

《Technical Report》

Generation of Water and Steam Properties for LWR

Byung Jin Jun, Chang Kun Lee, Ji Bok Lee and Jong Hwa Chang

Korea Atomic Energy Research Institute

(Received August 14, 1980)

Abstract

Subroutines to enable fast and accurate generation of water properties—enthalpy, specific volume, viscosity, thermal conductivity and saturation entropy—which are usually basic requirements for nuclear calculation of LWR, have been developed. The sources of data were quoted from "ASME Steam Tables (1967)" and their Revision (1975).

It is ensured that the obtained values from this routine fall within 0.2% difference compared with the reference data, in the ranges of temperature and pressure for LWR nuclear calculation.

요 약

경수의 엔탈피, 비체적(比體積), 점성, 열전도도 및 임계엔트로피 등은 경수로의 핵특성 분석에 필수적인 자료이다. 본 보고서에서는 상기 자료를 신속, 정확하게 구할 수 있는 부(副)프로그램을 개발하여 경수로의 핵계산코드에서 보편적으로 사용할 수 있게 하였다. 기본자료로 ASME Steam Tables (1967)과 이의 개정판 (1975)을 사용하였다.

경수로의 핵계산에서 사용되는 온도 및 압력의 영역에서 이 프로그램의 계산치는 기준치와 오차 0.2%내에 들어 있음이 입증되었다.

1. Introduction

Fast and accurate evaluation of thermodynamic and transport properties of water and steam is a basic requirement for LWR (Light Water Reactor) nuclear calculations. Reference (1) presents the results of the work of W.A. Coffman and L.L. Lynn for the development of a subroutine entitled WATER to obtain the required properties at virtually any pressure and temperature range. WATER was based on the Skeleton Tables of the Sixth International Conference

on the Properties of Steam²⁾ (ICPS). But it had been felt that WATER was not accurate enough for all design purposes and found to bear some errors in the liquid and vapor transport property data in this routine. By the efforts of L.L. Lynn at the Bettis Atomic Power Laboratory, more accurate and effective routine called HOH³⁾ was developed in 1967. This gave property data on P and T-Ts (where Ts is saturation temperature at the corresponding pressure) grid instead of P and T grid as in WATER, and used the most updated transport property data⁴⁾ by that time.

After the Eighth ICPS held in Giens, France in 1974, newly updated viscosity data⁵⁾ replaced those of reference (4). Furthermore, thermodynamic properties (enthalpy H and specific volume v) calculated by bilinear interpolation used in Bettis version HOH were considered not to be satisfactory in nuclear calculation which requires acuter values. Since Korea Atomic Energy Research Institute (KAERI) is not a domestic user of Argonne National Laboratory's Code Center, HOH and its related code MO899³⁾ are not available to KAERI, which naturally hampers our work.

Under such circumstances, the Reactor Management Division of KAERI decided to develop more accurate routine than Bettis version HOH, based entirely on the data in references (5) and (6) using more accurate interpolation method. The same calculational options, subroutine-calling parameters and subroutine name were used as Bettis version HOH to avoid modification of the main programs which use HOH as subprogram. The new routine was written in FORTRAN-IV for the convenience of further upgrading or modification, kept as small as possible to give more available memory to nuclear codes generally requiring large memory size, and also kept as fast and accurate as possible.

II. Available Properties

A. Independent Variables and Their Ranges

The subroutine HOH (hereinafter means KAERI-improved HOH, if not specifically commented elsewhere) tables are stored at several P and T - T_s (for liquid T_s - T) grid points. This was carried out to avoid storing values extrapolated metastably across the saturation line and to permit the use of a

large grid away from the saturation curve where property behavior is almost linear with T . P and T - T_s entries and ranges were adopted to be more accurate than ever, especially for those ranges of frequent uses in LWR calculations (see Appendix B).

The P and T ranges over which HOH supplies property values are:

Pressure

$$14.5 \text{ psia} \leq P \leq 2500 \text{ psia}$$

or

$$1 \text{ bar} \leq P \leq 172.3 \text{ bar}$$

Temperature

$$32 \leq T_s - 620 \leq T \leq T_s + 950, T = \text{deg } F.$$

or

$$0 \leq T_s - 327 \leq T \leq T_s + 510, T = \text{deg } C.$$

For the pressure value outside this range, HOH calculates no properties, and error flag will be set. For the temperature value outside this range, HOH extrapolates properties, and a message such that temperature was out of range, will be given, and no error flag will be set. If temperature extrapolation be attempted, the results would fall within 1% error for the temperature range up to $T_s + 1400 \text{ deg } F$.

Although P and T are the independent variables, it is possible to obtain properties at a given P and enthalpy H by first doing a "backward" interpolation to find the corresponding T , and then going into the property tables with P and T .

B. Saturation Properties

Saturation thermodynamic properties which can be obtained for a given P , are T_s , H_f , H_g , v_f , v_g , the derivatives dT_s/dP , dH_f/dP , etc., and the derivatives dH_f/dT_s , etc., and then the saturation entropies s_f and s_g .

Saturation transport properties obtainable for a given P are the dynamic viscosity μ_f and μ_g , and the thermal conductivity k_f and

k_g . All of the saturation properties are available in either cgs or British units (see Appendix A).

Plots of the saturation curves in British units are presented in Figures 1 through 9 of Appendix B. These curves were constructed by plotting data obtained by repeated calls on HOH.

C. Liquid, Vapor and Two-Phase Properties

For a given P and T , the following properties may be obtained from HOH;

$$H, \left(\frac{\partial H}{\partial T}\right)_P, \left(\frac{\partial H}{\partial P}\right)_T, v, \left(\frac{\partial v}{\partial T}\right)_P, \left(\frac{\partial v}{\partial P}\right)_T, \mu, \text{ and } k.$$

Two-phase properties and derivatives are not computed.

For a given P and H , the obtainable properties are the same as those for P and T except that H is obtained instead of T . Moreover, two-phase homogeneous properties (no derivatives) are computed.

The properties are available in either cgs or British units (see Appendix A).

Plots of H, v, μ , and k constructed in British units by repeated calls on HOH are given in Figures 2 through 8 of Appendix B.

D. Comparison with the Previous Data

The thermodynamic data taken from (2) and (6) are the same. The transport data (viscosity) from (5) differ a little from the data of (4). The major differences occur in liquid. For example, at 100 bar and 100 deg C, μ from (5) is 2847 ± 29 micropoise; from (4), however, it is 2810 ± 70 . Thermodynamic properties obtained by HOH have much more accuracy than by Bettis version HOH. For example, H at 5 bar and 150°C by HOH is 632.1 J/gm, but by Bettis version HOH⁹ is 630.8, and H in Skeleton Table²⁰ with

tolerance is 632.2 ± 0.3 . H at 150 bar and 300°C by HOH is 1338.3, that by (3) is 1340, and that in (2) is 1338 ± 1 .

Comparisons of the computed data by HOH are presented in Table 4.

III. Thermodynamic Properties

A. Saturation Properties

$T_s, H_f, H_g, v_f, v_g, s_f$ and s_g are stored on a grid of 21 pressures. All of the thermodynamic saturation properties except v_g are computed from the stored tables using cubic Bessel interpolation (see Appendix D) discussed in (1); v_g is obtained by the reciprocal of value calculated by the cubic Bessel interpolation of $1/v_g$. The tables are extended below 14.5 psia and above 2500 psia so that cubic Bessel interpolation is always used in the HOH pressure range. Thus the number of pressure entries for saturation properties in the HOH pressure range is 19.

The derivatives of T_s with respect to P , and of H and v with respect to P or T_s are obtained by derivation of the cubic Bessel interpolation function. This ensures derivatives which are continuous in P and T_s .

B. Liquid and Vapor Properties

Values of H and v are stored on a grid composed of the intersections of constant pressure lines and lines of constant T_s-T for the liquid, and/or constant $T-T_s$ for the vapor. The advantage of the $T-T_s$ grid over a T grid lies in the following two facts:

- i) Extrapolation across the saturation line is not necessary for constructing the data tables;
- ii) Most of the nonlinear behaviors of the properties occur near the saturation curve, thus allowing a large $T-T_s$ grid away from the saturation curve.

H and v values are stored at 16 P and several (varies depending on property and phase) T - T_s (or T_s - T) grid points. Numbers of T - T_s (or T_s - T) grids are 12 for liquid H , 15 for vapor H , 17 for liquid v , and 13 for vapor v .

Cubic Bessel interpolation in P and linear interpolation in T - T_s , respectively, take place instead of bilinear interpolation used in Bettis version HOH. If a value of H (or v) is desired at P_0 and T_0 , say, the first step is to locate P_{i-1} , P_i , P_{i+1} , and P_{i+2} on the P grid such that $P_i \leq P_0 < P_{i+1}$, and to locate ΔT_i and ΔT_{i+1} on the ΔT (T - T_s) grid such that $\Delta T_i \leq \Delta T_0 \leq \Delta T_{i+1}$, then cubic Bessel interpolation in P (ΔT_i) and P (ΔT_{i+1}) is performed at ΔT_i and ΔT_{i+1} , respectively, to obtain values H_1 and H_2 (or v_1 and v_2). As in the saturation vapor v_g calculation, reciprocal properties are obtained after cubic Bessel interpolation of $1/v$ for v_1 and v_2 of vapor. Finally, a linear interpolation in T is carried out to get the H (or v) value at P_0 and T_0 . If ΔT_0 is greater than the maximum $\Delta T(\Delta T_{\max})$ in the table, $\Delta T_{\max-1}$ and ΔT_{\max} would be adopted, and extrapolation in T would take place. When this happens, error flag is not set, but a message "temperature out of range, extrapolated" is given in the output list. Extrapolated values may have somewhat large error, but it was ensured that such error was within 1% range if $\Delta T - \Delta T_{\max}$ was less than 500 deg F .

The derivatives $\left(\frac{\partial H}{\partial T}\right)_P$ and $\left(\frac{\partial v}{\partial T}\right)_P$ are computed simply as the divided differences. Thus they are piecewise constant in T . The derivatives $\left(\frac{\partial H}{\partial P}\right)_T$ and $\left(\frac{\partial v}{\partial P}\right)_T$ are obtained by

$$\left(\frac{\partial x}{\partial P}\right)_T = \left(\frac{\partial x}{\partial P}\right)_{\Delta T} \pm \left(\frac{\partial x}{\partial \Delta T}\right)_P \cdot \frac{dT_s}{dP},$$

where the sign is + if $\Delta T = T - T_s$ (vapor),

and - if $\Delta T = T_s - T$ (liquid), and x may be H or v . $\left(\frac{\partial x}{\partial P}\right)_{\Delta T}$ are calculated by linear interpolation of $\left(\frac{\partial x}{\partial P}\right)_{\Delta T_i}$ and $\left(\frac{\partial x}{\partial P}\right)_{\Delta T_{i+1}}$ in ΔT which are derivatives of cubic Bessel interpolation function at $(P_0, \Delta T_i)$ and $(P_0, \Delta T_{i+1})$. The tables are extended below 14.5 psia and above 2500 psia so that cubic Bessel interpolation is always used in the HOH range (see Appendix B). Thus the number of pressure grids for non-saturation properties in the HOH pressure range is 14.

C. Homogeneous Properties

When P and H are supplied and it turns out that $H_f < H < H_g$, homogeneous property values are computed from

$$Y = (1-x)Y_f + x \cdot Y_g,$$

where Y is either thermodynamic or transport properties, and x is quality. P and T partial derivatives which are meaningless in the saturation region, are not computed.

IV. Transport Properties

Both the dynamic viscosity μ and thermal conductivity k are computed in either cgs or British units from the curve fits adopted by (5) or (6). None of the transport properties is stored as tabular values.

A. Dynamic Viscosity

The interpolating equation of μ is adopted by the Eighth ICPS as referred to in (5). The equation is given as below:

$$\mu = \mu_0 \exp \left\{ \frac{\delta}{\delta^*} \sum_{i=0}^5 \sum_{j=0}^4 b_{ij} \left(\frac{T^*}{T} - 1 \right)^i \left(\frac{\delta}{\delta^*} - 1 \right)^j \right\},$$

where

$$\frac{\mu_0}{\text{micropoise}}$$

Table 1. Numerical Values of the Coefficients b_{ij}

$i=$	0	1	2	3	4	5
$j=0$	0.501938	0.162888	-0.130356	0.907919	-0.551119	0.146543
1	0.235622	0.789393	0.673665	1.207552	0.0670665	-0.084337
2	-0.274637	-0.743539	-0.959456	-0.687343	-0.497089	0.195286
3	0.145831	0.263129	0.347247	0.213486	0.100754	-0.032932
4	-0.0270448	-0.0253093	-0.0267758	-0.0822904	0.0602253	-0.0202595

$$= \left(\frac{T}{T^*} \right)^{1/2} \left(\sum_{k=0}^3 a_k \left(\frac{T^*}{T} \right)^k \right)^{-1}$$

μ : denotes the dynamic viscosity in micropoise,

δ : denotes density in g/cm³,

T : denotes absolute temperature (°K) on the 1968 Practical Temperature Scale,

T^* and δ^* : denote numerical constants which are close to but do not represent the corresponding critical constants,

a_k and b_{ij} are numerical constants.

The constants appearing in the preceding equations have the numerical values given below and in Table 1 for b_{ij} :

$$T^* = 647.27^\circ\text{K}$$

$$\delta^* = 0.317763\text{g/cm}^3$$

$$a_0 = 0.00181583$$

$$a_1 = 0.00177624$$

$$a_2 = 0.00105287$$

$$a_3 = -0.00036744$$

The correlating equation presented above is valid in the range of

$$0 < T < 800^\circ\text{C}$$

in temperature, and

$$0 < P < 1000\text{ bars}$$

in pressure. Thus this entirely covers the pressure and temperature ranges of HOH.

B. Thermal Conductivity

It was decided at the Eighth ICPS to replace the viscosity and thermal conductivity data of Water and Steam released as a result of the Sixth ICPS⁶⁾, with the newly updated transport data. As the result, new dynamic viscosity data and interpolating

equation as in previous section (IV-A) were generated. On thermal conductivity, however, Supplementary Release on Thermal Conductivity of Water Substance was decided upon; yet it has not been published. So the data and correlating equation presented in (6) were adopted as thermal conductivity. The correlating equation for liquid differs from that for vapor.

1. Correlating Equation for Vapor

Thermal conductivity values of vapor over the pressure range $1 < P < 175$ bars and temperature range $T_s \leq T \leq 700^\circ\text{C}$ can be obtained by

$$k = k_1 + \frac{2.1482 \times 10^{14}}{T^{4.2}} \rho^2 + \left(\sum_{i=0}^2 a_i T^i \right) \rho,$$

where k_1 is thermal conductivity of vapor at 1 bar and is given such as

$$k_1 = \sum_{i=0}^3 b_i T^i \text{ in m-watt/m}^\circ\text{K},$$

and others

k : denotes thermal conductivity in m-w/m² K,

ρ : denotes density in g/cm³

T : denotes temperature (°C) on the 1948 International Practical Scale of Temperature,

a_i and b_i are numerical constants as below

$$a_0 = 103.51$$

$$a_1 = 0.4198$$

$$a_2 = -2.771 \times 10^{-5}$$

$$b_0 = 17.6$$

$$b_1 = 5.87 \times 10^{-2}$$

$$b_2 = 1.04 \times 10^{-4}$$

$$b_3 = -4.51 \times 10^{-8}$$

Vapor conductivity values obtained by the above correlating formulae have $\pm 6\%$ tolerance.

2. Correlating Equation for Liquid

Thermal conductivity of liquid water from saturation pressure to 500 bar pressure in the temperature range from 0°C to 350°C can be obtained by

$$k = \sum_{i=0}^2 \sum_{j=0}^4 a_{ij} \left(\frac{T}{T_0} \right)^j (P - P_s)^i,$$

P : denotes pressure in bar,

P_s : denotes saturation pressure in bar at temperature T ,

T : denotes absolute temperature in $^\circ\text{K}$,

T_0 : denotes 273.15°K ,

a_{ij} are numerical constants given as in Table 2.

Table 2. Numerical Values of the Coefficients a_{ij}

$i =$	0	1	2
$j = 0$	-922.47	-0.94730	1.6563×10^{-3}
1	2839.5	2.5186	-3.8929×10^{-3}
2	-1800.7	-2.0012	2.9323×10^{-3}
3	525.77	0.51536	-7.1693×10^{-4}
4	-73.44	0.0	0.0

Liquid conductivity values obtained by the above correlating formulae have $\pm 2\%$ tolerance in $0^\circ\text{C} \leq T \leq 300^\circ\text{C}$ range, and $\pm 5\%$ in $300^\circ\text{C} \leq T \leq 350^\circ\text{C}$.

As shown in the above correlation, P_s should be searched first to obtain thermal conductivity of liquid. But P_s below 1 bar, or T_s below 100°C cannot be searched by P and T_s table of HOH described in Section III-A. To obtain P_s below 14.5 psia by interpolating, it requires numerous data points because of big variation of P_s vs. T . To avoid this unfavorable situation, the curve fit which gives good agreement in the range of $0 \leq T \leq 100^\circ\text{C}$ with data in (6), developed by the author, is used. This curve

fit is

$$P_s = \exp \left(\sum_{i=0}^2 a_i T^i \right),$$

where

P_s : denotes saturation pressure in psia,

T : denotes temperature in $^\circ\text{F}$,

a_i are numerical constants, i.e.,

$$a_0 = -3.65718$$

$$a_1 = 0.0411071$$

$$a_2 = 0.529867 \times 10^{-4}$$

V. Call Sequence for Subroutine HOH

A. General Comments

Saturation properties at a given P , properties and derivatives at given P and H , or properties and derivatives at given P and T are the options available when using HOH. A user may be given an additional choice of working in cgs units or British units (see Appendix A for the actual units).

Since tables in HOH were made in British units, working in cgs units requires a little more time for conversion. Repeated calls at one P or at the same region of P (see Appendix B) are handled much faster than the same number of calls at random pressure.

B. Property Option Table

In order to use HOH, the following FORTRAN-IV call sequence must be used.

CALL HOH (IOP, IUNIT, P, HT, PROP, NDERIV, IFLAG)

The arguments P and HT are real variables, IOP, IUNIT, NDERIV, and IFLAG are integer, and PROP is a one-dimensional real array which must be of dimension 8 or greater.

IOP, IUNIT, P and NDERIV must be supplied on entry. IOP is the option indicator (see Table 3 below). If IUNIT=0, all quantities must be in cgs units (P =bars,

$H=J/gm$, $T=deg\ C$), and if IUNIT=1, they must be in British units ($P=psia$, $H=Btu/lb$, $T=deg\ F$). NDERIV is the derivative option indicator. If NDERIV=0, none of the derivatives in Table 3 is computed; if NDERIV=1, the derivatives shown for the various options are computed. HT is not supplied when only saturation properties are desired; it is set equal to H for P and H options, and also equal to T for P and T options. On exit from HOH, PROP contains the various property and derivative values as shown in Table 3 below. Finally, if IFLAG is positive on exit, the pressure ranges would not be exceeded; the ranges of pressure as given in Section II-A will be exceeded, and no properties would be computed. And if temperature ranges were exceeded, message such as "temperature out of range, extrapolated" would be written in output list, but IFLAG would be positive.

When P and H are supplied and it turns out that $H_f < H < H_g$, homogeneous property values are computed (see Section III-C).

When P and T are supplied, liquid properties are computed for $T \leq T_s$, and vapor for $T \geq T_s$. No attempt is made to compute saturation region values. Thus derivatives are always computed when NDERIV=1.

IV. Storage Requirements, Timing and Accuracy

A. Storage

The HOH subroutines require about 2900 decimal (5500 in octal) locations when used on the CYBER-73 computer.

B. Timing

The following numbers are approximate average.

Time to get one property value and its

Table 3. Property Options from HOH

Options			Obtained in PROP (I) Array							
IOP	P	HT	I=1	I=2	I=3	I=4	I=5	I=6	I=7	I=8
1	P	—	T_s	$\frac{dT_s}{dP}$	H_f	H_g	$\frac{dH_f}{dP}$	$\frac{dH_g}{dP}$	$\frac{dH_f}{dT_s}$	$\frac{dH_g}{dT_s}$
2	P	—	T_s	$\frac{dT_s}{dP}$	v_f	v_g	$\frac{dv_f}{dP}$	$\frac{dv_g}{dP}$	$\frac{dv_f}{dT_s}$	$\frac{dv_g}{dT_s}$
3	P	—	T_s	$\frac{dT_s}{dP}$	μ_f	μ_g	k_f	k_g	—	—
4	P	—	T_s	$\frac{dT_s}{dP}$	s_f	s_g	—	—	—	—
11	P	H	T	—	$\left(\frac{\partial H}{\partial T}\right)_P$	$\left(\frac{\partial H}{\partial P}\right)_T$	—	—	—	—
12	P	H	T	v	$\left(\frac{\partial v}{\partial T}\right)_P$	$\left(\frac{\partial v}{\partial P}\right)_T$	—	—	—	—
13	P	H	T	μ	—	—	—	—	—	—
14	P	H	T	k	—	—	—	—	—	—
21	P	T	—	H	$\left(\frac{\partial H}{\partial T}\right)_P$	$\left(\frac{\partial H}{\partial T}\right)_T$	—	—	—	—
22	P	T	—	v	$\left(\frac{\partial v}{\partial T}\right)_P$	$\left(\frac{\partial v}{\partial R}\right)_T$	—	—	—	—
23	P	T	—	μ	—	—	—	—	—	—
24	P	T	—	k	—	—	—	—	—	—

derivatives at given P and H is about 3.5 msec (milliseconds), and time to get several property values at the same range of P and various H values is 2.5 msec each.

Time to get one property and its derivatives at given P and T is 3 msec, and time required to get several property values at the same range of P and various T values is 2 msec each. If derivatives are not wanted, time saving for about 0.5 msec can be expected.

For example, in the nuclear calculation for Kori-1 at hot full power, P varies near 2500 psia, and it is always located in the same range of 2200~2300 psia (see Appendix B), thus time required on one call of HOH can be assumed to be 2 msec.

C. Accuracy

A study on the accuracy of all properties obtainable by HOH, was performed by comparing HOH with ASME Steam Tables⁶⁾ or the Eighth ICPS Release⁵⁾. The pressure and temperature points adopted for comparison avoided the data table entries in the HOH as much as possible. All the property values vary nonlinearly especially in such regions as low pressure, low temperature (near 32°F), or near the saturation curve. Therefore, relatively large errors, can occur

in such regions. The HOH values have a good agreement with the reference data within 0.2% error range at almost all points. Table 5 presents the HOH values and the corresponding reference data with differences between them. These data points are chosen to cover such regions where relatively large errors occur, and HOH values with * in Table 4 mean extrapolated values by T.

4-2. Saturation Liquid Enthalpy

P (psia)	H _f (HOH) (Btu/lb)	H _f in ASME Steam Tables	Difference (%)
15	181.18	181.21	0.02
80	283.04	282.15	0.32
150	331.54	330.65	0.27
400	424.22	424.17	0.01
800	509.85	509.81	0.01
1200	571.90	571.85	0.01
1500	611.69	611.68	0.00
1900	660.36	660.36	0.00

4-3. Saturation Vapor Enthalpy

P (psia)	H _g (HOH) (Btu/lb)	H _g in ASME Steam Tables	Difference (%)
15	1150.8	1150.9	0.01
80	1183.5	1183.1	0.03
150	1194.4	1194.1	0.03
400	1204.6	1204.6	0.00
800	1199.4	1199.4	0.00
1200	1184.9	1184.8	0.01
1500	1170.1	1170.1	0.00
1900	1145.5	1145.6	0.01

Table 4. HOH-Reference Table^{5,7)} Comparison

4-1. Saturation Temperature

P (psia)	T _s (HOH) (deg F)	T _s in ASME Steam Tables	Difference (%)
15	212.99	213.03	0.02
80	312.94	312.04	0.29
150	359.32	358.43	0.25
400	444.66	444.60	0.01
800	518.25	518.21	0.01
1200	567.23	567.19	0.01
1500	596.21	596.20	0.00
1900	628.57	628.56	0.00

4-4. Specific Volume of Saturation Liquid

P (psia)	v _f (HOH) (ft ³ /lb)	v _f in ASME Steam Tables	Difference (%)
15	0.01672	0.01673	0.01
80	0.01758	0.01757	0.01
150	0.01810	0.01809	0.01
400	0.01934	0.01934	0.00
800	0.02087	0.02087	0.00
1200	0.02232	0.02232	0.00
1500	0.02346	0.02346	0.00
1900	0.02517	0.02517	0.00

4-5. Specific Volume of Saturation Vapor

P (psia)	v_g (HOH) (ft ³ /lb)	v_g in ASME Steam Tables	Difference (%)
15	26.287	26.290	0.01
80	5.470	5.471	0.02
150	3.0130	3.0139	0.00
400	1.1609	1.1610	0.01
800	0.5690	0.5690	0.00
1200	0.3625	0.3624	0.03
1500	0.2772	0.2772	0.00
1900	0.2028	0.2028	0.00

4-6. Saturation Liquid Entropy

P (psia)	s_f (HOH) (Btu/lb-F)	s_f in ASME Steam Tables	Difference (%)
15	0.3137	0.3137	0.00
80	0.4548	0.4534	0.31
150	0.5154	0.5154	0.25
400	0.6217	0.6217	0.00
800	0.7112	0.7111	0.01
1200	0.7714	0.7714	0.00
1500	0.8085	0.8085	0.00
1900	0.8522	0.8522	0.00

4-7. Saturation Vapor Entropy

P (psia)	s_g (HOH) (Btu/lb-F)	s_g in ASME Steam Tables	Difference (%)
15	1.7552	1.7552	0.00
80	1.6190	1.6208	0.11
50	1.5680	1.5695	0.10
400	1.4846	1.4847	0.01
800	1.4162	1.4163	0.01
1200	1.3683	1.3683	0.00
1500	1.3373	1.3373	0.00
1900	1.2981	1.2981	0.00

4-8. Liquid Enthalpy

P (psia)	T (deg F)	H(HOH) (Btu/lb-F)	H in ASME Steam Tables	Difference (%)
30	40	8.23	8.12	1.35
	100	68.09	68.08	0.00
	240	208.51	208.46	0.00
400	40	9.34	9.21	1.41
	240	209.45	209.24	0.10
	430	408.13	407.96	0.04
800	40	10.50	10.39	1.06
	300	271.26	271.07	0.07

1500	500	487.99	487.88	0.02
	40	12.49	12.45	0.32
	340	313.62	313.52	0.03
2200	580	588.62	588.36	0.04
	40	14.48	14.49	0.07
	390	366.86	366.85	0.00
2400	640	678.00	677.13	0.13
	40	15.07	15.07	0.00
	410	388.23	388.32	0.02
	650	693.84	693.05	0.10

4-9. Vapor Enthalpy

P (psia)	T (deg F)	H(HOH) (Btu/lb-F)	H in ASME Steam Tables	Difference (%)
30	260	1169.0	1169.0	0.00
	1000	1534.0	1534.0	0.00
	1500	1796.6*	1803.2	0.37
400	450	1208.7	1208.8	0.01
	1000	1523.5	1523.3	0.01
	1500	1797.1*	1798.2	0.06
800	520	1201.1	1201.3	0.02
	1000	1511.5	1511.4	0.01
	1500	1792.8*	1792.9	0.01
1500	600	1175.7	1176.3	0.05
	1000	1489.7	1490.1	0.03
	1500	1783.8	1783.7	0.01
2200	660	1147.7	1149.4	0.15
	1000	1467.5	1467.6	0.01
	1500	1774.4	1774.4	0.00
2400	670	1125.5	1129.3	0.34
	1000	1460.5	1460.9	0.03
	1500	1771.7	1771.8	0.01

4-10. Liquid Volume

P (psia)	T (deg F)	v (HOH) (ft ³ /lb)	v in ASME Steam Tables	Difference (%)
30	40	0.01599	0.01602	0.19
	100	0.01610	0.01613	0.19
	240	0.01690	0.01693	0.18
400	40	0.01600	0.01600	0.00
	240	0.01690	0.01690	0.00
	430	0.01909	0.01909	0.00
800	40	0.01597	0.01598	0.06
	200	0.01659	0.01659	0.00
	500	0.02041	0.02041	0.00
1500	40	0.01594	0.01594	0.00
	340	0.01776	0.01775	0.06
	580	0.02271	0.02270	0.04

2200	40	0.01588	0.01590	0.13
	390	0.01829	0.01828	0.05
	640	0.02582	0.02573	0.35
2400	40	0.01587*	0.01589	0.13
	410	0.01854	0.01853	0.05
	650	0.02647	0.02636	0.42

75	3807	3816±38
150	1851	1860±19
350	228.9	228.4±4.6
800	412.2	412±12

4-11. Vapor Volume

P (psia)	T (deg F)	v (HOH) (ft ³ /lb)	v in ASME Steam Tables	Difference (%)
36	260	13.950	13.954	0.03
	1000	28.946	28.943	0.01
	1500	38.909*	38.896	0.03
460	450	1.1734	1.1738	0.03
	1000	2.1329	2.1339	0.05
	1500	2.9152*	2.9037	0.40
800	520	0.5716	0.5717	0.02
	1000	1.0468	1.0470	0.02
	1500	1.4516*	1.4446	0.49
1500	600	0.2820	0.2820	0.00
	1000	0.5394	0.5394	0.00
	1500	0.7639	0.7639	0.00
2200	660	0.1772	0.1767	0.28
	1000	0.3541	0.3545	0.11
	1500	0.5166	0.5165	0.02
2400	670	0.1522	0.1525	0.20
	1000	0.3210	0.3214	0.12
	1500	0.4725	0.4724	0.02

4-13. Conductivity of Water and Steam

P (bar)	T (deg C)	k (HOH) (mw/m ² K)	k in ASME Steam Tables and its uncertainty
1	0	569	569±11
	50	643	643±13
	200	33.2	33.2±1.0
	400	54.9	54.9±1.6
	700	94.3*	94.3±3.8
10	0	570	570±11
	50	644	644±13
	200	35.2	35.1±2.1
	400	55.7	55.7±3.3
	700	95.0	95.0±5.7
75	0	575	575±11
	50	649	649±13
	200	670	670±13
	400	63.9	63.9±3.8
	700	101	101±6
150	0	581	581±12
	50	655	655±13
	200	676	676±14
	400	82.2	82.2±4.9
	700	108	108±6

4-12. Dynamic Viscosity of Water and Steam

P (bar)	T (deg C)	μ (HOH) (micropoise)	μ in the Release of 8th ICPS and its uncertainty
1	25	8892	8909±89
	75	3776	3773±38
	150	141.7	142.9±2.9
	350	223.3	224.3±4.5
	800	403.1*	405±12
10	25	8893	8911±89
	75	3780	3782±38
	150	1818	1824±18
	350	222.8	222.9±4.5
	800	403.5	404±12
95	25	8884	8898±89
	75	3794	3798±38
	150	1832	1841±18
	350	220.9	221.2±4.4
	800	407.5	407±12
150	25	8874	8887±89

Appendix A**Nomenclature and Conversion Factors**

Symbol	Definition	cgs units	British Units
B	British thermal units		
C _p	Specific heat at constant P	J/g-C	B/lb-F
H	Specific enthalpy	J/g	B/lb
J	Joule		
k	Thermal conductivity	mw/m-k	B/hr-ft-F
mw	Milliwatts		
P	Absolute pressure	bars	psia
s	Specific entropy	J/g-C	B/lb-F
T	Temperature	cm ³ /g	ft/lb

μ	Quality		
	Dynamic viscosity	Micropoise	lb ³ /hr-ft
Subscript	Definition		
c	critical point value		
f	saturated liquid value		
g	saturated vapor value		
P	at constant pressure		
s	saturation value		
T	at constant temperature		

Table 5. Conversion Factors

To Convert From	To	Multiply By
bars	psia	14.5038
B/hr-ft-F	mw/m-C	1730.4
B/lb	J/g	2.32596
B/lb-F	J/g-C	4.18680
C	F	1.8C+32
cm ³ /g	ft ³ /lb	0.0160185
ft ³ /lb	cm ³ /g	62.4278
J/gm	B/lb	0.429930
J/gm-C	B/lb-F	0.238846
lb/hr-ft	micropoise	4133.8
micropoise	lb/hr-ft	0.00024191
mw/m-C	B/hr-ft-F	0.00057789
psia	bars	0.0689476

Appendix B

Entries of Data Tables

(The unit of pressure is in psia, and that of temperature is in deg F)

1. Pressure Entries for Saturation Properties
14.5, 50, 100, 200, 280, 350, 500, 700, 900, 1100, 1400, 1600, 1800, 2000, 2100, 2200, 2300, 2400, 2500.
2. Pressure Entries for Non-Saturation Properties
14.5, 50, 100, 200, 350, 500, 700, 1000, 1400, 1700, 2100, 2200, 2300, 2500.
3. T_s - T Entries for Enthalpy of Liquid
20, 40, 60, 80, 100, 200, 250, 300, 400, 500, 620.
4. T_s - T Entries for Specific Volume of Liquid

20, 40, 60, 80, 100, 120, 140, 160, 180, 200, 240, 280, 320, 360, 400, 500, 620.

5. T - T_s Entries for Enthalpy of Vapor

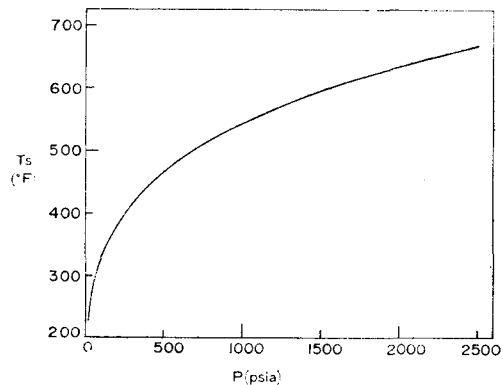
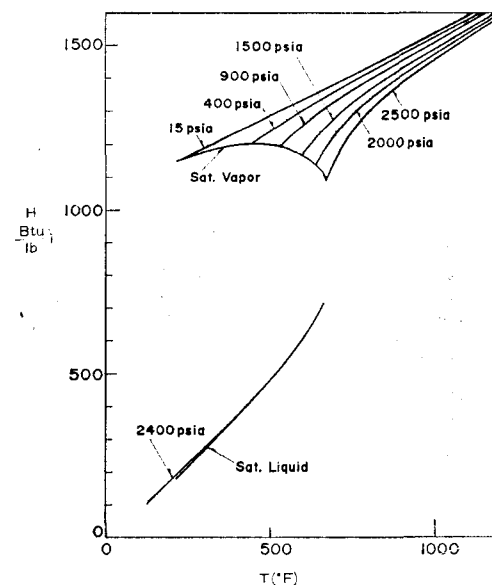
20, 40, 60, 80, 100, 120, 140, 160, 180, 200, 250, 350, 500, 700, 950.

6. T - T_s Entries for Specific Volume of Vapor

10, 20, 40, 60, 80, 100, 150, 200, 300, 400, 500, 700, 950.

Appendix C

Various Property Curves

Fig. 1. T_s versus P Fig. 2. H versus T at Constant P

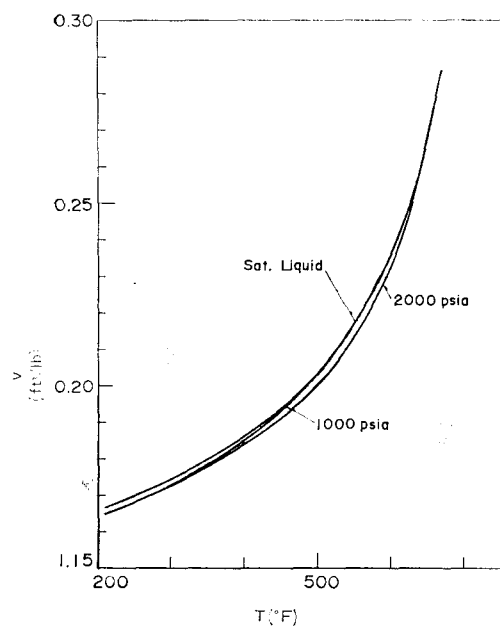


Fig. 3. Liquid v versus T at Constant P

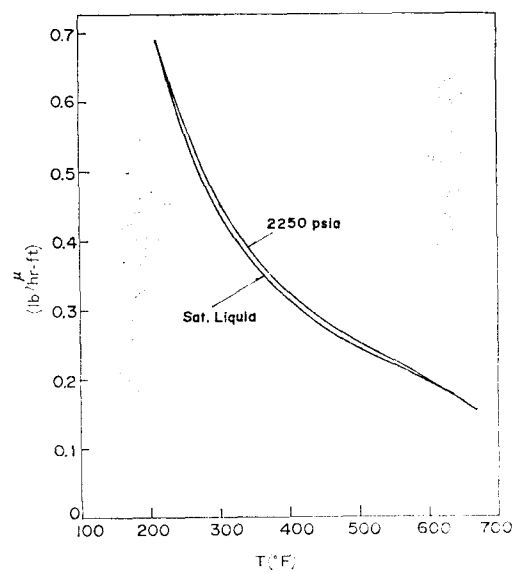


Fig. 5. Liquid μ versus T at Constant P

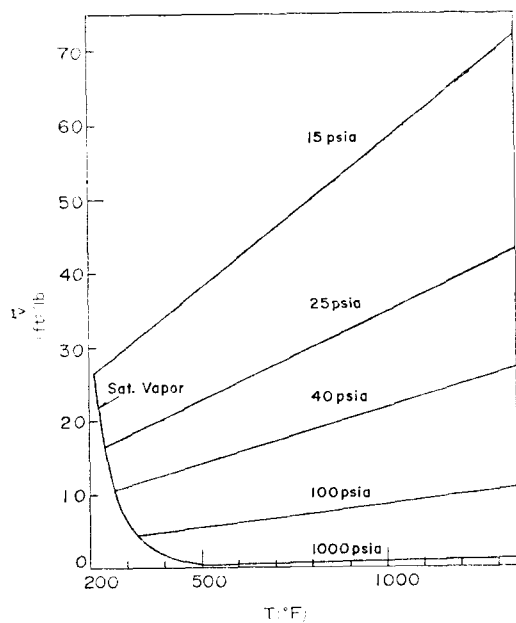


Fig. 4. Vapor v versus T at Constant P

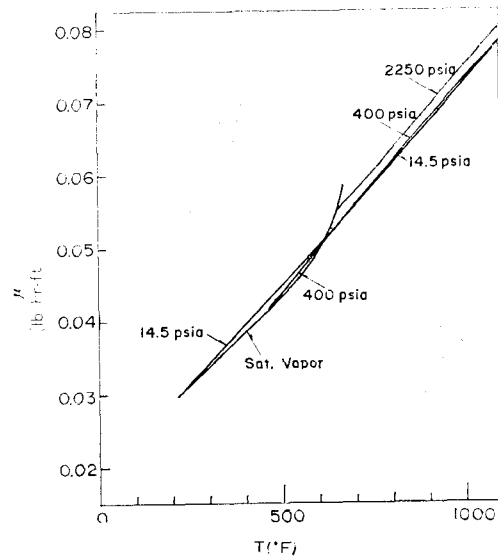
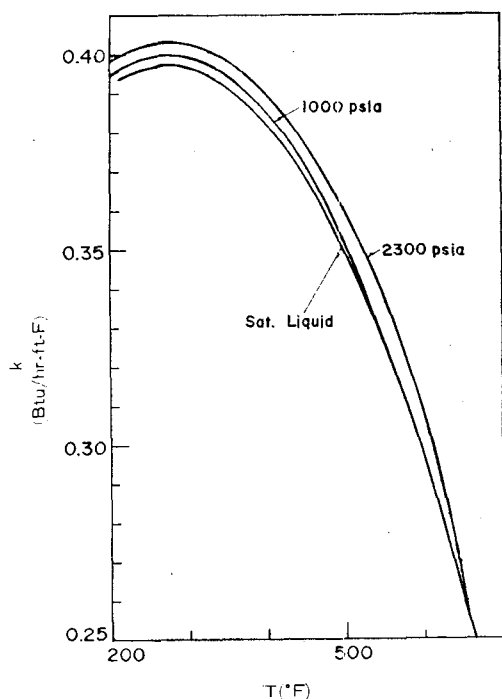
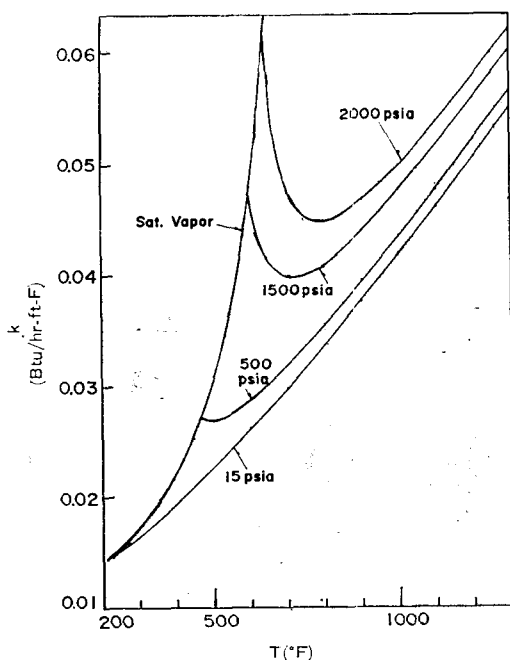
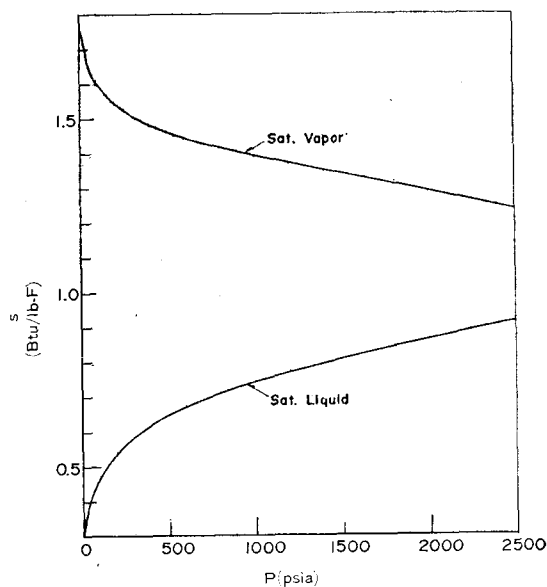


Fig. 6. Vapor μ versus T at Constant P

Fig. 7. Liquid k versus T at Constant P Fig. 8. Vapor k versus T at Constant P Fig. 9. Saturation s versus P

Appendix D

Cubic Bessel Interpolation

This is a four point interpolation technique which can guarantee continuity of derivative (see Figure 10). If one wants to interpolate a value y at x which is located in $x_i \leq x \leq x_{i+1}$ by cubic Bessel interpolation, there should be two more data points at x_{i-1} (below x_i) and at x_{i+2} (above x_{i+1}). Two parabolic equations, one passing through (x_{i-1}, y_{i-1}) , (x_i, y_i) , and (x_{i+1}, y_{i+1}) , [Y1 in Figure 10] and the other (x_i, y_i) , (x_{i+1}, y_{i+1}) , and (x_{i+2}, y_{i+2}) [Y2], can be constructed.

The final cubic interpolating Y , then, can be determined uniquely with the following boundary conditions;

$$Y(x_i) = y_i \quad \dots\dots\dots (D-1),$$

$$\left(\frac{dY}{dx}\right)_{x=x_i} = \left(\frac{dY_1}{dx}\right)_{x=x_i} \quad \dots\dots (D-2),$$

$$Y(x_{i+1}) = y_{i+1} \quad \dots\dots\dots (D-3),$$

$$\text{and } \left(\frac{dY}{dx}\right)_{x=x_{i+1}} = \left(\frac{dY_2}{dx}\right)_{x=x_{i+1}} \quad \dots (D-4).$$

If the cubic Bessel interpolating polynomial is set such as;

Table 6. Coefficients a_{kj}

$j =$	1	2	3
$k=i-1$	$-\frac{\Delta x_i}{\Delta x_{i-1}(\Delta x_{i-1} + \Delta x_i)}$	$\frac{2}{\Delta x_{i-1}(\Delta x_{i-1} + \Delta x_i)}$	$-\frac{1}{\Delta x_{i-1}\Delta x_i(\Delta x_{i-1} + \Delta x_i)}$
i	$\frac{\Delta x_i - \Delta x_{i-1}}{\Delta x_{i-1} \cdot \Delta x_i}$	$\frac{1 - 2\Delta x_{i+1}^2}{\Delta x_i^2} - \frac{2 + 5\Delta x_{i-1}}{\Delta x_{i-1} \cdot \Delta x_i} - 3$	$\frac{a_{22}}{\Delta x_i} + \frac{a_{21}}{\Delta x_i^2} + \frac{1}{\Delta x_i^3}$
$i+1$	$\frac{\Delta x_{i-1}}{\Delta x_i(\Delta x_{i-1} + \Delta x_i)}$	$-\frac{2(a_{21} + a_{31})}{\Delta x_i} - (a_{22} + a_{42})$	$\frac{a_{32}}{\Delta x_i} + \frac{a_{31}}{\Delta x_i^2} - \frac{1}{\Delta x_i^3}$
$i+2$	0.0	$-\frac{\Delta x_i + \Delta x_{i+1}}{\Delta x_{i+1}}$	$\frac{a_{42}}{\Delta x_i}$

$$Y = y_i + A_1(x - x_i) + A_2(x - x_i)^2 - A_3(x - x_i)^3 \dots \dots \dots (D-5),$$

the coefficients A_j can be constructed by

$$A_j = \sum_{k=i-1}^{i+2} a_{kj}(\Delta x_{i-1}, \Delta x_i, \Delta x_{i+1}, \Delta x_{i+2}) y_k \dots \dots \dots (D-6),$$

where the coefficients a_{kj} depend only on $x_i (i-1 \leq i \leq i+2)$ as presented in Table 5. Since a_{kj} are constants for all x in the same region ($x_i \leq x \leq x_{i+1}$) and independent on y , they can be used repeatedly if x varies in the same region and/or y might be other dependent variable. It is subroutine ARGUM with was programmed to obtain the coefficients a_{ki} .

The calling sequence of ARGUM is CALL ARGUM (X, A1, A2, A3, ISTEP). The argument X is a real array which contains x table. A_1, A_2, A_3 are one-dimensional real arrays which must be of dimension 4 or greater. ISTEP is an integer variable which indicates the location of x in X table. On exit from ARGUM, A_1, A_2 and A_3 contain a_{k1}, a_{k2} and a_{k3} ($k = \text{ISTEP}-1, \text{ISTEP}, \text{ISTEP}+1, \text{ISTEP}+2$), respectively. There is no error checking in ARGUM.

References

1. W.A. Coffman and L.L. Lynn, "WATER: A Large Range Thermodynamic and Transport Water Property FORTRAN-IV Computer Program", WAPD-TM-568, December 1966.
2. National Engineering Laboratory Steam Tables, prepared by R.W. Bain, Her Majesty's Stationery Office, Edinburgh, Scotland, 1964.
3. L.L. Lynn, "A Digital Computer Program for Nuclear Reactor Design Water Properties", WAPD-TM-680, Westinghouse Electric Co., July 1967.
4. J. Kestin and J.H. Whitelaw, "The Sixth International Conference on the Properties of Steam-Transport Properties of Water Substance", p. 82-104, 1966.
5. The Eighth International Conference on the Properties of Steam, Release on Dynamic Viscosity of Water Substance, ASME Steam Tables (1967) Appendix 6, September 1975.
6. C.A. Meyer, R.B. McClintock, G.J. Silvestri, and R.C. Spencer, Jr., "ASME Steam Tables", The American Society of Mechanical Engineers, New York, 1967.

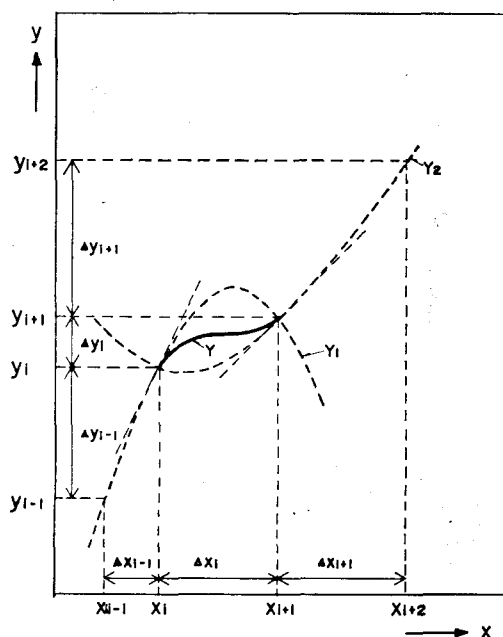


Fig. 10. Cubic Bessel Interpolating Polynomial