STANDARDIZED STEAM PROPERTY TABLES

DESIGNATED A

VIRTUAL HISTORIC MECHANICAL ENGINEERING LANDMARK

by

THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS

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Sketch of an AEOLIPILE, invented by Hero of Alexandria (c. 10 - 70 CE)

ASME HISTORIC MECHANICAL ENGINEERING LANDMARK
STANDARDIZED STEAM PROPERTY TABLES

INTRODUCTION

Steam property tables, for brevity often simply called *steam tables, are vital and invaluable compilations of a vast amount of data about the thermodynamic and other related properties of steam and water. Properties of a material are characteristics that can be observed and measured. Five examples of these properties of water and steam are (1) the temperature at which water boils, which in turn depends on the pressure of the water, (2) the quantity of energy (typically heat energy) required to heat a known mass of water at a given temperature to boil into steam, (3) the quantity of energy required to increase the temperature of the steam to a desired value, (4) the density of water or steam as a function of its temperature and pressure and (5) the quantity of energy to be removed from water to freeze it to ice. Two other properties of steam and water that are of great interest to engineers are its (6) enthalpy (total heat) and (7) entropy. Explanations of these latter two are beyond the scope of this brochure. Further information about those two properties may be found in several of the reference papers listed on p.12. The properties enumerated above are only seven examples of the literally dozens of steam and water properties that have been determined through measurement and research.

Steam property data was amassed beginning in the 1840s, about the end of the Industrial Revolution. Engineers and scientists recognized that such knowledge was needed to design or improve machines to efficiently utilize steam, for example, a steam locomotive or a steam turbine to drive an electric generator or to propel a ship. Refining that data and extending the research into ever higher steam temperatures and pressures steam continues to this day.

The History and Heritage Committee of the American Society of Mechanical Engineers (ASME) recognizes that the development of standardized steam property tables represents a genuine and major advance in the practice of mechanical engineering. The Committee, therefore, decided to designate the creation of standardized steam property tables as a Historic Mechanical Engineering Landmark. (For more about ASME's landmark program, see the last page of this brochure.)

Normally, when ASME designates a Landmark, a physical artifact exists to which a bronze plaque describing the significance of the landmark to mechanical engineering is affixed in a formal designation ceremony. In this case no suitable tangible artifact exists, so standardized steam property tables are being designated as a "*Virtual*" Historic Mechanical Engineering Landmark. Virtual landmarks are included along with tangible landmarks in the roster of ASME's Landmarks posted on ASME's web site, asme.org Each landmark page has a link to its commemorative brochure.

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* When one searches the Internet for "Steam Tables" the results come up in two groupings:

1. A table, usually found in a cafeteria or restaurant, that holds food containers which are kept hot by steam circulating beneath them and
2. Books, tabulations, charts, and links to computer software giving thermodynamic and other properties of steam and water. It is obviously this grouping that is the subject of this landmark.

On the Cover: An aeolipile, also known as a Hero's engine, is a simple device which spins when the central water container is heated by fire. The resulting steam exiting the nozzles (small "L"-shaped pipes) produce torque to rotate the device, much like water causes a lawn sprinkler to spin. The Greco-Egyptian mathematician and scientist Hero of Alexandria (c. 10 - 70 CE) described the device in the 1st Century CE, and many sources give him the credit for its invention.

The aeolipile that Hero described is the earliest known steam engine or reaction steam turbine. The name – derived from the Greek word Αἴολος and Latin word *pila* – translates to "the ball of Aeolus", Aeolus being the Greek god of the air and wind.

Illustration courtesy of Wikipedia

HISTORY OF STEAM PROPERTY TABLES

During the Industrial Revolution (mid 18th Century to mid 19th Century), and arguably well before that, mechanical engineers exploited steam for a myriad of uses such as to (1) drive machines (e.g., water pumps, steam locomotives, ships, electric generators) with steam engines or steam turbines, (2) heat buildings, (3) promote chemical processes and (4) extract oil from wells. Steam is the vapor (gas) phase of water and is produced by heating water until it boils and then, if desired, heating the steam to a higher temperature. Reliable data of the properties of both water and steam is vital to mechanical engineers, especially those working with heat engines. Steam has many different properties. In addition to the seven properties mentioned in the introduction to this brochure, there are many other thermodynamic, physical, and chemical properties of water and steam that are of interest to engineers and scientists.

Steam is not a "Perfect Gas", so it does not obey the perfect (or ideal) gas laws nor is there a simple formula to calculate its properties over a wide range of conditions. Thus, properties of water and steam must be determined through measurements in combination with thermodynamic relationships. Once the properties are determined at discrete points, formulas are developed to interpolate values between known points or to extrapolate the data beyond the measured points. In the early years, these properties of H_2O, in both the liquid (water) and gas (steam) phases, were published in tabular form in books known as Steam Tables. In more recent times, steam properties have been expressed in equations that can be implemented in computer code, so it is not necessary for engineers to work from a printed table of properties.

18th AND 19th CENTURIES

In the late 1700s, Scottish inventor and engineer James Watt (1736–1819) measured some basic steam properties but since the science of thermodynamics had not yet been developed, not much use was made of them. Watt is better known for the improvements he made, c. 1776, to Thomas Newcomen's steam engine of 1712. The earliest known steam property tables date from the 1840s when Victor Regnault (1810–1878), assisted by William Thomson (later Lord Kelvin) (1824–1907), published some basic steam properties, based on their laboratory measurements.

In 1859, Scottish engineer William J.M. Rankine (1820–1872) published *A Manual of the Steam Engine and Other Prime Movers* which included an appendix containing rudimentary steam property tables. Rankine is known for developing the Rankine Cycle, an ideal thermodynamic cycle in which a working fluid, e.g., steam, converts the heat energy in steam into useful work in a steam engine.

Hugh L. Callendar (1863–1930) created a set of equations dealing with steam properties at high temperatures based on his research. Around 1900 his first steam tables were published.

20th CENTURY

During the early decades of the 20th Century various researchers published sets of steam property tables. For example, in 1906 in Germany, Richard Mollier (1863–1935) published what can be considered the first modern steam property table because he introduced the concept of the property enthalpy.

Another influential set of steam tables, first published in 1910, was *Tables and Diagrams of the Thermal Properties of Saturated and Superheated Steam* by Harvey N. Davis (1881 - 1952) and Lionel S. Marks (1871–1955). Davis was involved in ASME's organizing meeting for steam property tables in 1921 and served as ASME's 57th President (1938–1939). Marks is also known for publishing, in 1916, the first edition of what is today known as *Marks' Standard Handbook for Mechanical Engineers*).

These pioneering efforts were supplemented by the publication of steam property tables by a variety of other researchers working in different countries. Unfortunately, some of the data differed between tables, particularly at higher steam pressures. This was a problem. Standardized steam properties play a major role in commercial matters since steam properties are used by engineers in the designing and testing of machines such as steam turbines, and, in turn, in setting performance guarantees for such machines.

This calorimeter is the instrument used at the National Bureau of Standards, now known as National Institute of Standards and Technology (NIST), in the 1920s and 1930s to measure the heat of vaporization and related properties of steam at temperatures below 100 ℃; these data still play a significant role in modern steam tables.

(Photo courtesy of NIST)

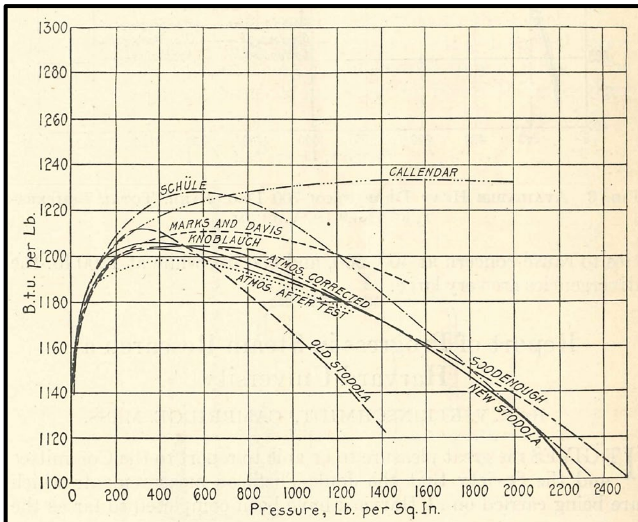

FIG. 1 TOTAL HEAT CONTENT OF SATURATED STEAM AT VARIOUS PRESSURES AS GIVEN IN DIFFERENT STEAM TABLES

From article "Progress in Steam Research" published in *Mechanical Engineering* magazine Vol. 47, No. 2 February 1925

The chart above shows the considerable variation in the enthalpy (total heat content) of saturated steam as a function of steam pressure as given by various existing steam tables c. 1925.

ASME recognized the need for *standardized* steam property tables, so on June 23, 1921 it assembled a group of 14 scientists and engineers who met at Harvard University to address the issue. That initial meeting led to the formation of ASME's Research Committee on the Thermal Properties of Steam. The work begun by this ASME group, and its successor subgroups, continues to the present day, a century later. The data were refined over the years and extended to ever higher pressure and temperature.

21st CENTURY

In this century, the compilation of standardized steam properties has shifted from printed tables to computer software. Printed tables, nonetheless, continue to be used for quick estimates or when a computer is not readily available.

INTERNATIONAL COOPERATION IN THE 20th AND 21st CENTURIES

Growing recognition of the differences between the steam property tables developed and published by engineers and researchers in several industrialized nations demonstrated the need to establish such tables on a consistent and physically sound basis that would be recognized and accepted worldwide. This recognition led to a series of *international* steam table conferences, the first of which was held in 1929 in London with delegations from Czechoslovakia, Germany, the United Kingdom (U.K.) and the United States (U.S.). This 1929 conference led to the development of a "Skeleton Table" which gave the heat content (enthalpy) and specific volume (inverse of density) of water and steam on a grid of temperatures and pressures. An estimated uncertainty was assigned to each value at each point.

The second international conference was held in 1930 in Berlin, but agreement had not yet been reached on the values for the "Skeleton Tables". A third conference was held in 1934 in the U.S. at three locations: the National Bureau of Standards (now known as the National Institute of Standards and Technology) in Washington D.C., at MIT in Cambridge, Massachusetts and at ASME Headquarters in New York City. It was not until the 1934 conference that international agreement was finally reached on the values for the "Skeleton Tables".

In 1936, following this conference, MIT Professors Joseph H. Keenan (1900–1977) and Frederick G. Keyes (1885–1976) published "*Thermodynamic Properties of Steam*. This book of tables, popularly known as "K&K", was widely used for 30 years: from 1936 to 1966. (See next page.)

Then in 1937 in Germany, Werner Koch (1885–1950) published Steam Tables under the auspices of the Verein Deutscher Ingenieure (VDI), the Association of German Engineers.

In 1939 in England, Guy S. Callendar 1898–1964), son of Hugh L. Callendar, in collaboration with Alfred C. Egerton (1886–1959) published The *Callendar Steam Tables*.

Following a hiatus during World War II, the international conferences resumed with additional countries attending. The fourth conference was held in 1954 in Philadelphia, Pennsylvania with representatives from seven countries (Canada, France, Federal Republic of Germany, India, Japan, the U.K., and the U.S.). The fifth international conference was held in 1956 in London and the sixth in 1963 in New York with representation now increased to 11 countries, including the USSR. The seventh International Conference was held in 1968 in Tokyo, Japan with 12 countries represented.

Conference organizers felt that in addition to holding conferences, typically at three-to-five-year intervals, it would be prudent to create a permanent organization for the ongoing task of maintaining and improving steam property tables. Following preliminary planning, begun in 1968, such an organization was formally established in 1971 and named the International Association for the Properties of Steam (IAPS). In 1989 IAPS changed its name to the International Association for the Properties of Water and Steam (IAPWS). [For more information about this association, visit http://www.iapws.org]

Meanwhile the periodic conferences continued. In 2018 the 17th international conference was held in Prague, Czech Republic attended by scientists and engineers representing 27 countries.

IAPWS continues work to improve the formulations for other thermophysical properties of pure water (viscosity, thermal conductivity, surface, tension, dielectric constant, ionization constant, etc.) and on properties of heavy water (deuterium oxide, D_2O), on important aqueous mixtures such as seawater, and on developing consensus guidance for power plant chemistry.

ASME HISTORIC MECHANICAL ENGINEERING LANDMARK
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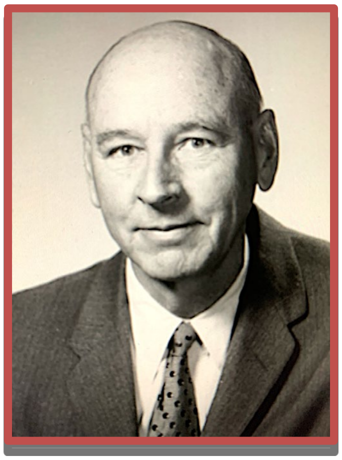
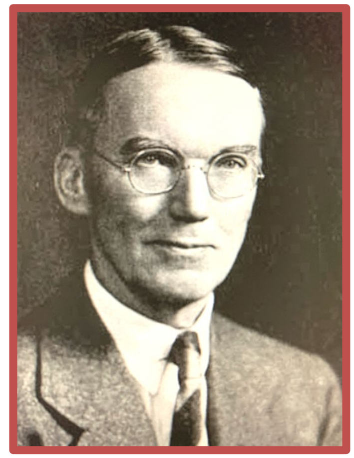
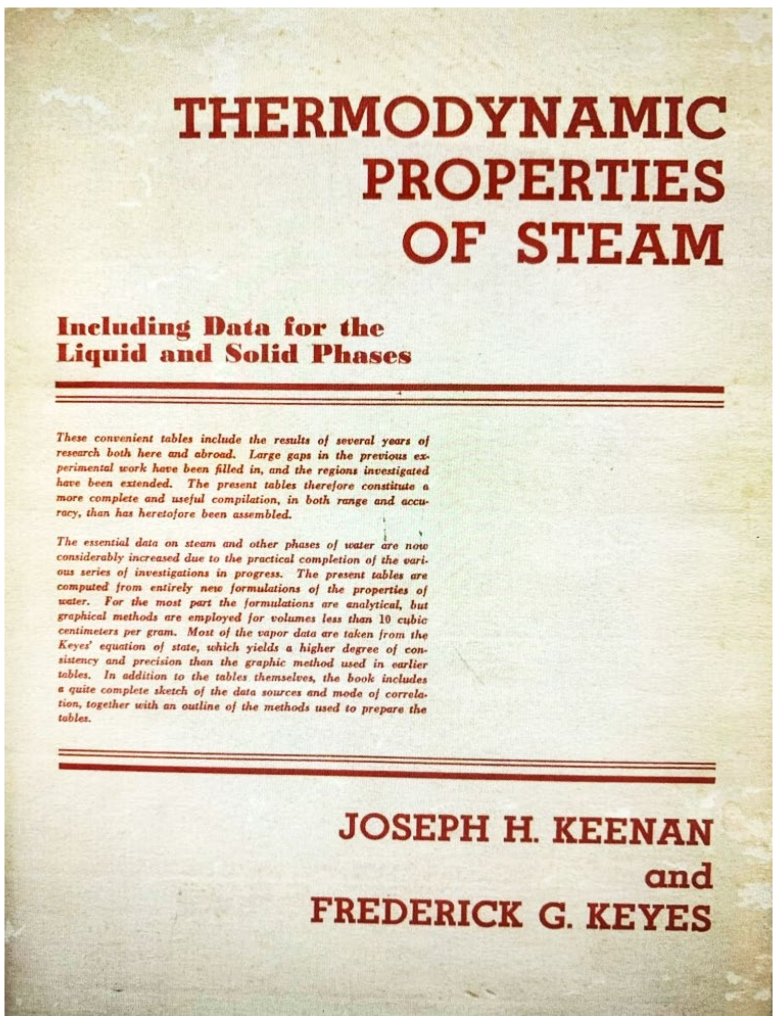


Joseph H. Keenan (1900–1977)

Undated photograph, courtesy of MIT



Undated photograph, courtesy of MIT



THERMODYNAMIC PROPERTIES OF STEAM

Including Data for the Liquid and Solid Phases

These convenient tables include the results of several years of research both here and abroad. Large gaps in the previous experimental work have been filled in, and the regions investigated have been extended. The present tables therefore constitute a more complete and useful compilation, in both range and accuracy, than has heretofore been assembled.

The essential data on steam and other phases of water are now considerably increased due to the practical completion of the various series of investigations in progress. The present tables are computed from entirely new formulations of the properties of water. For the most part the formulations are analytical, but graphical methods are employed for volumes less than 10 cubic centimeters per gram. Most of the vapor data are taken from the Keyes' equation of state, which yields a higher degree of consistency and precision than the graphic method used in earlier tables. In addition to the tables themselves, the book includes a quite complete sketch of the data sources and mode of correlation, together with an outline of the methods used to prepare the tables.

JOSEPH H. KEENAN and FREDERICK G. KEYES

Thermodynamic Properties of Steam" was published in 1936 by MIT Professors Joseph H. Keenan and Frederick G. Keyes. These tables, popularly known as "K&K", were widely used for 30 years. To meet industrial requirements, in 1967 a new formulation, known as IFC-67, was published by ASME extending the range of steam properties to include steam at higher pressures and temperatures than those of K&K.

ASME HISTORIC MECHANICAL ENGINEERING LANDMARK
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ASME's CONTINUED INVOLVEMENT IN STEAM PROPERTY TABLES

In 1953 ASME reactivated its then-dormant Research Committee on the Properties of Steam to develop a new set of steam property tables and to extend its range to include steam at higher pressures and temperatures than the extant tables. At that time engineers were seeking to design more thermally efficient steam-electric power plants by extending steam conditions into what is known as the supercritical region. Work began on the engineering of electric generating units utilizing steam at supercritical conditions — steam at a pressure and temperature above the critical point where the pressure is so great that the density of steam is indistinguishable from the density of water. The data points in K&K were sparse and uncertain in that area and, therefore, did not meet industrial needs.

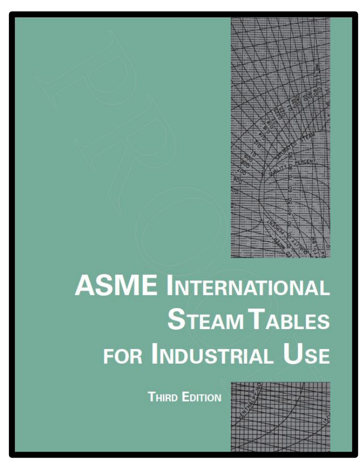
The effort by ASME and others again resulted in renewed international collaboration and, in 1967, in a new formulation known as IFC-67. The new formulation covered a much higher range of temperatures and pressures than the 1936 K&K tables. For the first time, computers were used to represent the properties of steam and water by equations and to generate the tables for printing.

As better data became available and computer techniques for representing properties improved, IAPWS adopted, in 1995, a new formulation for general and scientific use, commonly referred to as IAPWS-95. A formulation for the power industry was then fitted to IAPWS-95, sacrificing a minuscule amount of accuracy for greatly increased computational speed. This formulation for industrial use, known as IAPWS-IF97, remains the standard for the power industry today.

In 2000, ASME published "*ASME International Steam Tables for Industrial Use*" based on IAPWS-IF97, replacing, after 33 years, the 1967 ASME tables.

Photo from the March 1968 issue of *Mechanical Engineering* magazine.

A computer-driven drafting machine prints a Mollier chart, a graph showing certain steam properties in graphical rather than in tabular form. A Mollier chart is very useful to engineers designing steam power plants. The man pictured in the dark jacket is Robert C. Spencer (1926–2019), who participated in the development of the ASME steam tables, for which he received ASME's George Westinghouse gold medal in 1987.



In 2000 ASME published "*ASME Steam Tables for Industrial Use*" based on IAPWS-IF97. The Third Edition, pictured above, was published in 2014. Photo courtesy of ASME.

Table S-3 (continued). Properties of Superheated Steam and Compressed Water

t (°C)	0.08 MPa (t_{sat} = 93.49 °C)			0.09 MPa (t_{sat} = 96.69 °C)			0.10 MPa (t_{sat} = 99.61 °C)			t (°C)
	v	h	s	v	h	s	v	h	s	
Sat. Liq.	0.001 038 5	391.64	1.2328	0.001 040 9	405.13	1.2694	0.001 043 1	417.44	1.3026	Sat. Liq.
Sat. Vap.	2.0872	2665.2	7.4339	1.8695	2670.3	7.3942	1.6940	2674.9	7.3588	Sat. Vap.
0	0.001 000 2	0.04	-0.0001	0.001 000 2	0.05	-0.0001	0.001 000 2	0.06	-0.0001	0
5	0.001 000 0	21.10	0.0763	0.001 000 0	21.11	0.0763	0.001 000 0	21.12	0.0763	5
10	0.001 000 3	42.10	0.1511	0.001 000 3	42.11	0.1511	0.001 000 3	42.12	0.1511	10
15	0.001 000 9	63.06	0.2245	0.001 000 9	63.07	0.2245	0.001 000 9	63.08	0.2245	15
20	0.001 001 8	83.99	0.2965	0.001 001 8	84.00	0.2965	0.001 001 8	84.01	0.2965	20
25	0.001 003 0	104.91	0.3672	0.001 003 0	104.92	0.3672	0.001 003 0	104.93	0.3672	25
30	0.001 004 4	125.81	0.4368	0.001 004 4	125.82	0.4368	0.001 004 4	125.83	0.4368	30
35	0.001 006 0	146.71	0.5051	0.001 006 0	146.72	0.5051	0.001 006 0	146.73	0.5051	35
40	0.001 007 8	167.61	0.5724	0.001 007 8	167.61	0.5724	0.001 007 8	167.62	0.5724	40
45	0.001 009 9	188.50	0.6386	0.001 009 9	188.51	0.6386	0.001 009 9	188.52	0.6386	45
50	0.001 012 1	209.39	0.7038	0.001 012 1	209.40	0.7038	0.001 012 1	209.41	0.7038	50
55	0.001 014 5	230.30	0.7679	0.001 014 5	230.30	0.7679	0.001 014 5	230.31	0.7679	55
60	0.001 017 1	251.20	0.8312	0.001 017 1	251.21	0.8312	0.001 017 1	251.22	0.8312	60
65	0.001 019 8	272.12	0.8935	0.001 019 8	272.13	0.8935	0.001 019 8	272.14	0.8935	65
70	0.001 022 7	293.06	0.9550	0.001 022 7	293.07	0.9550	0.001 022 7	293.07	0.9550	70
75	0.001 025 8	314.01	1.0156	0.001 025 8	314.02	1.0156	0.001 025 8	314.02	1.0156	75
80	0.001 029 0	334.97	1.0754	0.001 029 0	334.98	1.0754	0.001 029 0	334.99	1.0754	80
85	0.001 032 4	355.96	1.1344	0.001 032 4	355.97	1.1344	0.001 032 4	355.98	1.1344	85
90	0.001 035 9	376.98	1.1927	0.001 035 9	376.98	1.1926	0.001 035 9	376.99	1.1926	90
95	2.0964	2668.3	7.4423	0.001 039 6	398.02	1.2502	0.001 039 6	398.03	1.2502	95
100	2.1268	2678.5	7.4698	1.8875	2677.1	7.4126	1.6960	2675.8	7.3610	100
105	2.1570	2688.6	7.4968	1.9145	2687.3	7.4398	1.7205	2686.1	7.3885	105
110	2.1871	2698.7	7.5232	1.9414	2697.5	7.4664	1.7448	2696.3	7.4154	110
115	2.2171	2708.7	7.5492	1.9682	2707.6	7.4926	1.7691	2706.5	7.4417	115
120	2.2470	2718.7	7.5747	1.9949	2717.6	7.5183	1.7932	2716.6	7.4676	120
125	2.2768	2728.6	7.5999	2.0216	2727.6	7.5436	1.8173	2726.7	7.4931	125
130	2.3066	2738.5	7.6247	2.0481	2737.6	7.5685	1.8413	2736.7	7.5181	130
135	2.3363	2748.4	7.6491	2.0746	2747.6	7.5931	1.8653	2746.7	7.5428	135
140	2.3659	2758.3	7.6732	2.1010	2757.5	7.6173	1.8891	2756.7	7.5671	140
145	2.3955	2768.2	7.6969	2.1274	2767.4	7.6411	1.9130	2766.7	7.5911	145
150	2.4250	2778.0	7.7203	2.1538	2777.3	7.6646	1.9367	2776.6	7.6147	150
155	2.4545	2787.9	7.7435	2.1800	2787.2	7.6879	1.9605	2786.5	7.6380	155
160	2.4840	2797.7	7.7663	2.2063	2797.1	7.7108	1.9841	2796.4	7.6610	160
165	2.5134	2807.6	7.7889	2.2325	2806.9	7.7334	2.0078	2806.3	7.6837	165
170	2.5428	2817.4	7.8112	2.2587	2816.8	7.7558	2.0314	2816.2	7.7062	170
175	2.5721	2827.2	7.8333	2.2848	2826.7	7.7779	2.0550	2826.1	7.7283	175
180	2.6014	2837.1	7.8551	2.3109	2836.5	7.7998	2.0785	2836.0	7.7503	180
185	2.6307	2846.9	7.8767	2.3370	2846.4	7.8214	2.1021	2845.8	7.7719	185
190	2.6600	2856.7	7.8980	2.3631	2856.2	7.8428	2.1256	2855.7	7.7934	190
195	2.6892	2866.6	7.9191	2.3891	2866.1	7.8640	2.1490	2865.6	7.8146	195
200	2.7184	2876.4	7.9400	2.4151	2875.9	7.8849	2.1725	2875.5	7.8356	200
205	2.7477	2886.2	7.9607	2.4411	2885.8	7.9057	2.1959	2885.4	7.8563	205
210	2.7768	2896.1	7.9812	2.4671	2895.7	7.9262	2.2194	2895.2	7.8769	210
215	2.8060	2906.0	8.0015	2.4931	2905.5	7.9465	2.2428	2905.1	7.8973	215
220	2.8352	2915.8	8.0216	2.5190	2915.4	7.9667	2.2661	2915.0	7.9174	220
225	2.8643	2925.7	8.0415	2.5450	2925.3	7.9866	2.2895	2924.9	7.9374	225
230	2.8934	2935.6	8.0613	2.5709	2935.2	8.0064	2.3129	2934.8	7.9572	230
235	2.9225	2945.5	8.0808	2.5968	2945.1	8.0259	2.3362	2944.7	7.9768	235
240	2.9516	2955.4	8.1002	2.6227	2955.0	8.0454	2.3596	2954.7	7.9962	240
245	2.9807	2965.3	8.1194	2.6486	2964.9	8.0646	2.3829	2964.6	8.0155	245
250	3.0098	2975.2	8.1385	2.6745	2974.9	8.0837	2.4062	2974.5	8.0346	250
255	3.0389	2985.1	8.1574	2.7003	2984.8	8.1026	2.4295	2984.5	8.0535	255
260	3.0680	2995.1	8.1761	2.7262	2994.8	8.1213	2.4528	2994.4	8.0723	260
265	3.0970	3005.0	8.1947	2.7520	3004.7	8.1399	2.4761	3004.4	8.0909	265
270	3.1261	3015.0	8.2131	2.7779	3014.7	8.1584	2.4994	3014.4	8.1094	270

UNITS: v in m^3/kg ; h in kJ/kg ; s in kJ/(kg·K)

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A typical page from *ASME International Steam Tables for Industrial Use (2014)*. This page shows the properties specific volume, enthalpy, and entropy of H_2O at three different pressures. The values above the horizontal lines in the chart indicate that H_2O is in the liquid (water) phase. Values below the horizontal lines indicate H_2O is in the vapor (steam) phase. Temperature is in ºC, Pressure (absolute) is in megapascals [MPa]. Note: 0.10 MPa is approximately standard atmospheric pressure.

WHO USES STEAM PROPERTY TABLES ?

Two different and distinct groups utilize steam property data. First are researchers. They need accurate properties of water and steam, for example to model water as a solvent in chemical processes, to describe thermodynamics of aqueous electrolytes, or to calibrate instruments using accurately known properties. Second are industrial employees, principally those working in the electric power industry. They use the data for engineering and designing steam and combined-cycle electric power plants and the equipment and machines required for those plants, e.g., boilers, steam generators (in supercritical pressure units and nuclear power plants), heat recovery steam generators (in combined-cycle power plants), steam turbines, and heat exchangers utilizing steam such as feedwater heaters and steam condensers.

Other industrial users, such as oil refineries and paper mills, require knowledge of steam properties in designing equipment for those facilities. Steam is also used to heat buildings, sterilize soil, and clean things.

Each group of users has different needs for steam properties. Therefore, today IAPWS has two separate tracks: (1) Steam Property Formulations for "General and Scientific Use" with property values intended to be kept current based on the latest state-of-the-art experimental data and theory and (2) Steam Property Formulations for "Industrial Use" with property values that can be relied on for decades and with formulations that can be efficiently used by a computer in performing iterative design calculations.

Steam Properties are so important to the electric power industry because that industry uses immense quantities of steam to generate electricity. In 2020, for example, approximately 76 percent of the electricity generated in the *world* came from power plants utilizing steam, either in conventional steam cycles or in combined cycles. The steam was generated in boilers or steam generators by (1) burning a fossil fuel [coal, peat, natural gas, oil] or wood or biomass or fissioning nuclear fuel in a nuclear reactor or (2) in combined-cycle plants by burning natural gas or fuel oil in a gas turbine or (3) from steam generated in geothermal wells. (The world's electricity produced *without* utilizing steam in 2020 was produced in hydro-electric plants [16 percent] and in other plants utilizing wind, solar energy, tidal and other energy sources [8 percent].)

The power industry and the equipment manufacturers design power cycles and equipment utilizing the then-current steam property tables and then guarantee the performance of the equipment based on calculations using those tables. Significant financial considerations come into play if equipment fails to meet or exceeds its performance guarantees as determined by testing the operating power plant.

ADVANCEMENT OF A TECHNOLOGY

Mechanical engineers were inspired by the groundbreaking work of the French engineer Sadi Carnot (1796–1832) who recognized that the thermal efficiency of steam power plants — or other heat-driven power cycles — is strongly dependent on the temperature of the steam or other “working fluid”. Thermal efficiency is the percentage of heat energy in the fuel that is converted into power. Thermal efficiency also depends on the temperature at which waste heat is rejected or discharged from the power plant. The higher the *difference* in those two temperatures, the higher the thermal efficiency. As a result of Carnot’s work, he is considered by some to be the “father” of the science of thermodynamics.

Carnot’s work, published in 1824, entitled R*eflections on the Motive Power of Fire and on Machines Fitted to Develop that Power* set the stage for the steady improvement of the efficiency of steam power plants beginning in the late 19th Century and continuing to today.

(See chart on the following page.)

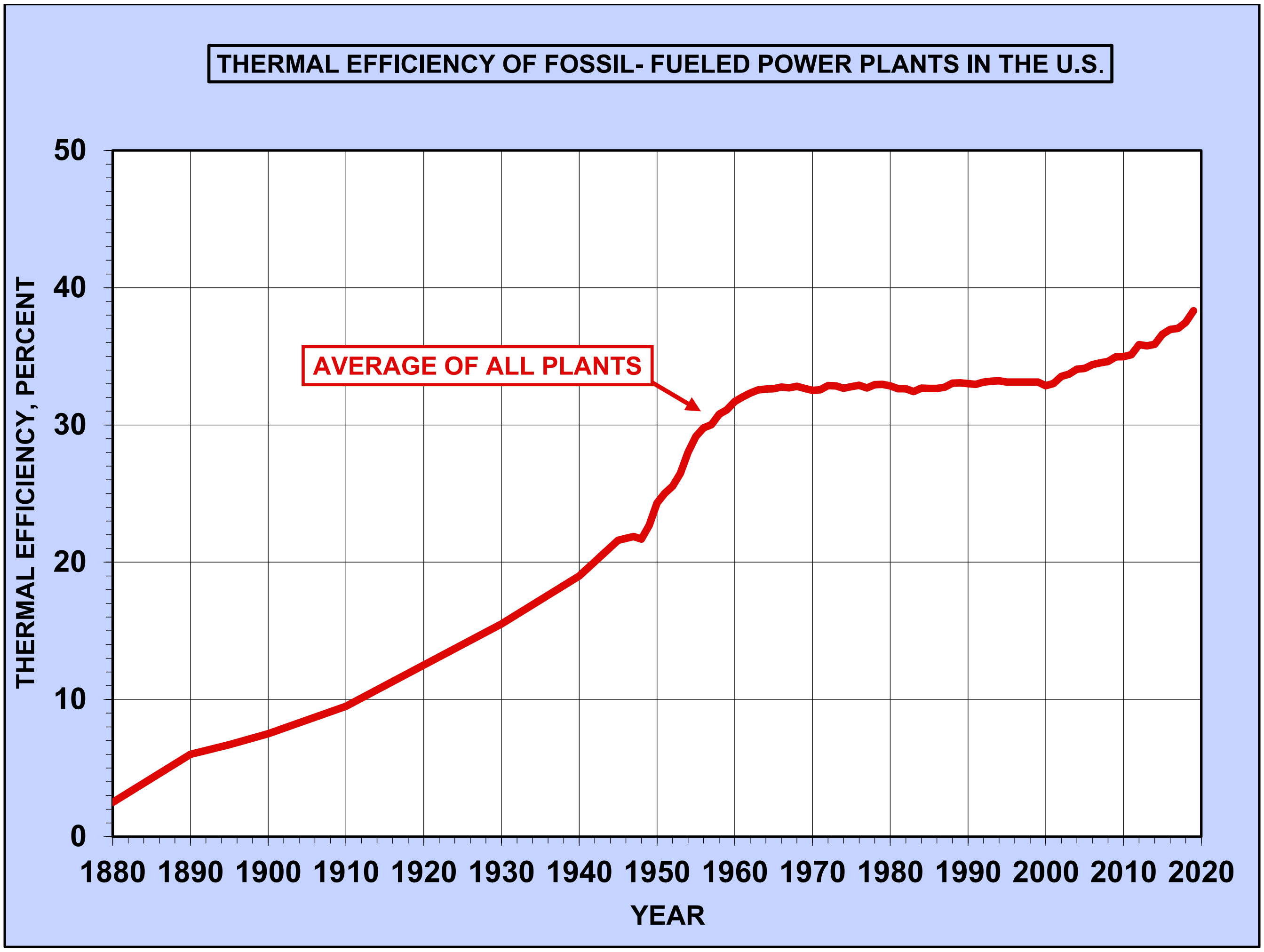
For more information about Carnot’s seminal work, which was designated an ASME *virtual* Historic Mechanical Engineering Landmark in 2021, visit asme.org and search for Landmarks, then Landmark # 275.

Beginning in the late 19th Century and continuing through most of the 20th Century, engineers advanced the efficiency of steam power plants by designing new ones to operate with steam at a higher temperature and pressure than existing plants. To do so required the best available data from steam property tables. It also required developing new materials to safely tolerate long-term operation at the higher steam temperatures and pressures. The higher cost of building such plants was economically justified because the fuel consumption required to produce a given quantity of electrical energy was reduced.

In 2003 two power plants, engineered and designed to operate with steam at the highest steam temperature and pressure exploited to date, were designated by ASME as Historic Mechanical Engineering Landmarks: Philo Unit 6 (commissioned in 1957) and Eddystone Unit 1 (commissioned in 1960). Both units were designed to operate with steam at supercritical conditions. (See page 6 for the definition.) For more information about these pioneering plants, visit asme.org and search for Landmarks, then Landmark #226 (Eddystone Unit 1) and # 228 Philo Unit 6).

Beginning in the late 1990s, further increases in thermal efficiency in electric power production enabled some installations to approach 60 percent thermal efficiency with units that utilize both combustion (gas) turbines **and** steam turbines in a combined cycle. Although Carnot could not have envisioned the specifics of such combined cycle machines, he recognized their possibility when, in 1824, he speculated that:

“One of the gravest inconveniences of steam is that it cannot be used at high temperatures without necessitating the use of vessels of extraordinary strength. It is not so with air for which there exists no necessary relation between the elastic force and the temperature. Air, then, would seem more suitable than steam to realize the motive power of falls of caloric from high temperatures; perhaps at low temperatures steam may be more convenient. We might conceive even the possibility of making the same heat act successively upon air and vapor of water. It would be only necessary that the air should have, after its use, an elevated temperature, and instead of throwing it out immediately into the atmosphere, to make it envelop a steam boiler, as if it issued directly from a furnace.”



This chart shows the thermal efficiency of fossil-fueled power plants operating in the U.S. over the past 140 years. The data reflects the weighted *average* of all plants operating in a particular year. The most efficient (typically the newest) plants in any year were as much as eight percentage points above the average. From 1900 to 1960 the steam temperature of the newest power plants increased at an average rate of 6.1 ºC (11 ºF) per year. In 1960 the maximum steam temperature in fossil-fueled power plants was 621 ºC (1150 ºF) and has not increased since. In fact, it has slightly regressed. The maximum steam pressure also increased in steps, reaching a maximum of 34.5 MPa (≃5000 psi) in 1960 and has not increased since and, in fact, also regressed because economic considerations did not justify higher steam temperature or pressure.

As steam flows through a steam turbine its pressure and temperature drops as energy is transferred from the steam to the turbine. Beginning in 1924, plants were built in which the steam was reheated after it flowed partway through the turbine. That reheating increased the plant's thermal efficiency. Beginning in 1957 some plants were designed with double reheating, increasing thermal efficiency slightly more. Then, beginning in the late 1990s, combined-cycle plants began coming on-line, thus resuming the trend of increasing efficiency since the thermal efficiency of combined-cycle plants is 50 percent or greater, with the latest ones exceeding 60 percent.

Data Source: Technical papers and trade publications (1880–1948)
U.S. Energy Information Administration (1949–2019)

Since this is a *virtual* Historic Mechanical Engineering Landmark — no tangible artifact exists to which a plaque can be affixed — if there were a plaque it would read:

HISTORIC MECHANICAL ENGINEERING LANDMARK

STANDARDIZED STEAM PROPERTY TABLES

1921

ENGINEERS DESIGNING EQUIPMENT TO PRODUCE OR UTILIZE STEAM NEED TO KNOW STEAM'S THERMODYNAMIC PROPERTIES. BEGINNING IN THE 1840S TABULATIONS OF SUCH PROPERTIES WERE PUBLISHED WORLDWIDE, BUT SIGNIFICANT DIFFERENCES EXISTED BETWEEN PUBLISHED TABLES.

RECOGNIZING THE NEED FOR STANDARDIZED TABLES, IN 1921 ASME FORMED A RESEARCH COMMITTEE ON THERMAL PROPERTIES OF STEAM. THIS COMMITTEE PURSUED EFFORTS TO RESOLVE DIFFERENCES BETWEEN TABLES, ENCOURAGED STANDARDIZATION EFFORTS WITH OTHER COUNTRIES, AND, IN 1929, WAS INFLUENTIAL IN CONVENING THE FIRST OF A SERIES OF ONGOING INTERNATIONAL STEAM TABLE CONFERENCES. THAT EFFORT ULTIMATELY PRODUCED STANDARDIZED STEAM PROPERTY TABLES ADOPTED INTERNATIONALLY.

STEAM PROPERTY TABLES CONTINUE TO BE UTILIZED BY ENGINEERS IN INDUSTRY, ESPECIALLY THE ELECTRIC POWER INDUSTRY.

ASME SETTING THE STANDARD

THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS-2021

FOR FURTHER READING

This brochure, written to accompany the designation of an Historic Mechanical Engineering Landmark, is written to be understandable and useful not only to engineers, but also to persons who may not be experts in the technology. There are literally hundreds of research papers on the subject of steam properties. If readers are interested in delving further into the subject, the papers listed below are a good source of information. They are listed in chronological order by date of publication.

Note: Some of the papers and articles in this list were referenced, without citation, in the preparation of this brochure. For further detailed information about the International Association for the Properties of Water and Steam (IAPWS), visit http://www.iapws.org

Davis, H. N., and J. H. Keenan, "Recent Research on the Thermal Properties of Steam," *Mechanical Engineering,* 51 (1929): 921-931.

Greene, A. M., 'Early U.S. Steam Tables –A Historical Summary of Tabulations Published in This Country Prior to 1921," *Mechanical Engineering,* 56 (1934): 715-717, 764.

Keenan, J. H., and F. G. Keyes, "The Present Status of Steam Properties," *Mechanical Engineering,* 77 (1955): 127-132.

Haywood, R. W., "6th Int'l Conference on Properties of Steam," *Trans. ASME*, 87 (1965): 93-98.

Potter, J. H., "Essay on the Nature of Steam – II," *ASME Paper 66-WA/PWR-7,* (1966).
Note: This paper includes a list of 108 technical papers on the subject written between the years 1802 – 1965.

Cotton, K. C., et al., "Effects of New International Formulation on Turbine-Generator Performance Calculations," *ASME Paper 67-PWR-9,* (1967).

White H. J., Jr., "Fifty years of international cooperation on the properties of steam," in *Proceedings of the 9th International Conference of the Properties of Steam*, J. Straub, and K. Scheffler, eds. (Pergamon, New York: 1980), 18-24.

Bellows, J. C., et al., "New Steam Properties are Coming," *61st American Power Conference*, (1999).

Harvey, A. H., and W. T. Parry, "Keep Your "Steam Tables Up-To-Date," *Chemical Engineering Progress,* (November 1999), 45-49.

Harvey, A. H., "Steam Tables," *Encyclopedia of Physical Science and Technology*, Third Edition, v. 16 (2001).

Harvey, A. H., and J. M. H. Levelt Sengers, "Thermodynamic Properties of Water and Steam for Power Generation," in *A Century of Excellence in Measurements, Standards, and Technology*, NIST Special Publication 958, D.R. Lide, ed., (Washington: GPO, 2001), 49-52.

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We also acknowledge the many engineers, scientists, and chemists, several of whom are mentioned in this brochure, who, over the years added to the breadth and depth of knowledge of steam properties. This knowledge enabled engineers to advance the design of steam-electric power plants, leading to greater thermal efficiency and concomitant lower cost of generating electricity.

ASME HISTORIC MECHANICAL ENGINEERING LANDMARK
STANDARDIZED STEAM PROPERTY TABLES
THE HISTORY AND HERITAGE PROGRAM OF ASME

Since the invention of the wheel, mechanical innovation has critically influenced the development of civilization and industry as well as public welfare, safety, and comfort. Through its History and Heritage program, the American Society of Mechanical Engineers (ASME) encourages public understanding of mechanical engineering, fosters the preservation of this heritage, and helps engineers become more involved in all aspects of history.

In 1971 ASME formed a History and Heritage Committee composed of mechanical engineers and historians of technology. This Committee is charged with examining, recording, and acknowledging mechanical engineering achievements of particular significance. For further information, please visit http://www.asme.org

LANDMARK DESIGNATIONS

There are many aspects of ASME's History and Heritage activities, one of which is the landmarks program. Since the History and Heritage Program began, 275 artifacts have been designated throughout the world as historic mechanical engineering landmarks, heritage collections or heritage sites. Each represents a progressive step in the evolution of mechanical engineering and its significance to society in general.

The Landmark Program illuminates our technological heritage and encourages the preservation of historically important works. It provides an annotated roster for engineers, students, educators, historians, and travelers. It also provides reminders of where we have been and where we are going along the divergent paths of discovery.

ASME helps the global engineering community develop solutions to real world challenges. ASME, founded in 1880, is a not-for-profit professional organization that enables collaboration, knowledge sharing and skill development across all engineering disciplines, while promoting the vital role of the engineer in society. ASME codes and standards, publications, conferences, continuing education, and professional development programs provide a foundation for advancing technical knowledge and a safer world.

ABOUT THIS LANDMARK

The nomination of Standardized Steam Property Tables to be designated a Historic Mechanical Engineering Landmark, as well as this commemorative brochure, was prepared by Dick Pawliger, P.E. (Ret.). Dick, a member of ASME since 1959 was elected a Life Fellow in 1997 and has served on ASME's History and Heritage Committee since 2004 and as its Chair from 2009 to 2015. He spent his 40-year engineering and management career with American Electric Power Co., helping to engineer, develop, construct, and operate large steam-electric power plants with ever increasing thermal efficiency as designs evolved to exploit the advantages of utilizing steam at high temperature and pressure.