=3H90., XRIGHT=4H730., YTOP=5H7000., YBOTOM=3H10.
YLOG10=. TRUE.
XWIDTH=8., YWIDTH=10.,
DEN=. 01, . 02, . 04, . 06, . 08, . 09, 1., 6., 10., 14., 20.,
DEGREE=180., 250., 343., 500., 700.,
ENTRO=1. 1, 1. 5, 1. 9, 2. 3, 2. 7, 3. 1, 3. 5$

```


where

YLOG10=. TRUE. plots log of y-axis

XWIDTH=8. length in inches of x-axis

YWIDTH=10. length in inches of y-axis

See figure 8 for plot produced.

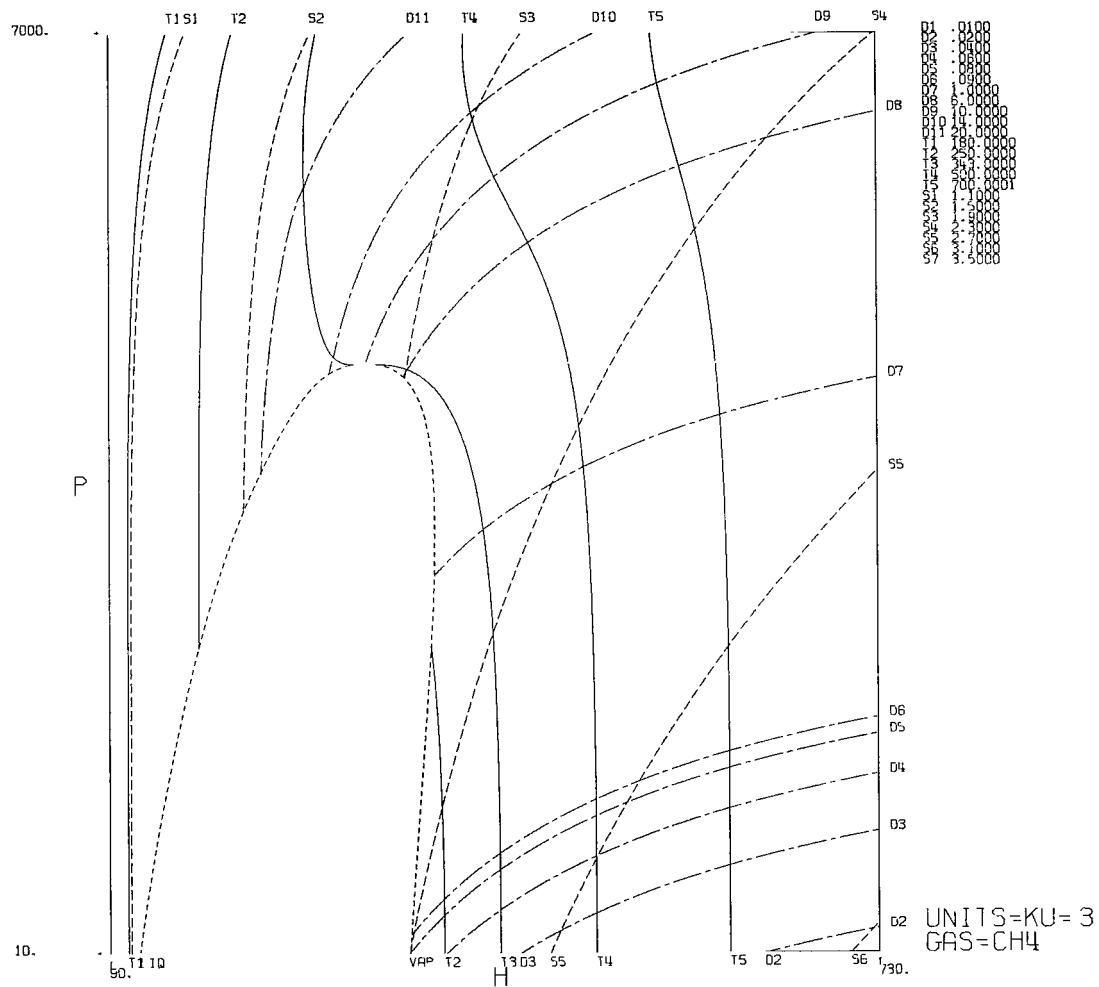


Figure 8. - Enthalpy S against log of pressure P for fluid methane.

DESCRIPTION OF THE PROGRAM

SELECTED DESIGN FEATURES

Algorithm Used to Generate Data

The geometric array, called GEOM in the program, has 86 storage locations that contain numbers from 0 to 1. The numbers are generated in such a way that successive differences between them form a geometric progression. Equation (8) is used by the program to generate these numbers:

$$\text{GEOM}(K) = \frac{r^{K-1} - 1}{r^{n-1} - 1} \quad K = 1, 2, 3, \dots, n = 86 \quad (8)$$

where

K K^{th} term

n total number of terms

r ratio

The purpose of this algorithm can best be illustrated by considering that on a temperature-entropy chart the critical-pressure line will show that, near the critical region, entropy will change rapidly with a small change in temperature. Therefore, to accurately draw this portion of the line on a temperature-entropy chart, many (T, S) points will have to be generated in this area, especially where the sudden change in slope occurs. Now, the GEOM array has the feature of providing the program with the means of doing this.

The method of generating these points using the GEOM array is as follows: Temperature limits for the segment of the curve in this area are established, and the difference is computed.

$$\text{Critical temperature} = \text{TCRIT} = \text{Lower limit}$$

$$\text{TCRIT} + .5 * (\text{TCRIT}) = \text{TSUPER} = \text{Upper limit}$$

$$\text{DELTA} = \text{TCRIT} - \text{TSUPER}$$

Then the following equation is used to generate temperature values for the TS array:

$$T(K) = TSUPER + (DELTA*GEOM(K)) \quad K = 1, 2, \dots, 86$$

A call to GASP is then made with each T, along with the critical-pressure value, and the TS array is formed. By using subroutine CREATE, parameter values are established for the array that the logical function CURVE uses to draw the curved line.

Saturation Data (The "A" Array)

For purposes of explanation the double-subscripted "A" array will be thought of as a matrix with 32 rows and 87 columns. The elements of row 31 are temperature values that are generated by the program (in subroutine ARRAY). They are ordered from the critical temperature, which is stored in A(31, 1), to the lower temperature limit of the fluid, which is stored in A(31, 87). (The spacing of the temperatures in the A array are such that for drawing purposes very little error, if any, is introduced in the plotted curves.) For a given temperature, say the Jth, all the desired saturation properties are computed and stored in the appropriate A(I, J) element of the Jth column. For each property, separate rows are allotted for liquid and vapor values; row 32 is reserved for the pressure; and row 1 contains stored symbols that the program uses to label the plot drawn. See table X.

The Critical Region

For purposes of definition the critical region of a temperature-entropy chart is the area bounded by the temperature limits TCRITH and TCRITL. These limits are calculated by subroutine GETGAS for each gas by using the following equations:

$$TCRITL = STT$$

$$TCRITH = TCRIT + (TCRIT - STT)$$

where

TCRIT critical temperature of gas

STT constant equal to temperature that is slightly below critical temperature of gas

See table VI.

Data in this region, especially near the critical point, are not conducive for plotting

purposes. The reason is that, if these data are used, distortions will appear on the graph for lines of constant parameter and the saturation locus. Consequently, this could be misleading and could lead to erroneous conclusions when reading a plot. The results of avoiding data in this area can readily be seen in the figures illustrating the output of GASPLOT.

DESCRIPTION OF SUBROUTINES

Subroutine That Computes and Processes Data in the Liquid and Vapor Regions

This subroutine, called **PLINE**, generates and processes all data in the liquid and vapor regions. Every constant-parameter routine calls subroutine **PLINE** for the purpose of obtaining data that will be used to describe a segment of an isoparametric line. Also, through its other entry, **PLINE2**, this subroutine accepts data for processing that have been generated by other subroutines, namely, the saturation and two-phase-region data.

When this subroutine is called to compute data, **ENTRY PLINE** examines its arguments and the common block **/OPTION/**. Information obtained here instructs **PLINE** on what property values or data points are needed and in what range of temperature or pressure to compute these data. Specifically, the purposes and/or definitions of the arguments and quantities in the common block **/OPTION/** are explained in table VII.

After all the data have been computed and stored in the proper array, or when **ENTRY PLINE2** is used, the subroutine goes through the following procedure to prepare the data for the logical function **CURVE**, which draws the line segment on the Calcomp plotter: First, it examines the logical switches **RECIP**, **XLOG10**, and **YLOG10** to see if they have been set to **TRUE**. In the event that **RECIP** is set to **TRUE**, the data for the y-axis are inverted. If the **XLOG10** switch equals **TRUE**, the log of the data for the x-axis is computed. And if the **YLOG10** switch is set to **TRUE**, the \log_{10} of the data for the y-axis is computed. Secondly, it calls subroutine **CREATE** through **ENTRY CREAT**. This subroutine creates parameter values for each (x, y) data point, where parameter values are equal to the lengths along the straight-line segments through the given data points. Finally, it calls the logical function **CURVE**, which uses the data points and associated parameter values to draw the line.

Another function that **PLINE** performs, but only if the **LABEL** switch is set equal to **TRUE**, is that of saving the symbol assigned to the constant parameter and also the coordinates of the point or points, if any, of intersection that the isoparametric line made with the plot boundaries. These values are saved in arrays located in the common block **/SIGN/**, which subroutine **MARK** uses when labeling a chart.

Subroutines That Compute Data in the Two-Phase Region

The subprogram `GASP` does not compute values in the two-phase region but does provide values on the saturation loci. At present, `GASPLOT` requires data in this area when a temperature-entropy chart is requested. If subroutine `CHART` determines that a T-S chart is to be drawn, the `TSPLOT` switch is set equal to `TRUE`; and the following subroutines are then made available for use:

- (1) Subroutine `quality` (for constant-quality lines)
- (2) Subroutine `INDOME` (for constant-density lines)
- (3) Subroutine `INH` (for constant-enthalpy lines)

Each of these subroutines makes use of the `A` array, which contains the saturation temperatures and the property values associated with them. The equations used by each subroutine to generate points for the `TS` array follow:

Subroutine `QUALITY`:

$$T = A(31, I) \quad I = 1, 2, 3, \dots, 87$$

$$S = S_L + X(S_V - S_L)$$

- `T` saturated temperature taken from `A` array in element `A(31, I)`, see table X
`S` entropy value in two-phase region for temperature `T` and quality number `X`
`SL` saturated-liquid entropy for temperature `T`
`X` given quality number
`SV` saturated-vapor entropy for temperature `T`

Subroutine `INDOME`:

$$T = A(31, I) \quad I = 1, 2, 3, \dots, 87$$

$$X = \frac{(D_L - D)D_V}{(D_L - D_V)D}$$

where

$$S = S_L + X(S_V - S_L)$$

- D_L saturated-liquid density for temperature T
 D_V saturated-vapor density for temperature T
 D constant-density parameter
 X computed quality number for temperature T and constant-density parameter D ,
 where D is less than D_L and greater than D_V
 S entropy value in the two-phase region for temperature T and constant-density
 parameter D

Subroutine INH:

$$T = A(31, I) \quad I = 1, 2, 3, \dots, 87$$

$$X = \frac{H - H_L}{H_V - H_L}$$

$$S = S_L + X(S_V - S_L)$$

where

- H_L saturated-liquid enthalpy for temperature T
 H_V saturated-vapor enthalpy for temperature T
 H constant-enthalpy parameter
 X computed quality number for temperature T and constant-enthalpy parameter H ,
 where H is less than H_V or greater than H_L
 S entropy value in the two-phase region for temperature T and constant-enthalpy
 parameter H

Constant-Parameter Subroutine

The purpose of a constant-parameter subroutine is to properly segment the drawing of an isoparametric line. There are two reasons why these lines are drawn in segments

- (1) To allow for discontinuities that might occur if a line intersects the saturation curve
- (2) To provide enough data to accurately represent a line, especially where there is a sudden change in slope

A description of each constant-parameter subroutine follows. Note that the limits of the

plot requested are completely ignored by each subroutine when data points are requested for each line segment. This can be done because the logical function CURVE has been designed so as to draw only that portion of the line that is within the plot limits. This feature of CURVE enables the construction of the constant-parameter subroutines to be simple and rather straightforward.

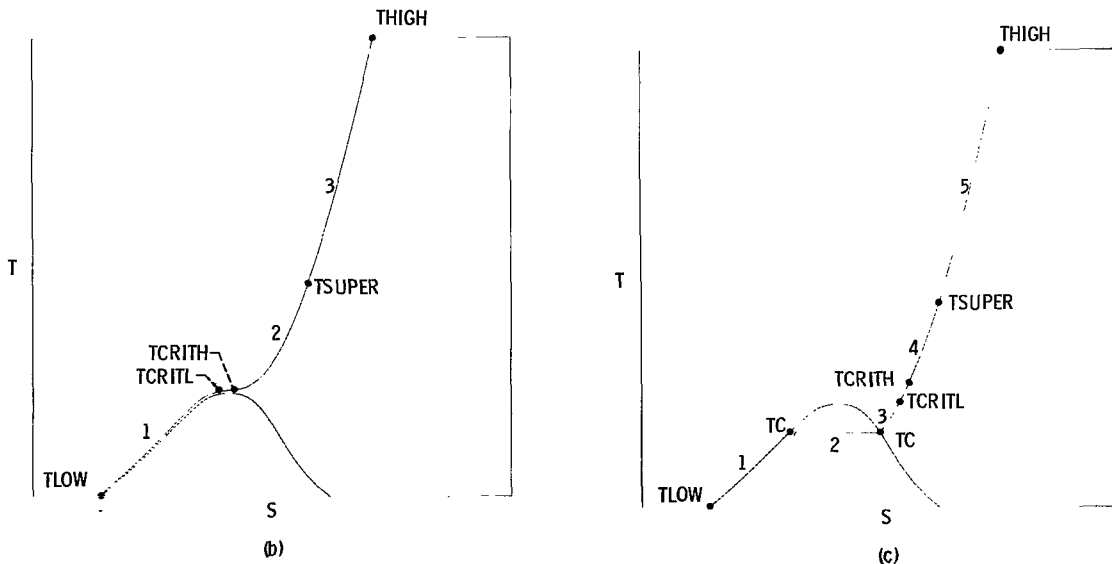
Subroutine CONSTP (constant pressure). - The number of line segments needed for a constant-pressure line depends on the pressure parameter being processed. If the value is greater than or equal to the critical pressure of the gas, there will be three line segments. If, on the other hand, it is less than the critical pressure, there will be five line segments.

When only three line segments are needed for a parameter line, the value of the pressure parameter is not associated with a saturation temperature (sketch b). Consequently, this line when drawn will not intersect the saturation curve. Temperature limits are assigned to each segment, and a call to PLINE is made. PLINE will then generate the proper data points within these limits in order to represent this line for the plot requested. PLINE then calls CURVE, which in turn will draw the line.

The temperature limits for these three line segments are

- (1) TLOW to TCRITL - the lower temperature limit in GASP for the gas to a temperature slightly below the critical temperature
- (2) TCRITH to TSUPER - temperature value slightly above the critical temperature to a value 1.5 times the critical temperature
- (3) TSUPER to THIGH, where THIGH is the upper temperature limit in GASP for the gas

When five line segments are needed for a constant-pressure line, the value of the parameter is associated with the saturation temperature (sketch c). Therefore, when this pa-



parameter line is drawn, it will intersect on both the liquid and vapor sides of the saturation curve. To find these points of intersection for the particular plot requested, CONSTP calls subroutine PSATX. One of the line segments then is a straight line drawn through the two-phase region connecting these points. The other four line segments have the temperature limits

- (1) TC to TLOW, where TC is the saturation temperature associated with the pressure parameter, which produces a line segment in the liquid region
- (2) TC to TCRITL, which produces a line segment in the vapor region
- (3) TCRITH to TSUPER
- (4) TSUPER to THIGH

Subroutine CONSTD (constant density). - The number of line segments needed to draw a constant-density line is three. If a temperature-entropy plot is being drawn, four line segments are needed, where one of the line segments is in the two-phase region (sketch d). This, however, will only occur when the density parameter is associated with a saturation temperature. In the event that it is, subroutine INDOME will compute the data points that represent this line.

The data points representing the other line segments are generated by assigning temperature limits to each desired segment and calling subroutine PLINE. In particular, the following temperature limits for the three other line segments are

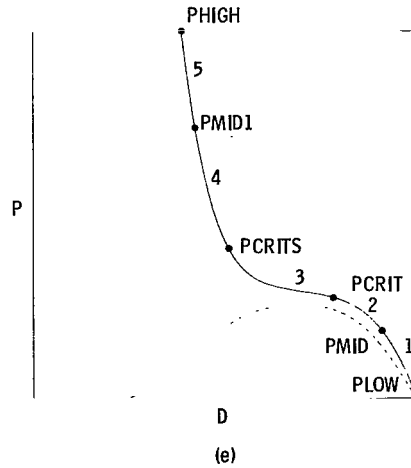
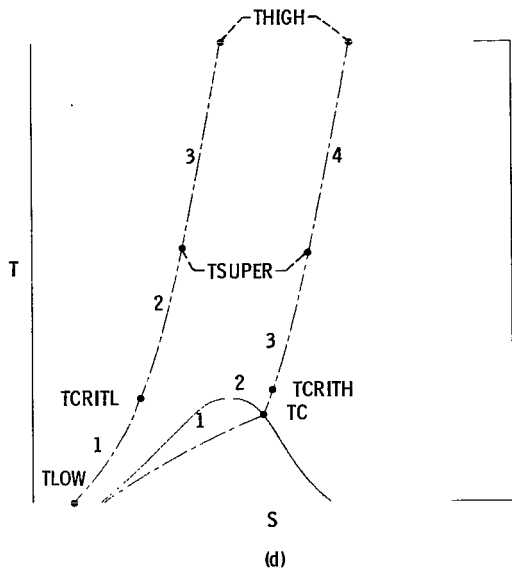
- (1) TCRIT to TLOW or TCRIT to TC, where TC is the saturation temperature associated with the density parameter. TCRIT to TC is used when the density parameter is associated with a saturation temperature
- (2) TCRIT to TSUPER
- (3) TSUPER to THIGH

This subroutine calls HSATX to find values on the saturation curve.

Subroutine CONSTT (constant temperature). - The number of line segments needed for a constant-temperature line depends on whether the temperature parameter being processed is greater than the critical temperature of the fluid. If the parameter value is greater than the critical temperature, five line segments are needed. If, on the other hand, the parameter value is less than the critical temperature, there will be four line segments.

Each line segment is assigned pressure limits, and a call to PLINE is made to generate the data points for the line. The logical function CURVE then uses these points to draw the line. The pressure limits assigned to the line segments for temperatures greater than critical (sketch e) are

- (1) PMID to PLOW
- (2) PCRIT to PMID
- (3) PCRIT to PCRITS
- (4) PCRITS to PMID1
- (5) PMID1 to PHIGH

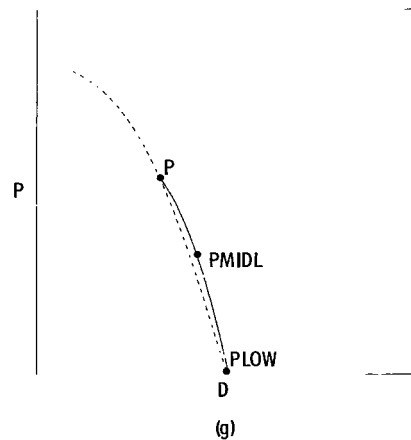
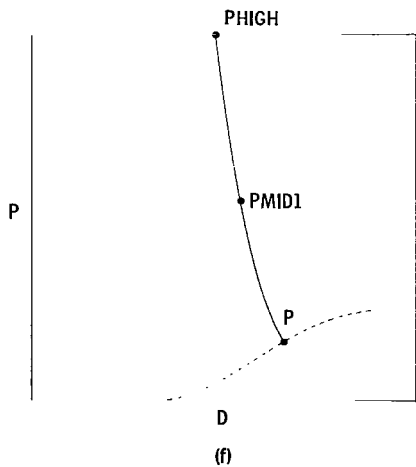


The pressure limits for temperatures less than critical are

- (1) P to PMID1 } In the liquid region (sketch f)
- (2) PMID1 to PHIGH }
- (3) P to PMIDL } In the vapor region (sketch g)
- (4) PMIDL to PLOW }

where

PLOW lower limit of pressure in GASP for gas
 PCRIT critical pressure of gas



PMID $0.5 \times \text{PCRIT}$
 PMIDL $(P + \text{PLOW}) \times 0.5$
 PHIGH upper limit of pressure in GASP for gas
 PMID1 $0.5 \times \text{PHIGH}$
 PCRITS $\text{PCRIT} + \text{PMID}$
 p saturation pressure associated with temperature parameter

This subroutine calls TSATX to find values on the saturation curve.

Subroutine CONSTH (constant enthalpy). - The number of line segments needed for a constant-enthalpy line depends on the value of the enthalpy parameter being processed. If the value is less than the critical enthalpy, called HCRIT in the program, two line segments are needed. If the value is greater than HCRIT and is associated with one saturation temperature, three line segments are needed. If, on the other hand, the value is associated with two saturation temperatures, four line segments are used. Finally, if the value is greater than HCRIT and is not associated with a saturation temperature, five line segments are used for the constant-enthalpy line. When a temperature-entropy chart is being drawn, one additional line segment is needed for the two-phase region, for only those parameters associated with a saturation temperature. The data points representing this line are computed in subroutine INH.

Pressure limits are assigned to each line segment by this subroutine, and a call to PLINE is made so that the proper data points can be generated. This subroutine then calls the logical function CURVE so that this line can be drawn.

The following are the pressure limits assigned (sketch h):

For two line segments:

- (1) P to PMID1
- (2) PMID1 to PHIGH

For three line segments:

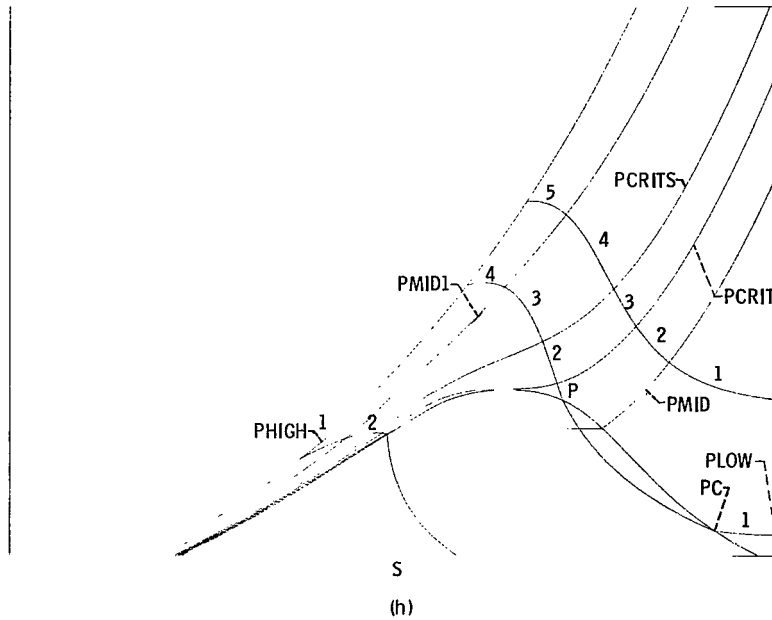
- (1) PC to PCRITS
- (2) PCRITS to PMID1
- (3) PMID1 to PHIGH

For four line segments:

- (1) P to PCRITS
- (2) PCRITS to PMID1
- (3) PMID1 to PHIGH
- (4) PC to PLOW

For five line segments:

- (1) PLOW to PMID
- (2) PCRIT to PMID



- (3) PCRIT to PCRITS
- (4) PCRITS to PMID1
- (5) PMID1 to PHIGH

where P is the saturation pressure associated with the enthalpy parameter. This subroutine calls HSATX to find values on the saturation curve.

Subroutine CONSTS (constant entropy). - The number of line segments used for a constant-entropy line is three (sketch i). However, where in the high-pressure and high-density region the value of the entropy parameter is small, one line segment is used.

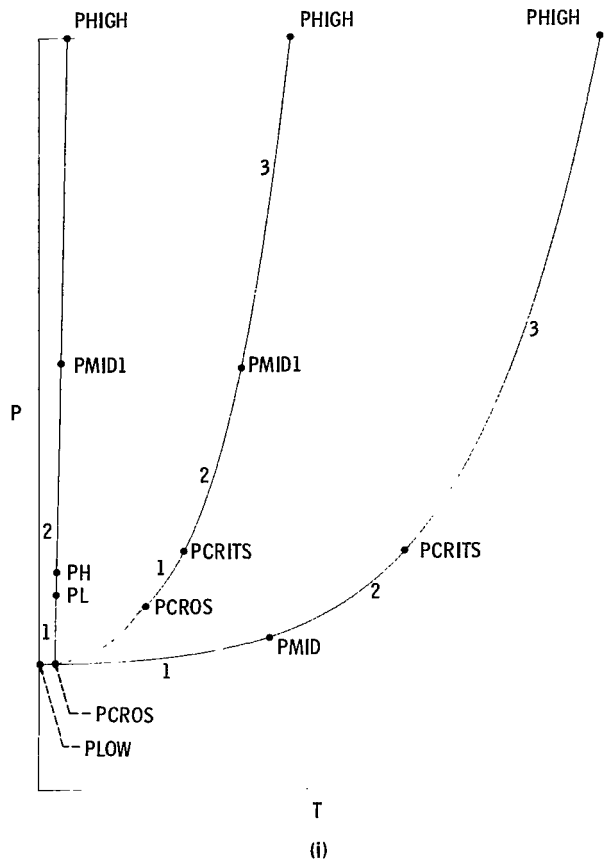
This subroutine assigns pressure limits to each line segment depending, of course, on the value of the entropy parameter being processed. If the entropy is greater than the critical entropy of the gas (called SCRIT in the program) and is not associated with a saturation pressure, the pressure limits for the three line segments are

- (1) PLOW to PMID
- (2) PMID to PCRITS
- (3) PCRITS to PHIGH

If the value of the entropy parameter is greater than SCRIT and is associated with a saturation pressure, the pressure limits for the three line segments are

- (1) PCROS to PCRITS
- (2) PCRITS to PMID1
- (3) PMID1 to PHIGH

where PCROS is the saturation pressure associated with this entropy value.



If the entropy value is less than SCRIT and is associated with a saturation pressure, the limits for the three line segments are

- (1) PCROS to PL
- (2) PH to PMID1
- (3) PMID1 to PHIGH

where PCROS is the saturation pressure associated with this entropy value and PL and PH are pressure values slightly below and above the critical pressure. In the event that the entropy value is not associated with a saturation pressure, the limits are the same as the preceding ones except that PCROS is the pressure associated with the entropy value at TLOW. If PCROS is greater than PCRIT, only one line segment is needed and the limits are PHIGH to PCROS.

All Other Subroutines

Main program. - The main program reads all input using the NAMELIST input called /DATA/. It then regulates the flow of the program.

Subroutine BOUND. - This subroutine calculates the plot boundaries, in inches, that are needed by the logical function CURVE that draws the lines for the plot. In addition, it calculates values that are needed by the function statements TIN(X) and TIN(Y), which convert values obtained from the thermophysical properties package to inches.

Subroutine CHART. - This subroutine determines the type of chart requested. If it fails to recognize the symbols used for the x and y axes, it sets the logical switch WRONG to TRUE, writes an error message, and returns control to the main program. If, however, it accepts the symbols, the numbers NFI and NFD, obtained from a data table, are assigned to the x and y axes, respectively. These numbers act as "pointers" to the program so that it knows what values to use after a call to the thermophysical properties package.

Subroutine ARRAY. - This subroutine calls the thermophysical properties routine, in this case GASP, with the options KS = 1, KP = 63, and KR = 1. By starting at a temperature near the critical and decrementing by using the GEOM array to the lower bound in GASP, the values for D, S, H, CV, CP, GAMMA, C, MU, K, EXCESK, SIGMA, and P on the saturation curve are obtained and stored in the A matrix.

Subroutine DOME. - This subroutine obtains from the A matrix the proper (x, y) points on the saturation curve, for the chart requested. The values are stored in the TS(2, 87) array, and PLINE2 is called.

Subroutine GETGAS. - This subroutine checks to see if the gas requested is part of the thermophysical properties package. If it is not, the logical switch WRONG is set equal to TRUE, and control is sent back to the main program. If it is available, the logical switch is set equal to FALSE, and GETGAS then proceeds to obtain certain property values from the package and to store them in the common block /SAME/. (For a description of these property values and other variables and/or constants in the common block, see table IX.) GETGAS also stores the critical values temperature, pressure, density, enthalpy, and entropy in the appropriate places in the A array (see table X). Finally, GETGAS calls subroutine ARRAY, which in turn will fill the A matrix with the rest of the saturation properties.

Subroutine VECTER with ENTRY VECTD, ENTRY VECTH, and ENTRY VECTS. - This subroutine is called by the constant-parameter subroutines. The arrays D1(2, 87) to D8(2, 87) are formed with values from the A array and placed in blank common. These arrays are needed by the constant-parameter subroutines to determine if the constant parameter being considered intersects the saturation locus. For example, suppose a chart was requested for density D against conductivity K with constant-pressure lines. Subroutine CONSTP would call VECTER, and the following arrays would be stored in blank common:

D1(2, 87) T against P

where $D1(1, 1) = T1$ and $D1(2, 1) = P1$, and $D1(1, 2) = T2$ and $D1(2, 2) = P2$, and so forth

$D2(2, 87)$ T against D_L

$D3(2, 87)$ T against D_V

$D4(2, 87)$ T against K_L

$D5(2, 87)$ T against K_V

Subroutines PSATX, TSATX, SATX with ENTRY SATX1, and HSATX with ENTRY HSATX1. - These subroutines determine the point or points of intersection on the saturation locus by the constant-parameter line being considered. They make use of the arrays stored in blank common by subroutine VECTER and use subroutines from the interpolation package.

Subroutine CREATE with ENTRY CREAT. - This subroutine generates parameter values for each data point in the TS array, where parameter values are equal to the lengths along the straight-line segments through the given data points.

Subroutine MARK with ENTRY MARK1, ENTRY BORD, and ENTRY BORDF. - This subroutine draws the border and labels the chart. It writes the amount of gas used and the KU number. It lists all of the parameters read in together with the symbols assigned and marks every parameter line that intersects an axis, provided it is 0.3175 centimeter (0.125 in.) away from the last symbol marked.

Logical function CURVE. - This subroutine draws a curved line through the given (x, y) points using the Calcomp plotter. It eliminates those parts of a line outside the plot boundaries and saves all parameter crossings of those axes in the P array.

Subroutines PLOT, NUMBER, and SYMBOL. - These subroutines are from the Calcomp software package.

LABELING

An important consideration of graphical output is labeling. A plot or graph without proper identification could prove to be useless. Therefore, the GASPLOT program provides essential alphabetic and numeric labels to every plot produced except when the LABEL switch is set equal to FALSE. Since many of the plots produced by the program are quite complex, an attempt to program a sophisticated labeling subroutine could become a monumental task; therefore, labeling is kept at a minimum. Specifically, all plots are labeled in the following manner:

(1) The x and y axes are labeled with the Hollerith code read in through the NAMELIST input.

(2) The parameter values and the symbols assigned to them by the program are printed to the right of the plot.

(3) The Hollerith code for the gas and the unit specification number (KU) are printed to the right of the plot near the coordinate (XWIDTH, 0).

(4) The values for the numerical limits of the plot (XLEFT, XRIGHT, YTOP, YBOTOM) are printed near their respective coordinates. That is, the values of XLEFT and YBOTOM are printed near the coordinate (0, 0).

(5) Symbols are printed where curves intersect the plot boundaries.

In addition to placing symbols and numbers on the plots, the program provides a means of implementing dashed lines that helps to distinguish different types of parametric curves.

The method of providing this type of labeling to the plots is rather straightforward. A call to SYMBOL or NUMBER is made, with information obtained from the input data. However, to place symbols on the graph for those curves that intersect the plot boundaries and to draw dashed lines are somewhat more complicated and are discussed in detail in the following sections.

Printing Symbols at the Plot Boundaries

The logical function CURVE draws all curves and has the ability to scissor off a line at the plot boundaries. When a line being drawn crosses one of the plot boundaries (XMIN, XMAX, YMIN, YMAX), the parameter value, which contains the (x, y) point of intersection, is stored and saved in the P array. After the line is drawn, control returns to the calling subroutine, PLINE. Tests are then made on the P array to determine at what boundaries, if any, the crossing occurred. If the crossing, for example, occurred at XMAX, the y-value is saved in the XMAXC array and the symbol assigned by the program for this curve is saved in the XMAXL array. By using the same procedure for XMIN, YMAX, and YMIN, the following arrays are formed: YMAXC, YMAXL, YMINC, XMINL, YMINC, and YMINL. A call can now be made to subroutine MARK with these arrays to print symbols at points of intersection on the plot boundaries.

To further illustrate the method, consider the following call to subroutine MARK:

```
CALL MARK(XMAXC, XMAXI, XI, ONE, IXY)
```

where

XMAXC array that contains y-values in inches for curves that intersect XMAX line

XMAXL array that contains symbol associated with particular line being drawn
X1 constant equal to 25.7175 centimeters (10.125 in.)
ONE dummy variable
IXY number that indicates number of crossings on XMAX line

Subroutine **MARK** then calls **SYMBOL** (**IXY** times), keeping the x-coordinate equal to **X1** and changing the y-coordinate each time to **XMAC(I)** (**I** = 1 to **IXY**) and the symbol to **XMAXL(I)** (**I** = 1 to **IXY**).

Drawing Dashed Lines

The logical function **CURVE** draws all lines in segments of 0.127 centimeter (0.05 in.). Each time a segment is to be drawn, the next sequential element of the **DASH** array is examined in a cyclic manner. When the value is equal to zero, the pen is placed up. And if the element is nonzero, the pen is placed down. **CURVE** expects to find the **DASH** array as one of its arguments, where the first element of the array specifies the dimension. Some examples of the use of the **DASH** array in this program follow:

- (1) **DASH(1) = 1**, a continuous line is drawn
- (2) **DASH(1) = 2**
DASH(2) = 0 } Constant-quality lines are drawn (fig. 4)
- (3) **DASH(1) = 9**
DASH(2) = 1
DASH(3) = 1
DASH(4) = 0
DASH(5) = 1
DASH(6) = 0
DASH(7) = 1
DASH(8) = 1
DASH(9) = 1 } Constant-density lines are drawn (fig. 2)

CONCLUDING REMARKS

This report describes a FORTRAN V computer graphics program, **GASPLOT**, that draws a variety of thermophysical property charts. The primary reason for the development of **GASPLOT** was to provide users with a reliable, economical, and easy-to-use method of producing thermodynamic charts and, if desired, a technique for producing

thermophysical property charts of textbook quality.

GASPLOT has proved useful in the following ways: (1) the analysis of thermophysical data and trends of thermophysical property parameters; (2) the production of high-quality, precision, thermophysical properties charts; (3) the redrawing of charts to more useful scales; and (4) the production of charts with SI units. Furthermore, GASPLOT now provides a useful tool for analysis using such quantities as the Gibbs and Helmholtz functions or the chemical potential. Charts can be readily made that will show the relationship of these functions with the state variables and will also show their dependency in cycle analysis.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, January 26, 1977,
505-01.

APPENDIX A

INTERPOLATION PACKAGE

A double, three-point Lagrangian interpolation is used by the subroutines in this package. In this method, two parabolas are fitted to the given data - one through the three points centered above the argument value, and one through the three points centered below the argument. When the argument value is not surrounded on each side by at least two table values, single three-point or lower order interpolation is used.

Equation (A1) is Lagrange's three-point interpolation formula, where x is an argument between the tabular values a_1 and a_3 .

$$f(x) = \frac{(x - a_2)(x - a_3)}{(a_1 - a_2)(a_1 - a_3)} f(a_1) + \frac{(x - a_1)(x - a_3)}{(a_2 - a_1)(a_2 - a_3)} f(a_2) + \frac{(x - a_1)(x - a_2)}{(a_3 - a_1)(a_3 - a_2)} f(a_3) \quad (\text{A1})$$

Equation (A2) is a double, three-point interpolation.

$$D(x) = \frac{a_3 - x}{a_3 - a_2} \times L(x) + \frac{x - a_2}{a_3 - a_2} \times U(x) \quad (\text{A2})$$

where

$$L(x) = f(x, a_1, a_2, a_3)$$

$$U(x) = f(x, a_2, a_3, a_4)$$

The following subroutines are contained in the interpolation package that is used by GASPLOT:

A	argument of table names
F	complex function table names
X	argument values for which interpolated values are desired
NA	length of A
FZTRP(A, F, X, NA)	provides value of a complex function
RZTRP(A, F, FO, NA, X)	logical complex function that finds X such that $\text{REAL}(\text{FZTRP}(\text{A}, \text{F}, \text{X}, \text{NA})) = \text{FO}$

IZTRP(A, F, FO, NA, X)	logical complex function that finds X such that AIMAG(FZTRP(A, F, X, NA)) = FO
TLU(A, X, NA, J)	table lookup that gives index J of element in A immediately below X
SIZE(A, I, NA)	logical function that creates a vector I, which gives order by size of A (TRUE if A is in order)
ORDER(Z, I, NA)	orders A table according to index values in vector I, which was created by the logical function SIZE

For the logical functions RZTRP and IZTRP, only solutions larger than the value of X at entry are considered, and only the smallest of these is returned. If there is no solution, the value of X is unaltered and the functions are set equal to FALSE.

APPENDIX B

SUBPROGRAM GASP

The subprogram GASP is a family of FORTRAN IV subroutines that calculates the thermophysical properties of 10 fluids: parahydrogen, helium, neon, methane, nitrogen, carbon monoxide, oxygen, fluorine, argon, and carbon dioxide. The program accepts any two of pressure, temperature, and density as input variables. In addition, pressure and either entropy or enthalpy are also accepted as input variables. The properties available as output, in any combination, include temperature, density, pressure, entropy, enthalpy, specific heats, sonic velocity, viscosity, thermal conductivity, and surface tension. Table VIII is the operations sheet for the subprogram GASP.

APPENDIX C

MODIFICATIONS TO GASPLOT

The program GASPLOT can be modified to include

- (1) Other programs that compute thermophysical properties
- (2) Other charts not built into the program

OTHER PROGRAMS THAT COMPUTE THERMOPHYSICAL PROPERTIES

Although GASPLOT is designed specifically to be used with the subprogram GASP, it can readily be modified and adopted for use with other programs that compute thermophysical properties. To link GASPLOT to a different thermophysical properties package, a subroutine called GASP, which has seven arguments (KS, KP, T, P, D, H, KR), has to be written.

When designing this subroutine, the rules governing the operation of the subprogram GASP must be known (table VIII). This means that instructions are obtained by examining the KS and KR numbers. (In GASPLOT the KP option is set to 63.) Specifically, if KR = 1, GASPLOT is requesting all the saturation values for a given temperature T; and if KR = 0, GASPLOT is requesting all property values, other than saturation, for a given set of input values indicated by the KS number. All computed property values are then stored in the appropriate places allotted to them in the common block/PROPTY/, except temperature, pressure, density, and enthalpy. They must be stored in the arguments of the subroutine.

Another subroutine that has to be created is GETGAS. The purpose of this subroutine is described on page 27. For this subroutine to be properly linked to GASPLOT the following must be done:

- (1) Make sure all values in the common block /SAME/ are obtained or computed (table IX).
- (2) Make sure the logical switch WRONG is set.
- (3) Store TCRIT, PCRIT, DCRIT, HCRIT, and SCRIT in the proper storage locations in the A array (table X).
- (4) Call subroutine ARRAY. Call ARRAY(A, TLOW, STT, GEOM, NMAX, KU, PHIGH, PLOW, PCRIT).

OTHER CHARTS NOT BUILT INTO THE PROGRAM

At present, a user of GASPLOT is restricted to any combination of 13 parameters for the x and y axes. These parameters use temperature, pressure, density, entropy, enthalpy, conductivity, excess conductivity, viscosity, specific heat at constant volume, specific heat at constant pressure, ratios of specific heats, sonic velocity, and surface tension. To produce another chart that does not include one of these parameters, the subroutines ARRAY, GETGAS, and PLINE have to be modified. For illustration, let us consider a chart of a thermodynamic function of wide application, the Helmholtz free-energy function. The equation is

$$A = H - (P/D + T * S) \quad (C1)$$

In subroutine PLINE, after the call to WASP or GASP (refs. 1 and 2), insert the FORTRAN statement that computes equation (C1) and put the results in S.

$$S = H - (P/D + T * S) \quad (C2)$$

In subroutine ARRAY, replace the saturation entropy value after the call to WASP or GASP with the FORTRAN statements

$$SL = HL - (P/DL + T * SL) \quad (C3)$$

$$SV = HV - (P/DV + T * SV) \quad (C4)$$

And finally, in subroutine GETGAS, replace the FORTRAN statement that computes as SCRIT with

$$SCRIT = HCRIT - (PCRIT/DCRIT + TCRIT * SCRIT) \quad (C5)$$

When the user now requests a chart of where the x-axis equals S and the y-axis equals T, a T-A chart will be produced. See figure 9 for a T-A chart for water.

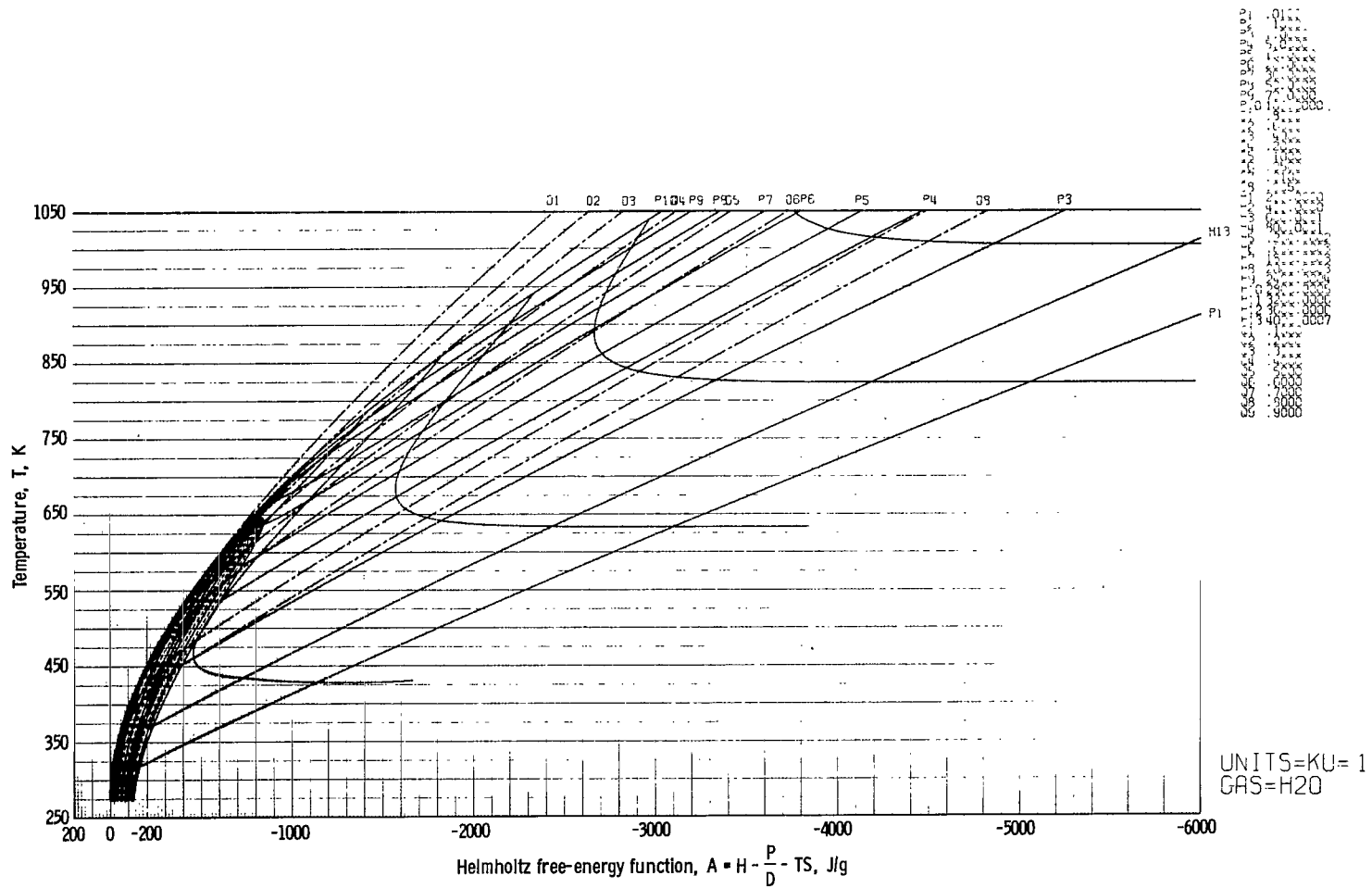


Figure 9. - T-A chart for water.

APPENDIX D

PROCEDURE FOR PRODUCING FIGURES WITH GREY-GRID BACKGROUND

Commercial graph paper is made of a series of interwoven periodic curves. The relative weight (darkness) of each line depends on the number and amplitude of the superimposed curves. By carefully selecting a filter, these grid lines can be reduced from black printing to grey printing¹, thereby forming a highly desirable grid background for presentation of scientific material in graphic form.

The procedure for producing figures with grey-grid background is as follows:

(1) A set of commercial average² graph paper is selected that comes closest to satisfying the given needs³. In many instances, it may be necessary to fabricate paper to the desired size by cutting and combining existing types of paper.

(2) Once the desired graph paper has been selected, three sheets are measured in a computer room with controlled humidity (40 percent) and temperature (70° F). The ordinates (left and right), the abscissas (top and bottom), and the diagonals are measured to within 0.013 centimeter (0.005 in.) by an HP Model 9100A desk calculator that has an extended memory and an x-y position-sensitive board with manual position scanner and crosshairs. As commercial graph paper is often not uniform or square, these measurements are quite important in determining the best paper to use for the grid background.

(3) The paper selected for the grid background is then taken to the photographic laboratory, where a negative of the grid paper is made, again in a controlled humidity-temperature environment. A type G filter, or four times normal, is placed over the graph paper, and a series of exposures are made and printed either one-to-one or at a reduction. These exposures are carefully examined with a photographic eye lens to assure the quality and spacing of the sequence of lines and dots that will characterize grey-printed grid.

(4) After the correct print has been selected, the paper is permitted to stabilize within the photographic laboratory. It is then returned to the controlled environment of the computing laboratory, where it is measured and checked for uniformity. The procedure is similar to that of step 2, except that this series of measurements establishes the XWIDTH and YWIDTH input values for GASPLOT.

¹To the eye, grey and black often reproduce or print black. Grey printing must appear as a sequence of broken lines or dots. Filtering of superimposed interwoven sine curves produce such dots and lines, which print grey.

²GASPLOT can be used to produce a series of charts with various scales such as log-log, log-semilog, or linear to aid in this selection.

³Green can be used, but it is more difficult to work with photographically.

(5) With the desired set of parameters, independent and dependent variables, the user commands GASPLOT to produce the desired Calcomp plot with no labeling.

(6) A new black ball-point pen is placed in the Calcomp writerhead, and the paper is carefully adjusted for uniform tension. The Calcomp hardware is located in nearly the same controlled environment as was the measuring equipment. It must be stressed that the Calcomp equipment (hardware and software) must be properly maintained for, otherwise, wear of the bevel gears will cause backlash and undue inaccuracies in the plot⁴. Also, the user's magnetic tape must be clean before GASPLOT is commanded to write the Calcomp instructions on it.

(7) The Calcomp plot is measured and checked against the values input as XWIDTH and YWIDTH as well as against the diagonals to assure that the plot is square and of the necessary size. Sometimes, due to hardware, software, and/or user errors, the plot will not match the grid to the necessary accuracy and therefore must be remade. Generally, a satisfactory new plot is produced by incrementing the original XWIDTH and YWIDTH by the difference between the measured and original values assigned to GAS-PLOT.

(8) The Calcomp plot is now taken to report typing where it is labeled by using directly and indirectly typed labels. In some cases, the plots may be typed on directly, but the print sometimes smudges, which comes out black on the printed copy. It may be better to use taped-in-place labeling typed on no-smear paper and light blue tick marks to indicated placement of the numbers. Sharp, clear, black letters and leaders are required for well-defined printed copy.

(9) The labeled Calcomp plot is again taken to the photographic laboratory, where a one-to-one transparency is produced. It is important to be able to position the copy accurately with respect to the camera to assure that the transparency and the original grey-grid background are the same size. A negative of the labeled plot is made and carefully opaqued to eliminate all the irregularities of the parent surface as well as of the negative itself. These irregularities will reproduce as lines, dots, etc., and it is important that the transparency be clear and that the lines of the graph, border, and labeling be black and sharp.

(10) The grey grid is carefully cut along its boundaries with a steel straightedge and surgeons scalpel on an illuminated glass light-table to assure sharp definition of the edges of the graph. The grey grid is fastened at two adjacent corners on a flat, white mat background with transparent tape.

(11) The transparency is overlaid onto the grey-grid positive, carefully matching the grid boundaries and other predetermined points. The transparency is fastened to the mat at the same two corners as the grey grid to permit any expansion (contraction)

⁴Worn gears, loose components, general excessive wear, and lack of general regular maintenance caused many problems in the earlier stages of development.

to occur in the same direction on both members. With practice, the overlay becomes straightforward.

(12) The composite figure is then placed in the object holder, and a vacuum is drawn on the plates to assure flat contact between the transparency and the grey grids.⁵ For best results, this negative should also be made at one-to-one to minimize the loss of line definition; however, these figures can be reduced to 80 percent without loss of definition and to 60 percent with little loss. The point is that the negative of the composite figure must be sharply defined and must have been produced with a minimum loss of definition. The glass print is made on Kodith type II, fast, low-gloss paper to achieve higher quality prints for reproduction. Figures 10 to 16 of this report have been produced by this procedure.

It should be noted that the Calcomp flat-bed plotter can be used to draw the figure directly on the grey-grid background, thereby eliminating the need for the composite figure. Labeling and reproduction may be accomplished directly.

⁵In some cases, a pressure-held glass plate may be sufficient.

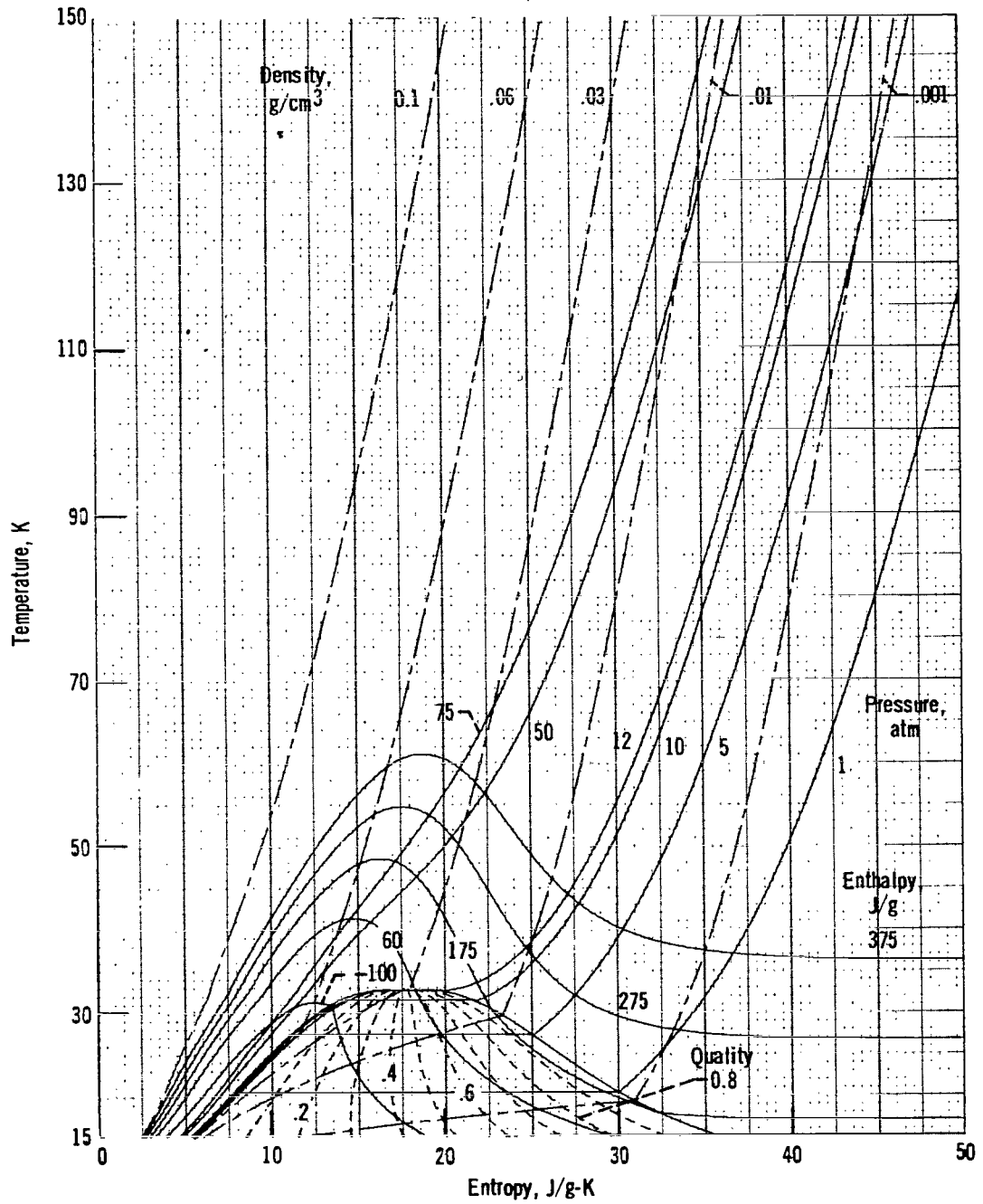


Figure 10. - Temperature against entropy with grey-grid background, for fluid hydrogen (KU = 2).

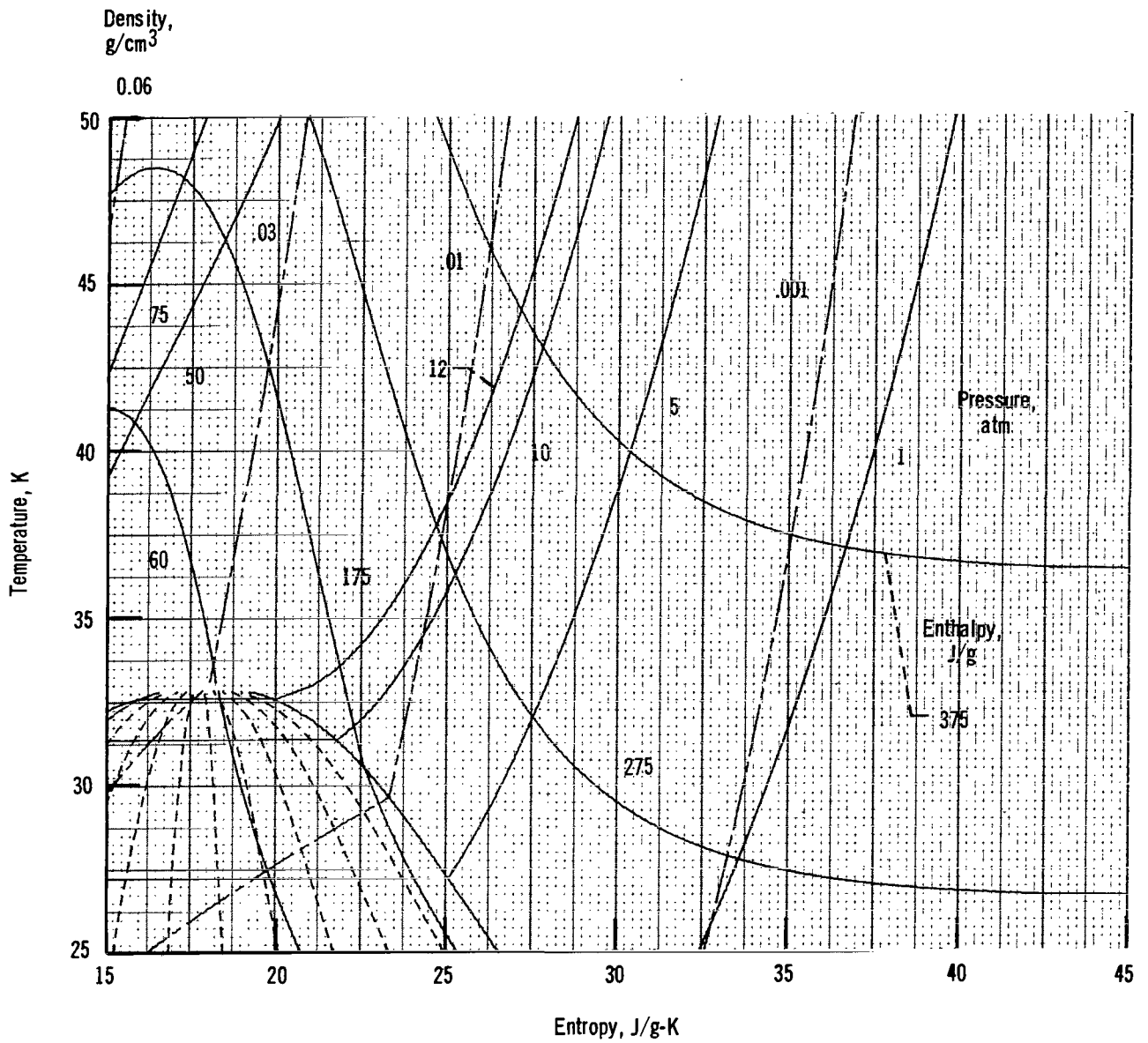


Figure 11. - Temperature against entropy (enlargement of vapor side of fig. 2) with grey-grid background, for fluid hydrogen (KU = 2).

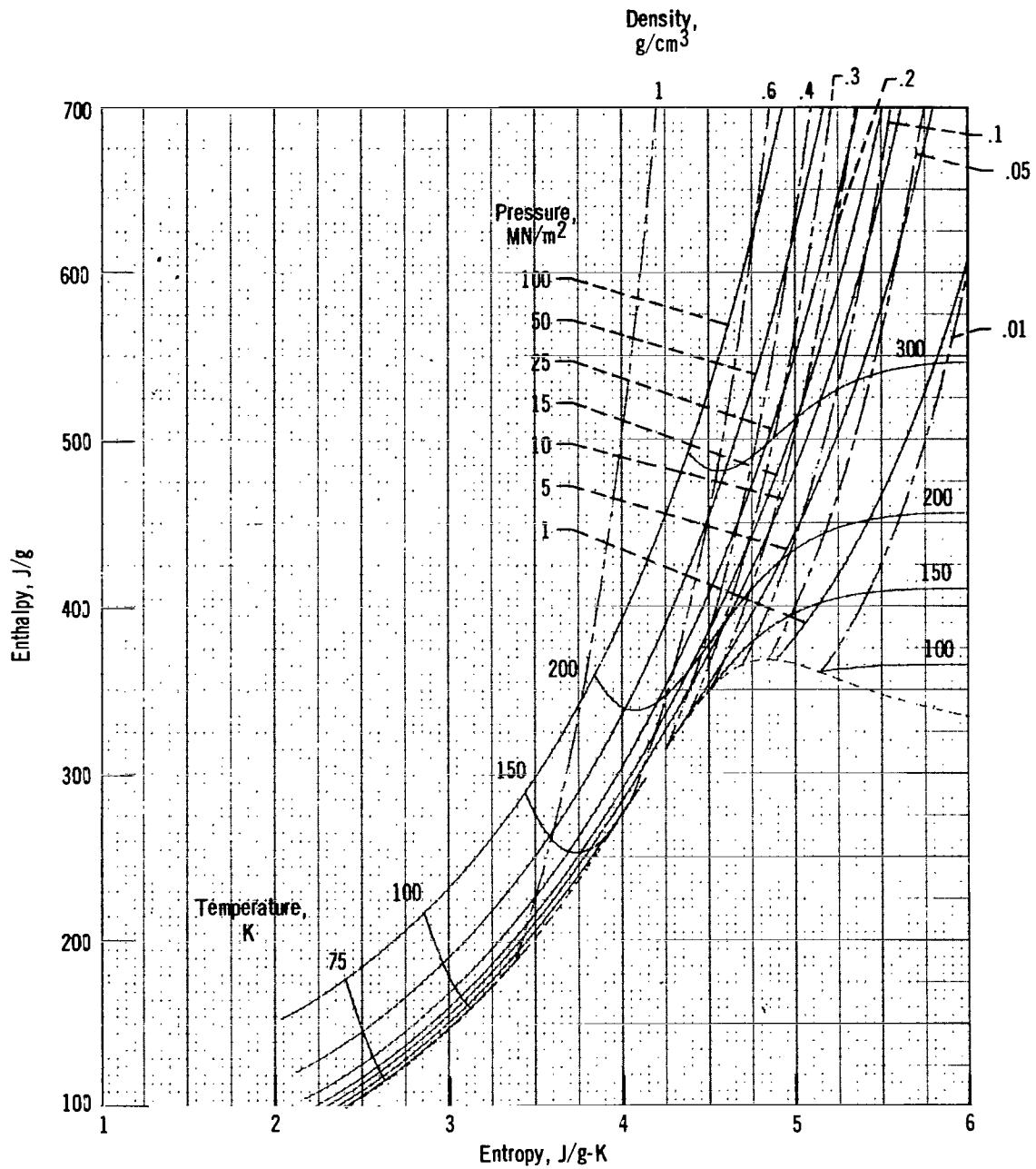


Figure 12. - Entropy against enthalpy with grey-grid background, for fluid oxygen (KU = 1).

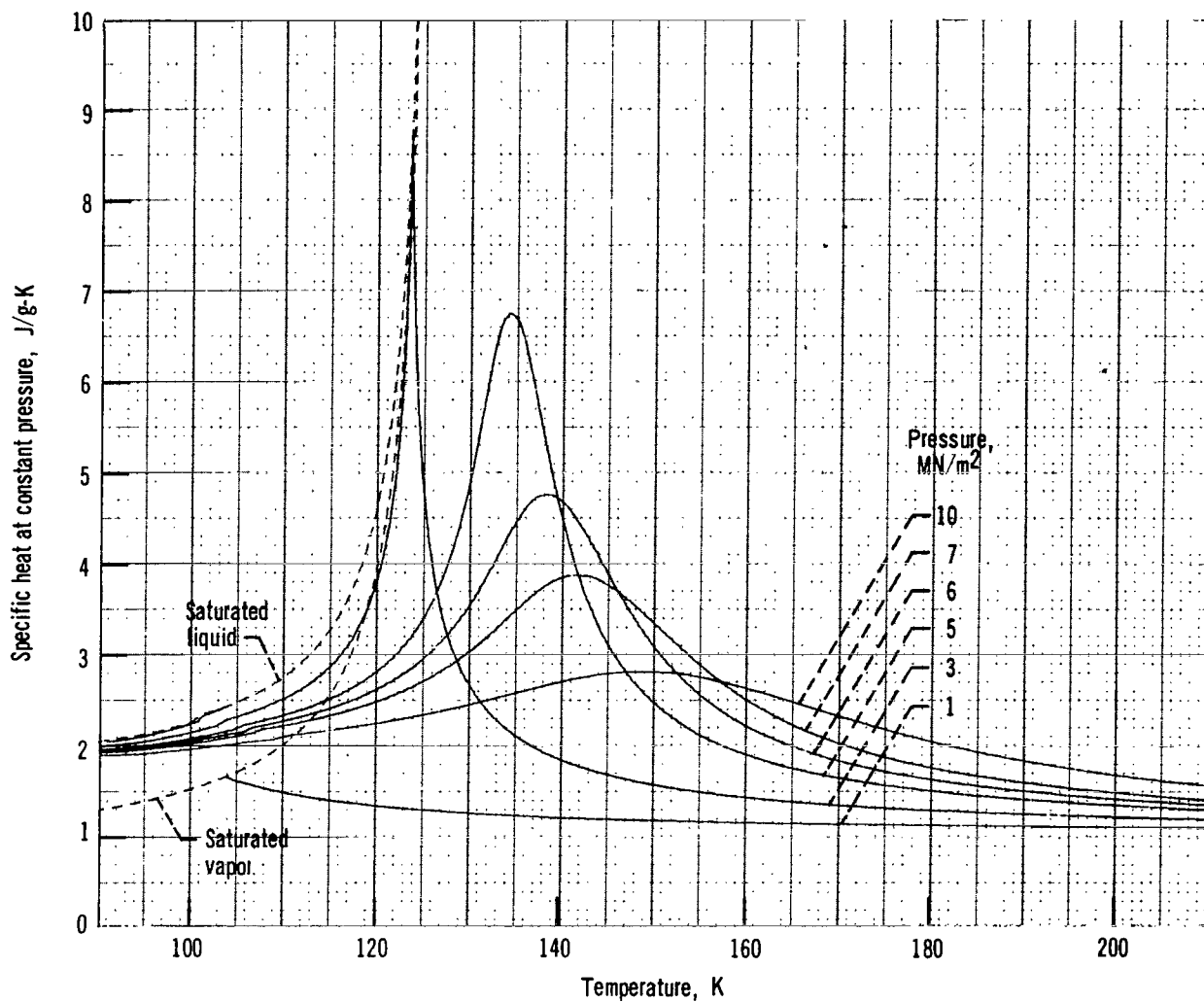


Figure 13. - Temperature against specific heat at constant pressure with grey-grid background, for fluid nitrogen (KU = 1).

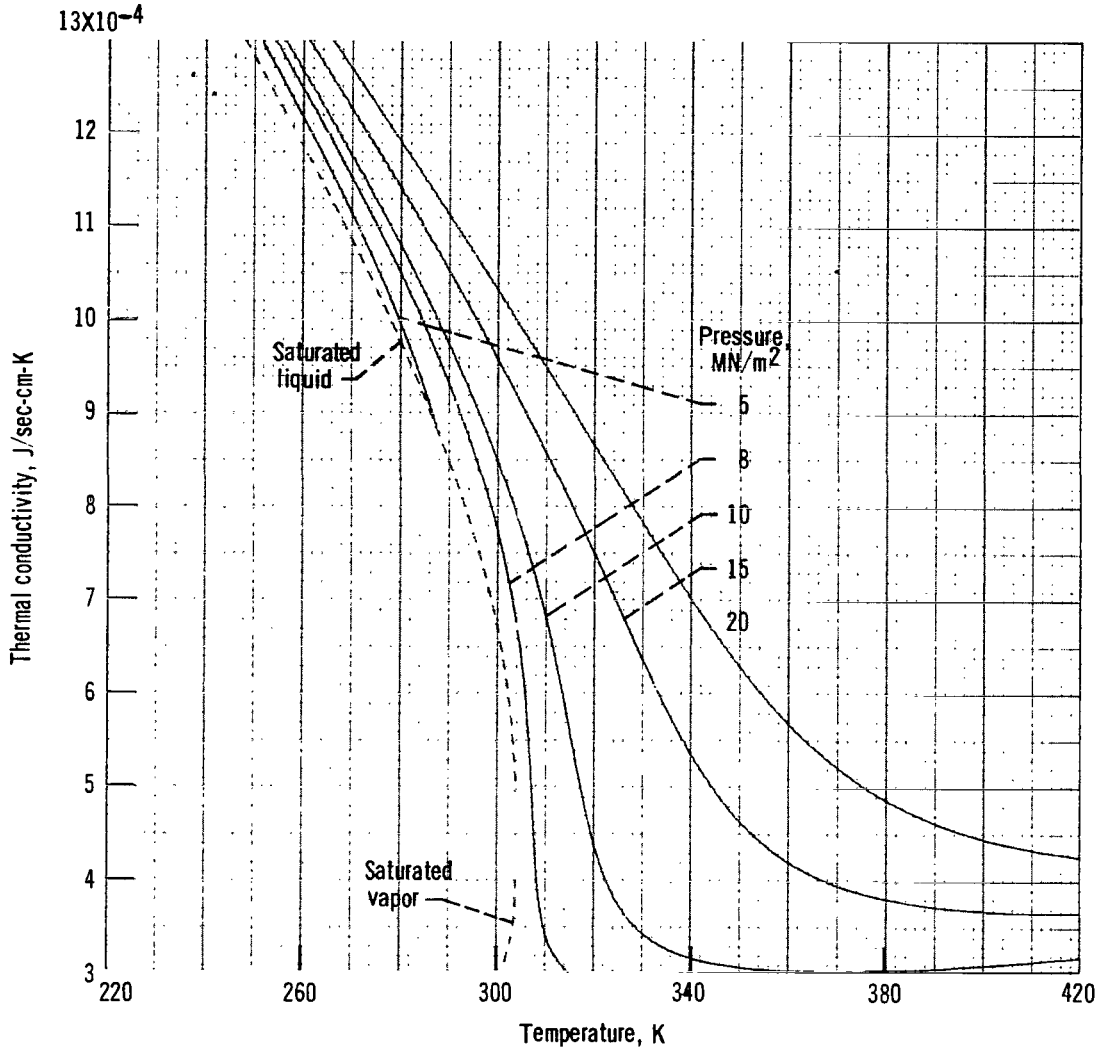


Figure 14. - Temperature against conductivity with grey-grid background, for carbon dioxide (KU=1).

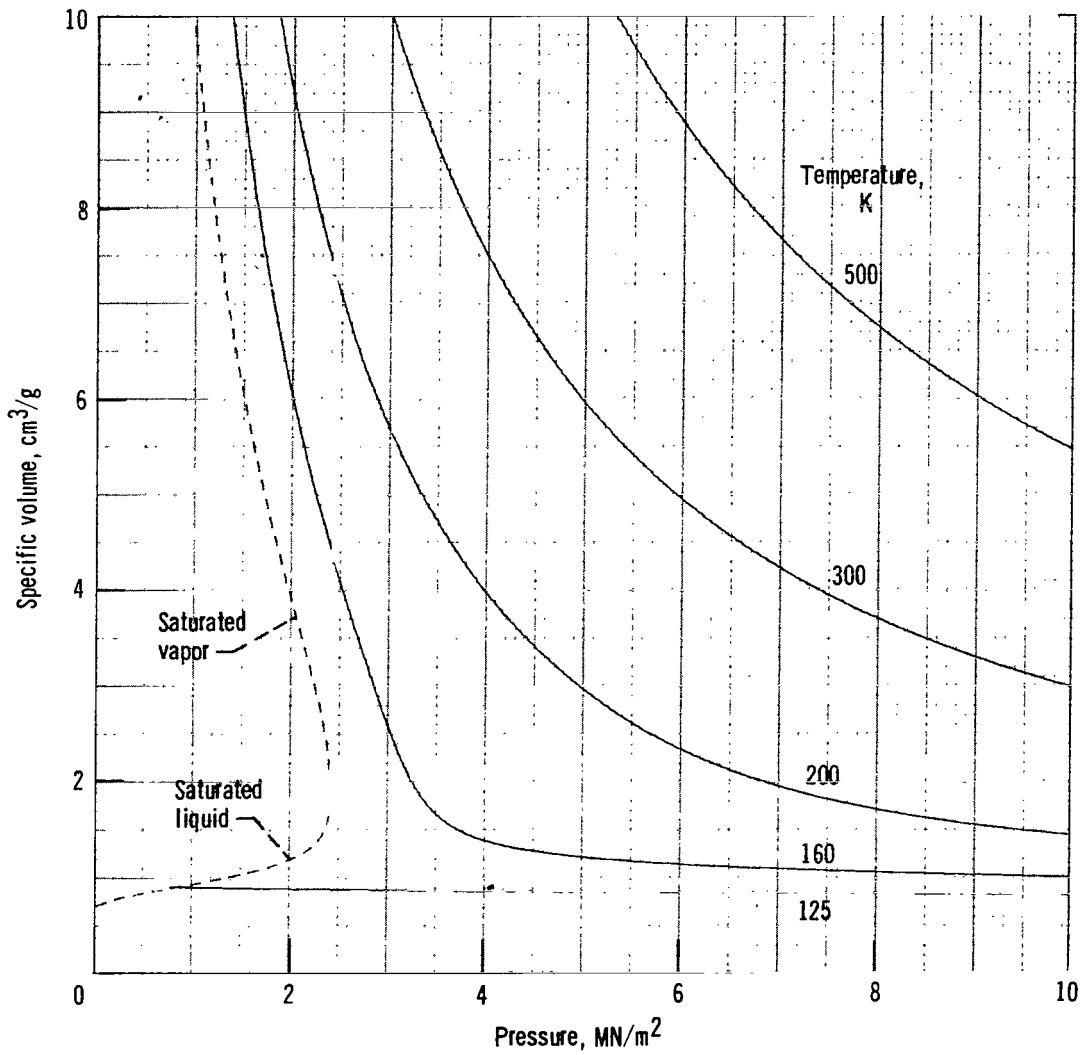


Figure 15. - Pressure against volume with grey-grid background, for fluid argon (KU = 1).

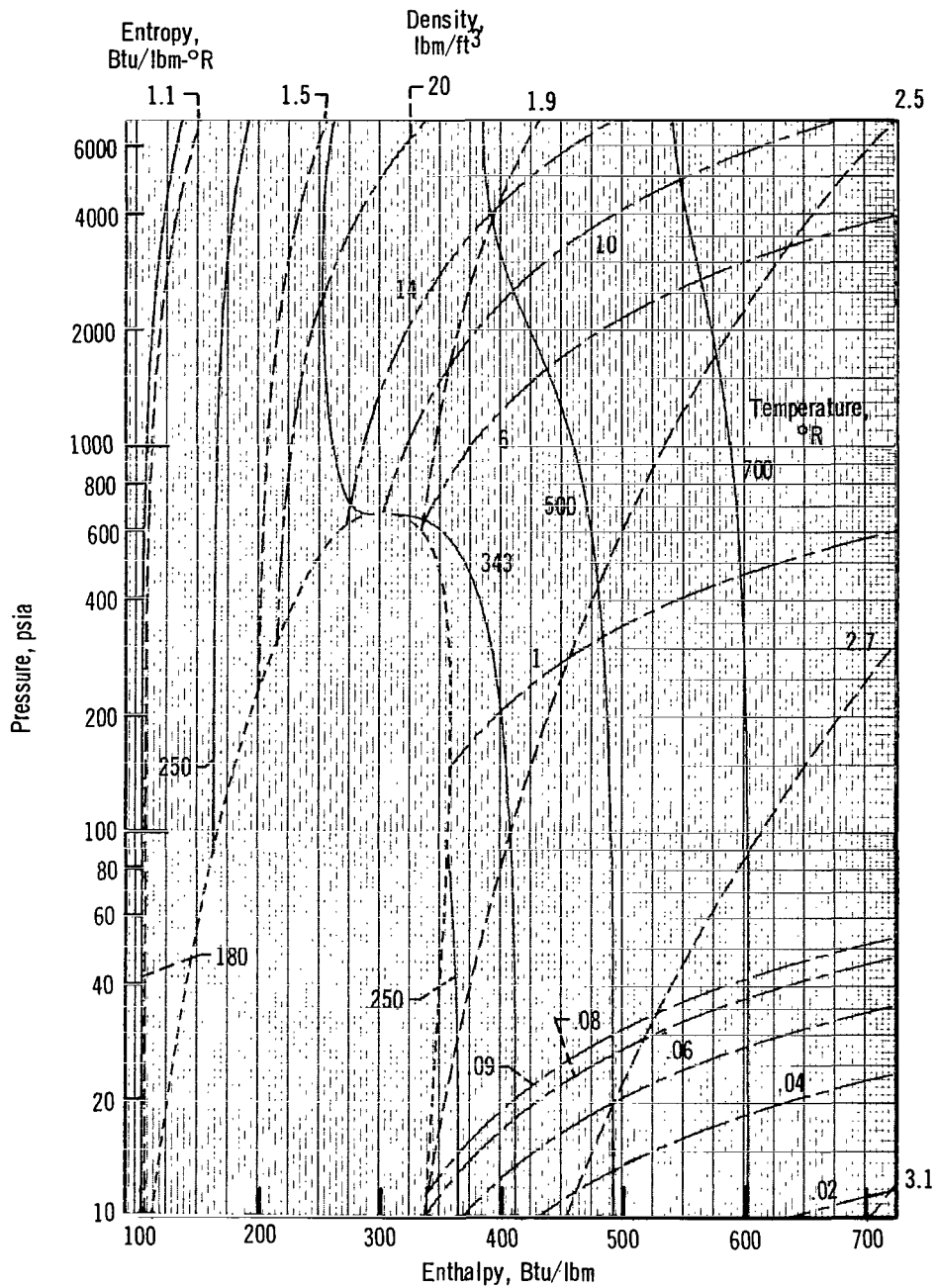


Figure 16. - Enthalpy against pressure with grey-grid background, for fluid methane (KU = 3).

APPENDIX E

SYMBOLS

A	Helmholtz free-energy function
C	sonic velocity
C_p	specific heat at constant pressure
C_v	specific heat at constant volume
H	enthalpy
H_L	saturated-liquid enthalpy
H_V	saturated-vapor enthalpy
P	pressure
S	entropy
S_0	reference entropy
S_L	saturated-liquid entropy
S_V	saturated-vapor entropy
T	temperature
V	volume
X	quality number
α	constant parameter
α_L	saturated liquid for constant parameter
α_V	saturated vapor for constant parameter
γ	isentropic expansion coefficient
ϵ	density
η	viscosity
Λ	transport property
λ	thermal conductivity
ω	energy variable
Subscript:	
c	critical

REFERENCES

1. Hendricks, Robert C.; Baron, Anne K.; and Peller, Ildiko C.: GASP - A Computer Code for Calculating the Thermodynamic and Transport Properties for Ten Fluids: Parahydrogen, Helium, Neon, Methane, Nitrogen, Carbon Monoxide, Oxygen, Fluorine, Argon, and Carbon Dioxide. NASA TN D-7808, 1975.
2. Hendricks, Robert C.; Peller, Ildiko C.; and Baron, Anne K.: WASP - A Flexible FORTRAN IV Computer Code for Calculating Water and Steam Properties. NASA TN D-7391, 1973.

TABLE I. - DESCRIPTION OF INPUT TO BE ENTERED INTO NAMELIST/DATA/

[All input to GASPLOT is entered by means of NAMELIST input into NAMELIST/DATA/. Each NAMELIST input corresponds to one set of input and defines one plot. GASPLOT accepts multiple input data sets.]

Variable name	Dimension	Type	Standard value	Description
DEGREE	49	R	---	Constant-temperature values in units specified by KU
DEN	↓	↓	---	Constant-density values in units specified by KU
ENTHAL	↓	↓	---	Constant-enthalpy values in units specified by KU
ENTRO	↓	↓	---	Constant-entropy values in units specified by KU
GAS	--	A	---	Hollerith code specifying requested fluid (table III)
KU	--	I	---	Units specification (table II)
LABEL	--	L	. TRUE.	If TRUE, labels will be put on plots
PRES	49	R	---	Constant-pressure values in units specified by KU
QUAL	49	R	---	Constant quality numbers
RECIP	--	L	. FALSE.	If TRUE, reciprocal of YAXIS will be plotted
XAXIS	--	A	---	Hollerith code for parameter to be plotted on x-axis (table IV)
XLEFT	--	A	---	Hollerith representation of x-axis value at (0, 0) in units specified by KU
XLOG10	--	L	. FALSE.	If TRUE, log(XAXIS) will be plotted
XRIGHT	--	A	---	Hollerith representation of x-axis value at (XWIDTH, 0) in units specified by KU
XWIDTH	--	R	10.	Length of x-axis in inches
YAXIS	--	A	---	Hollerith code for parameter to be plotted on y-axis (table IV)
YBOTOM	--	A	---	Hollerith representation of y-axis value at (0, 0) in units specified by KU
YLOG10	--	L	FALSE.	If TRUE, log(YAXIS) will be plotted
YTOP	--	A	---	Hollerith representation of y-axis value at (0, YWIDTH) in units specified by KU
YWIDTH	--	R	10.	Length of y-axis in inches

TABLE II. - UNITS SPECIFICATION NUMBER

Physical quantity	Units specification number, KU		
	1	2	3
Temperature	K	K	^o R
Density	g/cm ³	g/cm ³	lbm/ft ³
Pressure	MN/m ²	atm	psia
Enthalpy	J/g	J/g	Btu/lbm
Entropy, specific heat	J/g-K	J/g-K	Btu/lbm/ ^o R
Sonic velocity	cm/sec	cm/sec	ft/sec
Dynamic viscosity	g/cm-sec	g/cm-sec	lbm/ft-sec
Thermal conductivity	J/cm-sec-K	J/cm-sec-K	Btu/ft-sec- ^o R
Surface tension	dyne/cm	dyne/cm	lbf/ft

TABLE III. - HOLLERITH CODES FOR FLUID

Gas	Hollerith code	Gas	Hollerith code
Argon	AR	Carbon dioxide	CO2
Methane	CH4	Neon	NE
Nitrogen	N2	Carbon monoxide	CO
Oxygen	O2	Helium	HE
Fluorine	F2	Parahydrogen	H2

TABLE IV. - HOLLERITH CODES FOR x AND y AXES

Parameter	Hollerith code	Parameter	Hollerith code
Entropy	S	Surface tension	SIGMA
Enthalpy	H	Ratio of specific heats	GAMMA
Conductivity	K	Specific heat at constant volume	CV
Viscosity	MU	Specific heat at constant pressure	CP
Density	D	Conductivity plus excess conductivity	EXK
Sonic velocity	C		
Temperature	T		
Pressure	P		

TABLE V. - LIMITS FOR PARAMETER VALUES FOR EACH FLUID
CONTAINED IN SUBPROGRAM GASP (REF. 1)^a

Fluid	Pressure		Temperature		Density		Entropy		Enthalpy	
	PLOW	PHIGH	TLOW	THIGH	DLOW	DHIGH	SLOW	SHIGH	HLOW	HHIGH
CH ₄	0.01167	50.67	90.66	600.	0.1E-4	0.57	4.0065	14.567	222.3	2 007.
N ₂	.0101325	50.67	64.	1000.	.1444E-3	1.12	-.1734	6.405	2.12	1 262.
O ₂	.0101325	100.	54.35	500.	.15E-3	1.5	2.027	7.50	88.47	739.
A	.0101325	50.66	87.78	1000.	.1E-3	1.48	1.26	4.99	70.06	725.
CO ₂	.0101324	50.67	216.56	1000.	.83E-5	1.25	2.543	6.55	381.35	1 567.
Ne	.0101325	20.29	24.54	600.	.00015	1.35	-.172	7.54	.063	694.
CO	.0101325	20.27	68.14	600.	.5E-4	.86	2.55	8.42	120.14	908.
He ^b	.0101325	10.133	3.0	600.	.4E-4	.21	1.35	39.8	5.33	3 167.
F ₂	.011	20.3	53.48	500.	1.E-6	2.25	1.58	6.26	-158.	405.
H ₂	.000101325	100.	13.8	3000.	.1E-4	.11	1.61	129.12	-309.	49 289

^aUnits, KU=1 (table II).

^bProperties not considered accurate below 6K.

TABLE VI. - THERMODYNAMIC CRITICAL AND
PSEUDOCRITICAL VALUES FOR EACH GAS^a

Fluid	TCRIT	STT	Fluid	TCRIT	STT
Ch ₄	190.77	190.6676	Ne	44.4	44.0728
N ₂	126.3	126.19248	CO	132.91	132.7584
O ₂	154.78	154.639	He	5.2014	5.09740
A	150.7	150.59577	F ₂	144.31	144.2066
CO ₂	304.21	304.099	H ₂	32.976	32.868

^aUnits, KU=1 (see table II).

TABLE VII. - ARGUMENTS OF SUBROUTINE PLINE(BEGIN, END, PARA, J, NP, DASH)

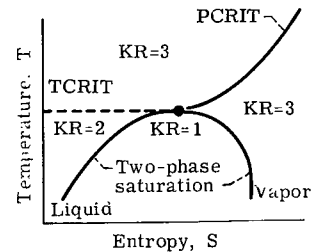
Name	Type	Description
BEGIN	R	Starting temperature or pressure value
END	R	Final temperature or pressure value
PARA	R	Numerical value of constant parameter
J	I	Integer equal to 0 or 1 (If 1, it indicates that line segment intersected saturation curve and this point is stored in TS array.)
NP	I	Integer indicating number of data points to compute
DASH	I	Array that indicates what type of line to draw (not used by PLINE but passed on to CURVE); see section LABELING in main text
Common block /OPTION/:		
TVARY	R	Logical switch that, when set to TRUE, indicates BEGIN and END are temperature values
NFI	I	Number used as pointer to obtain proper property value for x-axis
NFD	I	Number used as pointer to obtain proper property value for y-axis
RECIP	L	Logical switch that when set to TRUE will cause program to invert data on y-axis
KSS	I	Option for GASP call (table VIII, appendix B)
GEOM	R	Array of numbers of a geometric progression; see section SELECTED DESIGN FEATURES in main text
SYX	A	Storage location that contains LABEL symbol assigned to constant parameter

TABLE VIII. - OPERATIONS SHEET FOR SUBROUTINE GASP^a

COMMON PROPTY KU, DL, DV, HL, HV, S, SL, SV, CV, CVL, CVV, CP, CPL, CPV, GAMMA, GAMMAL, GAMMAV, C, CL, CVP, MU, MUL, MUV, K, KL, KV, SIGMA, EXCL, EXCV, EXCESK
 COMMON/DERIV/PDT, PTV, PDTL, PDTV, PTVL, PTVV
 REAL MU, MUL, MUV, K, KL, KV
 CALL SETUP(NAMGAS): Name fluid - HE for helium, CH4 for methane, NE for neon,
 N2 for nitrogen, CO for carbon monoxide, O2 for oxygen, AR for argon,
 CO2 for carbon dioxide, F2 for fluorine, H2 for parahydrogen

CALL GASP (KS, KP, T, P, D, H, KR)

- Region
 - KR-0 Unknown, check KR returned
 - KR-1 Saturation
 - KR-2 Liquid
 - KR-3 Gas and/or fluid
- Enthalpy, J g
- Density, g cm³
- Pressure, MN m²
- Temperature, K



Thermodynamic and transport properties^b

- KP-0 Only P, ρ , and T returned
- KP-1 H Enthalpy, J g; (H), (HL), (HV)
- KP-2 S Entropy, J (g)(K); (S), (SL), (SV)
- KP-4 C_v Specific heat at constant volume, J (g)(K); (CV), (CVL), (CVV)
- C_p Specific heat at constant pressure, J (g)(K); (CP), (CPL), (CPV)
- γ Ratio of specific heats, C_p/C_v; (GAMMA), (GAMMAL), (GAMMAV)
- c Sonic velocity, cm sec; (C), (CL), (CVP)
- $\partial P / \partial \rho$ Slope of PVT surface along an isotherm, MPa/(g/cm³), (PDT), (PDTL), (PDTV)
- $\partial P / \partial T$ Slope of PVT surface along an isochore, MPa/K, (PTV), (PTVL), (PTVV)

- KP-8 μ Dynamic viscosity, g (cm)(sec); (MU), (MUL), (MUV)
- KP-16 k Thermal conductivity, W (cm)(K); (K), (KL), (KV)
- KP-32 σ Surface tension, dyne cm; (SIGMA)

Input specification of independent properties

- KS-1 ρ f(T, P); given T, P find ρ
- KS-2 P f(T, ρ); given T, ρ find P
- KS-3 T f(P, ρ); given P, ρ find T
- KS-4 T, ρ f(P, H); given P, H find T, ρ
- KS-5 T, ρ f(P, S); given P, S find T, ρ

^aNotes:

1. The units indicator, KU, must be set such that 1 < KU < 5 or no valid property values can be determined. See table VIII.
2. Reset KR#1 for each call to GASP to be assured of nonsaturation calculations (unless T = T_{sat} and P = P_{sat}).

3. Sample call:

```
COMMON/PROPTY (as indicated above)
COMMON/DERIV/ (as indicated above)
REAL (as indicated above)
DATE NAMGAS 2HO2
CALL SETUP(NAMGAS)
KU=2; KR=0
CALL GASP(2, 4, 100., P., .39996 E-2, H, KP)
Returns: P = 1 atm; Cv = 0.6636;  $\gamma$  = 1.43.
```

^bKP input is \sum KP options if more than one property is requested. For example, if enthalpy and entropy are desired, set KP equal to 3.

TABLE IX. - ARGUMENTS OF SUBROUTINE GETGAS (GAS, KU, A, GEOM, WRONG)

Name	Type	Description
GAS	A	Hollerith code for chemical formula of a gas
KU	I	Units specification (table II)
A	R	32-by-87 dimensioned array for saturation values
GEOM	R	Array of numbers ranging in value from 0 to 1 and differences between them forming a geometric progression
WRONG	L	Logical switch (If set to TRUE, it indicates the gas is not part of thermophysical package.)
Common block /SAME/:		
CST	R	Default constant set in main program
PCRIT	R	Critical pressure
TCRIT	R	Critical temperature
TCRITL	R	Temperature slightly below critical, usually equal to STT
TCRITH	R	Temperature slightly above critical
THIGH	R	Upper limit of temperature for gas in property package
TLOW	R	Lower limit of temperature for gas in property package
STT	R	Temperature slightly below critical
DELT	R	Delta temperature equal to TCRIT - STT
NMAX	I	Constant in main program set equal to 86
NZ	I	NMAX + 1
PHIGH	R	Upper limit of pressure for gas in property package
PLOW	R	Lower limit of pressure for gas in property package
DCRIT	R	Critical density
HCRT	R	Critical enthalpy
SCRIT	R	Critical entropy
PMID	R	$0.5 \times \text{PCRIT}$
PMID1	R	$0.5 \times \text{PHIGH}$
PCRITS	R	$\text{PCRIT} + \text{PMID}$
TSUPER	R	$\text{TCRIT} + 0.5 \times \text{TCRIT}$
ZERO } ONE } TWO }	I	Integers 0, 1, 2

TABLE X. - THE A ARRAY (SATURATION VALUES)

Property		
-----	A(1, 1) . . . This row contains symbols for labeling plots . . .	A(1, 87)
Density:		.
Liquid	A(2, 1)=DCRIT	.
Vapor	A(3, 1)=DCRIT	.
Enthalpy:		.
Liquid	A(4, 1)=HCRIT	.
Vapor	A(5, 1)=HCRIT	.
-----	A(6, 1) ^a	.
Entropy:		.
Liquid	A(7, 1)=SCRIT	.
Vapor	A(8, 1)=SCRIT	.
-----	A(9, 1) ^a	.
Specific heat at constant volume:		.
Liquid	A(10, 1)	.
Vapor	A(11, 1)	.
-----	A(12, 1) ^a	.
Specific heat at constant pressure:		.
Liquid	A(13, 1)	.
Vapor	A(14, 1)	.
-----	A(15, 1) ^a	.
Ratio of specific heats:		.
Liquid	A(16, 1)	.
Vapor	A(17, 1)	.
-----	A(18, 1) ^a	.
Sonic velocity:		.
Liquid	A(19, 1)	.
Vapor	A(20, 1)	.
-----	A(21, 1) ^a	.
Viscosity:		.
Liquid	A(22, 1)	.
Vapor	A(23, 1)	.
-----	A(24, 1) ^a	.
Conductivity:		.
Liquid	A(25, 1)	.
Vapor	A(26, 1)	.
Surface tension:	A(27, 1)	.
-----	A(28, 1) ^a	.
Reacting conductivity:		.
Liquid	A(29, 1)	.
Vapor	A(30, 1)	.
Temperature	A(31, 1)=TCRIT	.
Pressure	A(32, 1)=PCRIT	-A(32, 87)

The elements of row 31 are temperature values from TCRIT to the lower temperature limit of the gas. For a given temperature, say the Jth, all the associated saturation values are stored in the appropriate A(J, J) element of the Jth column.

^aNot used by program.



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