



**1967**

**ASME  
STEAM  
TABLES**

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**THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS**  
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# **THERMODYNAMIC AND TRANSPORT PROPERTIES OF STEAM**

comprising

## **TABLES AND CHARTS FOR STEAM AND WATER**

calculated using

**The 1967 IFC Formulation for Industrial Use**

in conformity with

**The 1963 International Skeleton Tables**

as adopted by

**The Sixth International Conference**

**on the ~~Properties of~~ Steam**

~~prepared by~~

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for

**ASME RESEARCH COMMITTEE  
ON PROPERTIES OF STEAM**

**THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS**  
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## Foreword

The publication of these new ASME Steam Tables represents the culmination of an ASME project which had its origin in 1954 when, at the Fourth International Conference on Properties of Steam held in Philadelphia, Pa., it was decided that the time had come to update our knowledge of the thermodynamic properties of steam. Fortunately, the Society was able to take advantage of the experience of a number of its members who were involved in a similar venture more than thirty years earlier.

Just as occurred previously, the project required fund raising, identification and technical supervision of new experimental research, extensive international cooperation and coordination, and the adoption of internationally accepted skeleton tables. This time, however, the demand for standardization of design and performance calculations could not be satisfied by skeleton tables alone. International agreement had to be reached on a set of equations which would reproduce these skeleton tables, provide a suitable interpolation scheme, and yet give reasonable computer efficiency when incorporated in the already complex computer programs used day after day for design and performance calculations.

A mere citation of names is hardly sufficient recognition for the long list of contributors to this project. It includes the sponsors, members of the ASME Research Committee on the Properties of Steam and its Technical Committee, the International Secretariat, the U.S. delegates and observers at the International Conferences, the various working groups established by the Sixth Conference, the subcommittees charged with the design and preparation of these tables, and the ASME headquarters staff which guided the manuscript through publication.

As might be expected of a committee whose work extends for nearly two decades, its membership has undergone some changes. Those who have served on the Properties of Steam Research Committee in the past are the first chairman, J. W. Parker,\* W. F. Allen, F. G. Brickwedde, A. G. Christie,\* F. W. Davis, H. D. Emmert, S. N. Fiala, C. C. Franck,\* M. Frisch, J. R. Hamann, J. H. Keenan, F. G. Keyes, P. H. Knowlton, Jr., E. H. Krieg, D. W. R. Morgan, A. C. Pasini, R. B. Smith, H. L. Solberg, R. M. VanDuzer, Jr., and L. S. Wilcoxson.

Because their contribution to the program might not otherwise be clear, the Society hereby records its appreciation to Professor Frederick G. Keyes, who served as chairman of the United States Commission to the International Coordinating Committee; to Professor Joseph H. Keenan, who served in a dual capacity as the national and international Secretary until 1963; to Professors Joseph Kestin and Bruce H. Sage, who served as U.S. Delegates; to John A. Tillinghast, Vice Chairman of the ASME Research Committee on Properties of Steam; and to Professor S. R. Beitler, ASME Director, Research, who served as the Executive Secretary for the Sixth International Conference on Properties of Steam.

These credits would be incomplete if we did not acknowledge the special contribution made by the Steam Division of Westinghouse Electric Corporation and the Large Steam Turbine-Generator Department of the General Electric Company in assigning senior staff engineers and allocating programming and computer time leading up to the adoption of the 1967 IFC Formulation, and to the preparation of these tables. Finally, we are indebted to George A. Hendrickson for drawing the figures and charts, to Joseph Hilsenrath of the National Bureau of Standards for editorial assistance, and to Ernest H. Garbinski for his untiring efforts in this endeavor.

*Walker L. Cisler*  
Chairman

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# I Introduction

Nearly a half century has elapsed since The American Society of Mechanical Engineers began a concerted and sustained effort to provide reliable and consistent tables of the thermodynamic properties of steam and water. It started with the establishment in 1921 of the ASME Research Committee on Thermal Properties of Steam. This committee was instrumental in stimulating and arranging funds in the early 1920's for fundamental research at Government and university laboratories, resulting in data which are still used today.

The committee took advantage of parallel interests in England, Germany, and Czechoslovakia to achieve a coordinated research program of international scope, and, moreover, to provide for a formal machinery for reaching international agreement on the "best values" for the properties of this important substance. Such international agreement was important even then in providing a uniform standard for the specification and performance of equipment for generating and utilizing steam.

The First International Conference on Properties of Steam, London, England, 1929, concerned itself with a detailed examination of the tables of specific volume and enthalpy submitted by the various national delegations. The skeleton tables compiled at that conference served as the basis for the 1930 ASME Steam Tables, prepared by Professor J. H. Keenan and published by ASME. This conference recognized that considerable additional measurements would be required before a truly satisfactory representation of these properties could be agreed upon.

Progress was reviewed at the Second International Conference, held in Berlin, Germany, in 1930, at which time, significant modifications were made in the skeleton tables. The time, however, was not ripe for full agreement. Such agreement was reached in 1934 at the Third International Conference held in Washington, D.C., Cambridge, Mass., and New York, N.Y., with the adoption of skeleton tables giving the specific volume and enthalpy along the saturation line and at round values of temperature and pressure for the compressed liquid and superheated vapor. In addition, each entry in the tables had associated with it a tolerance, so that the two values would "constitute a criterion, internationally agreed upon, by which, the reliability of steam tables may be judged."<sup>1</sup> The skeleton tables and the experimental measurements which led up to them served as the basis for a number of publications, the most prominent of which was the Keenan and Keyes Steam Tables<sup>2</sup> which has served as the *vade mecum* of engineers these past 30 years.

The need was recognized for continued research on properties of steam and water by the Third International Conference, to an extent that solicitations and even recorded assurances from various delegations and institutions assured that the work on steam would be continued and extended.

The plan to hold a Fourth International Conference in Prague, Czechoslovakia, gave way in time to more pressing problems brought on by the Second World War. Almost twenty years elapsed before the thermodynamic properties of steam again became an active concern of the Society and the international scientific and engineering community. When the Fourth International Conference was held in Philadelphia, Pa., in 1954, it was evident that technological advances made in intervening years would require thermodynamic information outside of the temperature and pressure range of the existing steam tables. The Society established a research committee on the Properties of Steam, and charged it with the task of arranging for new research and re-establishing the program of international coordination which had proved so fruitful two decades earlier. The Society also accepted the invitation to serve as the permanent Secretariat for the International Conferences on Properties of Steam.

<sup>1</sup> A report on the "Third International Conference on Steam Tables," *Mechanical Engineering*, American Society of Mechanical Engineers, New York, Vol. 57, November 1935.

<sup>2</sup> J. H. Keenan and F. G. Keyes, *Thermodynamic Properties of Steam Including Data for the Liquid and Solid Phases*, John Wiley & Sons, Inc., New York, 1936.

## Introduction

By this time, interest had developed in Japan and the U.S.S.R. in thermodynamic tables for steam having the status of an international standard. Moreover, a considerable body of new experimental measurements had been reported or started by a number of institutions in the Soviet Union. Thus, at the time of the Fifth International Conference, London, 1956, it was evident that the work of examining the published data and supervising the then current research could be handled best by national commissions from the four countries in which the major experimental research was being carried on. It was further agreed, that the national commissions (Federal Republic of Germany, United Kingdom, Union of Soviet Socialist Republics, and the United States of America) would constitute the International Coordinating Committee – the working group of the Fifth International Conference.

The labors of the International Coordinating Committee were rewarded at a plenary session of the Sixth International Conference on the Properties of Steam, New York, N.Y., 1963, when the tables were adopted as “The International Skeleton Tables of 1963” (see Appendix 4). The temperature range of the skeleton tables is from 0 to 800°C and the pressure extends to 1000 bars – a considerable extension over the range of the 1934 Skeleton Tables. Where new experimental data reflected refined experimental techniques, they are, in turn, reflected in the narrower “tolerance” limits of the new tables. The skeleton tables adopted by 16 member nations of the Sixth International Conference, are the bases for the equations from which these ASME Steam Tables have been computed.

Long before the work of the International Coordinating Committee was completed, it was clear to most members of the working groups that the skeleton tables alone did not insure the degree of reproducibility originally envisioned for design and performance calculations owing to the relatively coarse grid of the skeleton tables and to the requirements of performing numerical differentiation and integration. It became important to ensure that each country handled the numbers in the same way when it came to compiling detailed tables such as the following, or, when incorporating the skeleton tables into a computer program for design and performance calculations. The Sixth International Conference was cognizant of this problem and established an International Formulation Committee (IFC) to:

“Develop at the earliest practical date a formulation for use with computers of the properties of steam as they are represented by the International Skeleton Tables of 1963. This formulation shall provide values that are, at all points, within the tolerances stated in the International Skeleton Tables of 1963, and shall be thermodynamically consistent.”

After two years of sustained effort, during which, delegates from Japan and Czechoslovakia joined those of the Federal Republic of Germany, United Kingdom, United States of America, and the Union of Soviet Socialist Republics, a conference was held in Prague, at which agreement was reached concerning the form and characteristics of the equations which would meet the requirements laid down by the Sixth International Conference. A year later (March 1966), the IFC met in Glasgow, Scotland. After much deliberation, unanimous agreement was reached among the six national delegations on a formulation, which, after some post-conference modifications, was recommended to the members of the Sixth International Conference.

While it was the general feeling of the IFC that the formulation did indeed satisfy the requirement for international standardization of steam tables for industrial use, it left much to be desired as a definitive equation of state for steam; thus, “The 1967 IFC Formulation for Industrial Use: A Formulation of the Thermodynamic Properties of Ordinary Water Substance.” Several of the countries participating in the Sixth International Conference are using this formulation to prepare more detailed tables for steam and water. This formulation, repeated in Appendix 1 as ratified and promulgated by the IFC, is the basis for the thermodynamic tables and figures in these new ASME Steam Tables.

The Sixth International Conference expanded the scope of its activity by establishing a panel of experts to develop skeleton tables for transport properties (viscosity and thermal conductivity) of steam and water. That panel completed its work at a meeting in Paris, France, in June 1964 and the transport properties given here are based on the skeleton tables and the empirical equations which they developed. These are discussed in a later section.

## II Thermodynamic Properties

The thermodynamic properties are presented here in nine tables and thirteen charts. These were computed from the equations adopted in the "1967 IFC Formulation for Industrial Use," which is reproduced in toto in Appendixes 1 and 2. As indicated earlier, it was not possible to settle on a single equation of state for the behavior of steam over the entire pressure and temperature range covered by these tables. It was possible to fit the existing experimental data with requisite precision if the range was divided into suitable subregions. Six such subregions were found useful and an equation of state fitted for each. The details of how these equations may be handled on a variety of computers are to be found in a paper by McClintock and Silvestri.<sup>3</sup>

In the discussion which follows, the equation numbers are those given in Appendixes 1, 2, and 5, and the subregions are those delineated in Figures 1 and 2 taken from the "1967 IFC Formulation for Industrial Use." These subregions have four interregional boundaries. Two are the constant temperature lines between Subregions 1 and 4 and 5 and 6 (622 F), and between Subregions 3 and 4 (705.47 F). Another is the saturation line well delineated in Tables 1 and 2. The fourth is that between the superheated and critical Subregions 2 and 3 and is shown in Table 8.

Discontinuities in property values exist along the interregional boundaries between Subregions 1 and 4 and between Subregions 2 and 3. The magnitude of these discontinuities is discussed and described in detail in Appendix 3. In the tables, property values lying on these interregional boundaries were calculated using the equations of Subregions 1 and 2 rather than those of Subregions 3 and 4.

### SATURATION PROPERTIES

Table 1 lists the saturation pressure and specific volume, entropy, and enthalpy values for saturated steam and for saturated water as well as the changes in these upon vaporization at round values of temperature from 705 to 32 F,\* and at the critical and triple points. The saturation pressure was calculated at the given temperature using Equation 5 (App. 1). Along the boundaries of Subregions 1 and 2, the saturated steam and water property values were calculated directly as a function of the temperature and saturation pressure using Equations 9.1 and 9.2 (App. 1). Along the boundaries of Subregions 3 and 4, where the independent variables of the equations are specific volume and temperature, the specific volume was varied until the pressure obtained from Equations 9.3 and 9.4 (App. 1) converged to the saturation pressure within,

$$\frac{p(\text{Eq 9.3 or 9.4}) - p(\text{Eq 5})}{p(\text{Eq 5})} < 5 \times 10^{-17}$$

except, at the critical point (705.47 F) where the specific volume was fixed at 3.17 cm<sup>3</sup>/g. The resulting specific volume and temperature were then used in Equations 9.3 and 9.4 to calculate the remaining property values.

In the first page of Table 2, the same functions plus the steam and water specific internal energies are given at round values of pressure from 30 to 0.2 inches of mercury. The remaining pages of Table 2 show all these functions from 3200 to 0.1 psia, and at the critical, boiling, and triple points.

<sup>3</sup> R. B. McClintock and G. J. Silvestri, "Formulations and Iterative Procedures for the Calculation of Properties of Steam," The American Society of Mechanical Engineers, New York, 1967; paper presented at the Joint Power Conference, Detroit, Mich., September 1967.

\*The temperature is given in decreasing order to facilitate visual interpolation.

Thermodynamic Properties

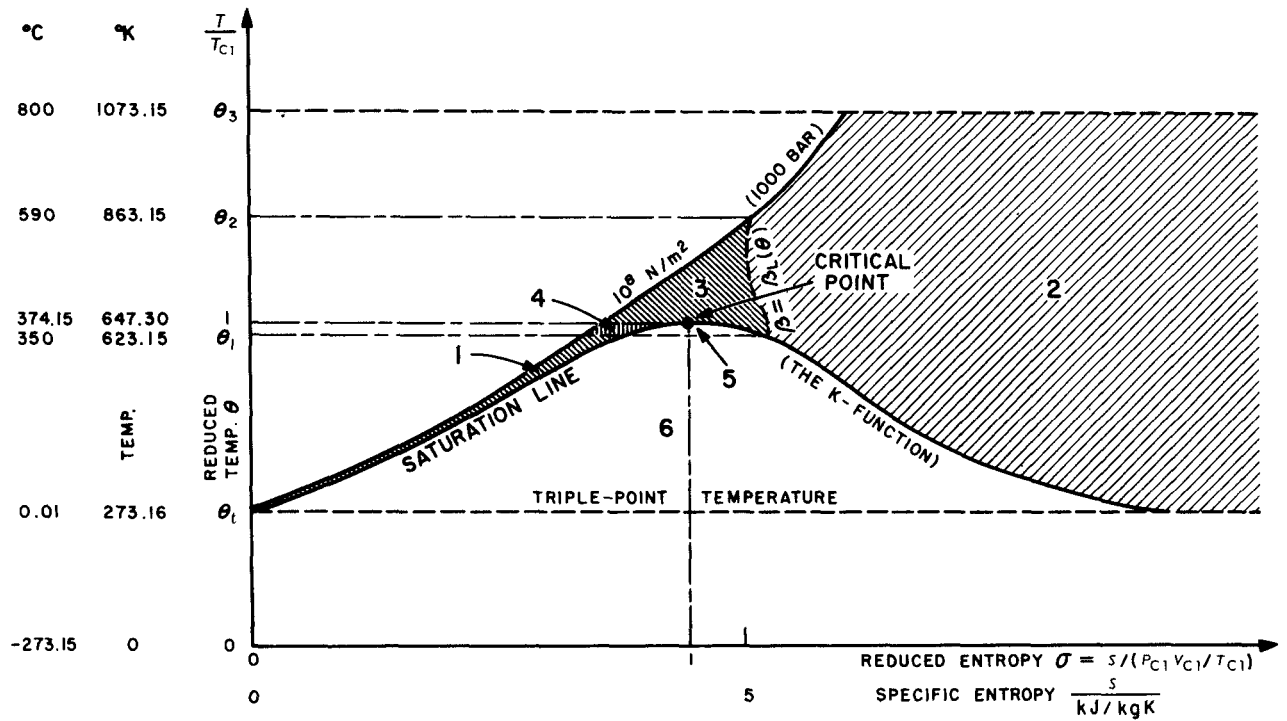


FIG. 1 ILLUSTRATION OF SUBREGIONS ON THE TEMPERATURE-ENTROPY DIAGRAM

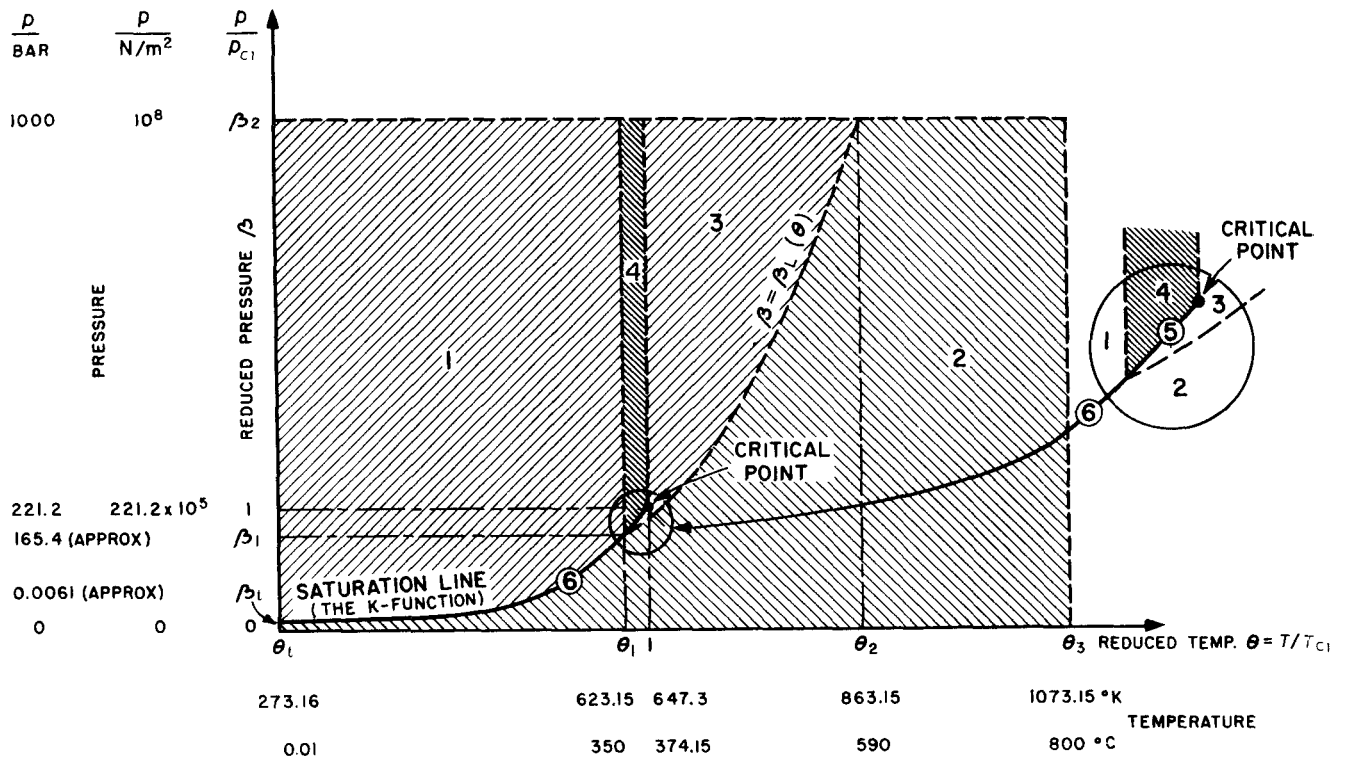


FIG. 2 ILLUSTRATION OF SUBREGIONS ON THE PRESSURE-TEMPERATURE DIAGRAM

The saturation temperatures at the desired pressures were obtained by iteration using Equation 5 with convergence on pressure to  $10^{-10}$  bars [except at the critical point (374.15 C), the boiling point (100 C) and triple point (0.01 C) where no iteration was required]. From this point the calculation procedures were identical to those of Table 1.

Discrepancies may exist between the tabulated values of  $h_{fg}$ ,  $v_{fg}$ ,  $s_{fg}$ , and those obtained by subtracting the corresponding liquid and vapor values since values for the liquid and vapor were rounded after the values of  $h_{fg}$ ,  $v_{fg}$ , and  $s_{fg}$  were computed.

### SUPERHEATED STEAM AND COMPRESSED WATER

Table 3, which constitutes the major portion of these Tables, is devoted to the specific volume, enthalpy, and entropy of the superheated steam and the compressed water for temperatures from 1500 to 32 F in 10-degree intervals, and pressures of 0.12 to 15,500 psia. The tabulated properties were calculated using procedures similar to those described for Table 1, except that the given pressure was used in place of that obtained from Equation 5.

### CRITICAL REGION

Table 4 provides the same properties at 2 F and 20 psia steps to permit more accurate interpolation in the critical region (800 to 650 F; 2800 to 3980 psia) where the properties vary rapidly. The procedures for calculating the values were the same as for Table 3.

### ISENTROPIC AND ISENTHALPIC TABLES

The arrangement of Tables 5 and 6 is designed to facilitate the solution of isentropic and isenthalpic flow problems. In Table 5, the enthalpy is tabulated as a function of the pressure for 6.0 to 0.25 inches and 0.12 to 15,500 psia, and of the entropy in steps of 0.01 Btu/lbm F. Calculations in Subregion 2 required the approximation of the temperature, which, together with the specified pressure, was used to calculate entropy using Equation 9.2. Iteration on the temperature was continued until convergence within  $2 \times 10^{-5}$  J/g  $\times$  C was achieved at each tabulated entropy. The resulting values of temperature and the specified pressure were then used to determine the enthalpy by Equation 9.2. For Subregion 3, approximations of the temperature and specific volume were used with an intermediate convergence on the desired pressure to calculate entropy by Equation 9.3. Iteration and convergence similar to that for Subregion 2 was utilized with the final step being the determination of enthalpy by Equation 9.3, using the final values of temperature and specific volume. In Subregions 5 and 6, procedures similar to those for Table 2 were utilized to determine the saturated steam and water values with iteration to the desired entropy.

Table 6 contains entropy values for the same pressure range as Table 5 and for enthalpy in steps of 10 Btu/lbm. The calculation procedure was similar to that for Table 5, with enthalpy and entropy interchanged.

### SUPERSATURATED STEAM

Shown in Table 7 are values for specific volume, enthalpy, and entropy of supersaturated steam at pressures of 0.12 to 1500 psia and from the saturation temperature to a temperature corresponding to approximately 4½ percent moisture. The calculation procedure follows that for Subregions 2 and 3 of Table 3.

### IFC BOUNDARIES

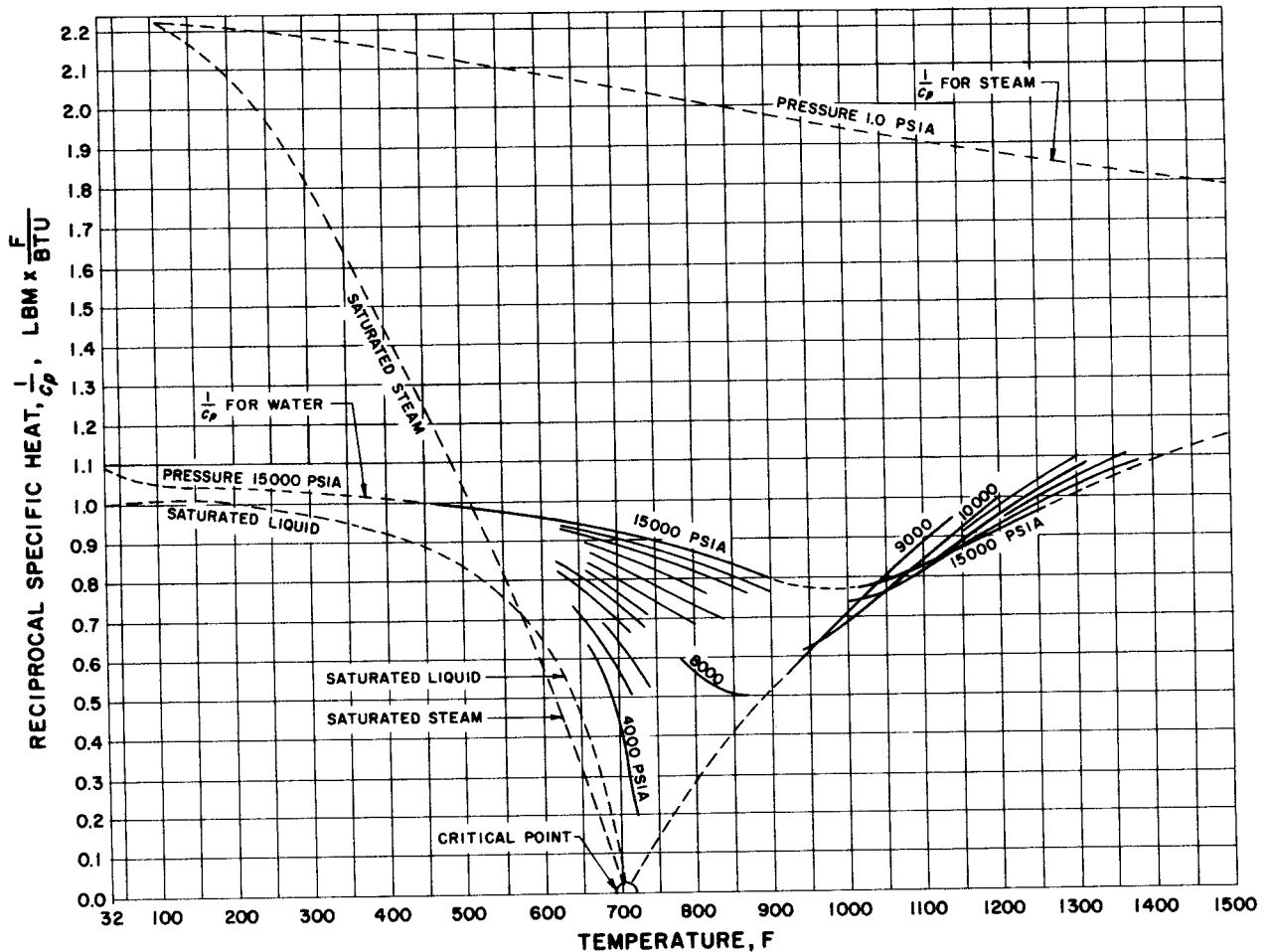
Table 8 gives the boundary between Subregions 2 and 3. Values of specific volume, enthalpy, and entropy have been calculated for each applicable pressure or temperature of Tables 3 and 4. The interregional boundary function (Equation 3.2.2, App. 1) is used to find the pressure at a given temperature. When pressure was the

Thermodynamic Properties

independent variable, iteration was used with Equation 3.2.2 and convergence to within  $5 \times 10^{-5}$  bars of the desired pressure. The values of specific volume, enthalpy, and entropy were evaluated using Equation 9.2 of Subregion 2. It should be noted that Equation 9.3 of Subregion 3 would provide slightly different values at these points, differing by the discontinuity on the interregional boundary.

SPECIFIC HEAT

Table 9 gives the specific heat at constant pressure (isobaric heat capacity) for the superheated vapor and the compressed liquid. The values have been calculated largely from the formulas contained in the "Supplement to the 1967 IFC Formulation" (see Appendix 2). A plot of the values resulting from the above equations showed local variations near the interregional boundaries of about 5 percent. In these regions (shown by solid lines in Figure 3) use was made of a graphical spline fit for smoothing the tables. It should be noted that Figure 3 gives the reciprocal of the specific heat, thereby avoiding the excursions to infinity which is characteristic of normal plots in this region.



PRESSURE	TEMPERATURE RANGES FAIRED	
4000 PSIA	660 F - 720 F	
5000 "	640 F - 720 F	
6000 "	680 F - 740 F	
7000 "	620 F - 720 F	
8000 "	620 F - 740 F	840 F - 860 F    920 F - 940 F
9000 "	660 F - 740 F	940 F - 1140 F
10000 "	660 F - 800 F	940 F - 1200 F
11000 "	660 F - 840 F	1000 F - 1300 F
12000 "	660 F - 820 F	1040 F - 1320 F
13000 "	620 F - 880 F	1060 F - 1380 F
14000 "	620 F - 900 F	1000 F - 1380 F
15000 "	470 F - 900 F	1020 F - 1260 F

FIG. 3 SPECIFIC HEAT FORMULA SHOWING GRAPHICALLY-FAIRED REGIONS



## III Transport Properties

### VISCOSITY

The values of viscosity of steam and water are given in Table 10 at 32 F and at 50-degree intervals of temperature from 50 to 1500 F at chosen values of pressure from 1 to 12,000 psia. Figure 4 shows the formula regions and outlines the sources of these data. The values are plotted in Figure 7.

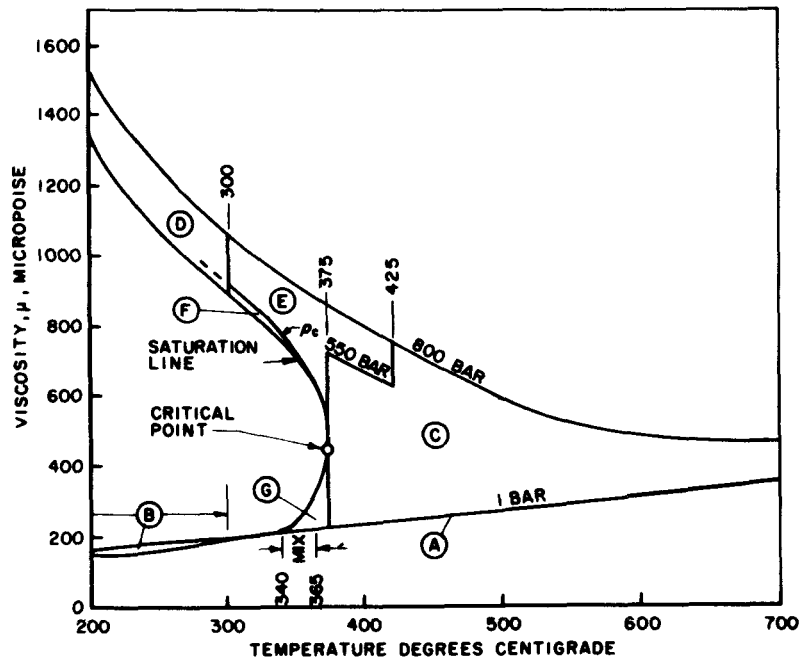
The kinematic viscosity, computed using the relation  $\nu = \mu \times g_c \times v$ , is plotted in Figure 8.

### THERMAL CONDUCTIVITY

The values of thermal conductivity of steam and water are given in Table 11 at 32 F and at 50-degree intervals of temperature from 50 to 1500 F at chosen values of pressure from 1 to 7500 psia. Figure 5 shows the formula regions and outlines the sources of these data. The values are plotted in Figure 9.

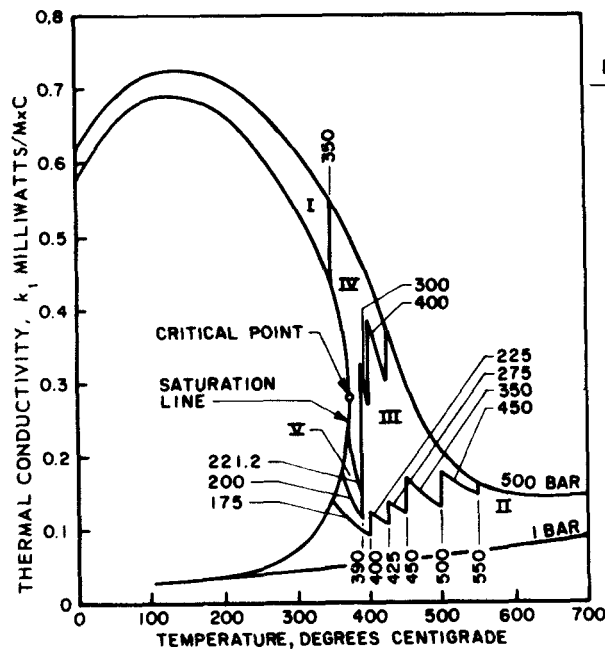
### PRANDTL NUMBER

The Prandtl numbers of steam and water are given in Table 12 at 32 F and at 50-degree intervals of temperature from 50 to 1500 F and at chosen values of pressure from 1 to 7500 psia. Point values are computed directly from Tables 9 ( $c_p$ ), 10 ( $\mu$ ), and 11 ( $k$ ), from the relation  $Pr = \mu c_p / k$ .



REGION	PRESSURE RANGE BAR	TEMPERATURE RANGE C	EQUATION
A	1 BAR	100 TO 700	2.1 APPENDIX 5
B	1 BAR TO SAT.	100 TO 300	2.2 APPENDIX 5
C	1 TO 800 BAR	375 TO 700	2.3 APPENDIX 5
D	SAT. TO 800 BAR	0 TO 300	2.4 AND 2.5 APPENDIX 5
E	$p_c < p < 800$ BAR	300 TO 375	INTERPOLATION } USING 1ST, APPENDIX 5
F	$550 \text{ BAR} < p < 800$ BAR	375 TO 425	
G	$p_{sat.} < p < p_c$	300 TO $T_{sat.}$	EXTEND (B) AND (C) MIX 340 TO 365 C
	1 BAR $< p < p_c$	300 TO 375	

FIG. 4 VISCOSITY FORMULA REGIONS



REGION	EQUATION
I	3.4 APPENDIX 5
II	3.1 AND 3.2 APPENDIX 5
III	S. BACH AND V. GRIGULL BRENNST WÄRME KRAFT 18 (1966) pp 125-127
IV & V	INTERPOLATION USING 1ST, APPENDIX 5

FIG. 5 THERMAL-CONDUCTIVITY FORMULA REGIONS