Chart 1a. Temperature vs. Specific Entropy - SI units

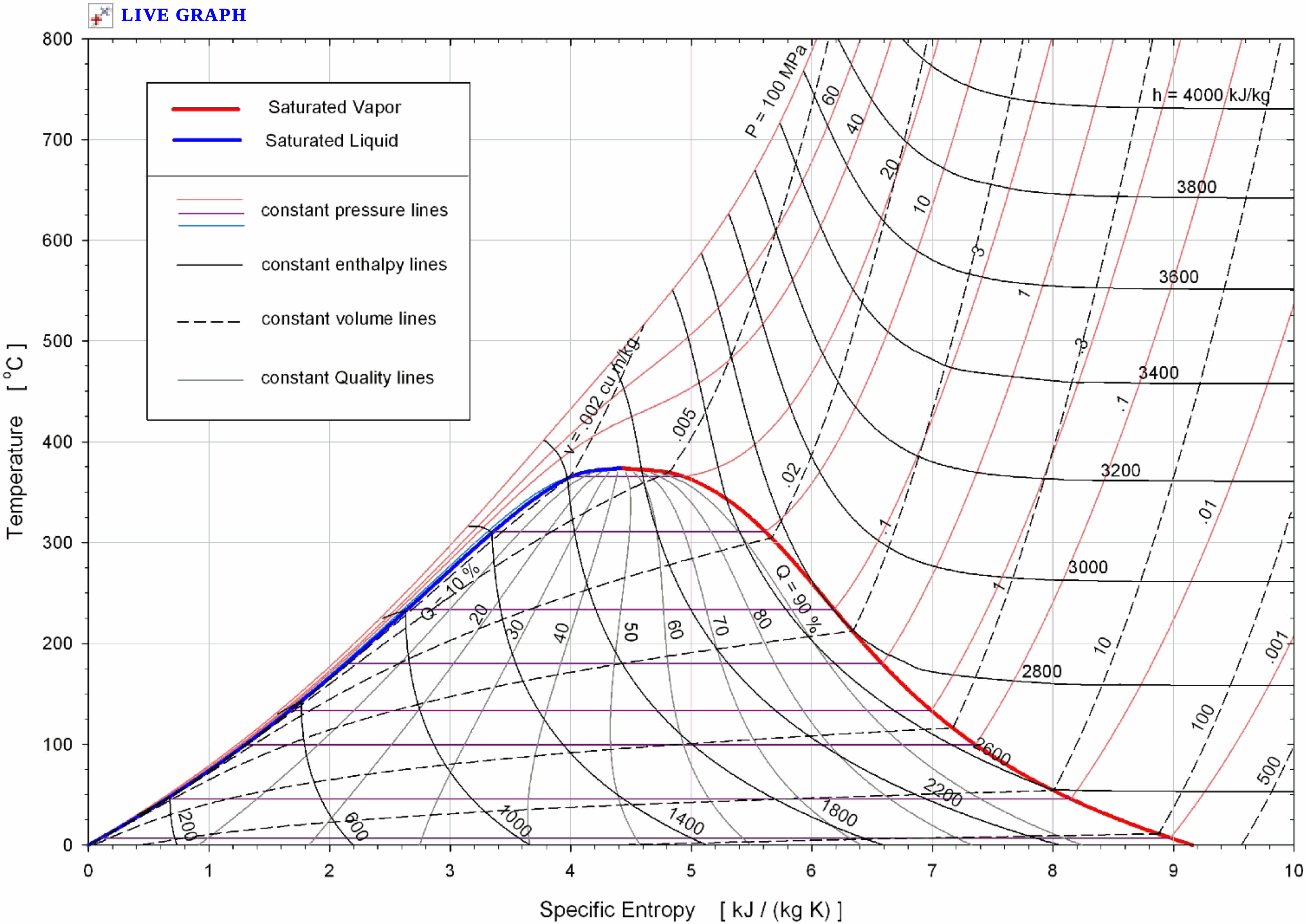


Chart 1b. Temperature vs. Specific Entropy - English units

LIVE GRAPH

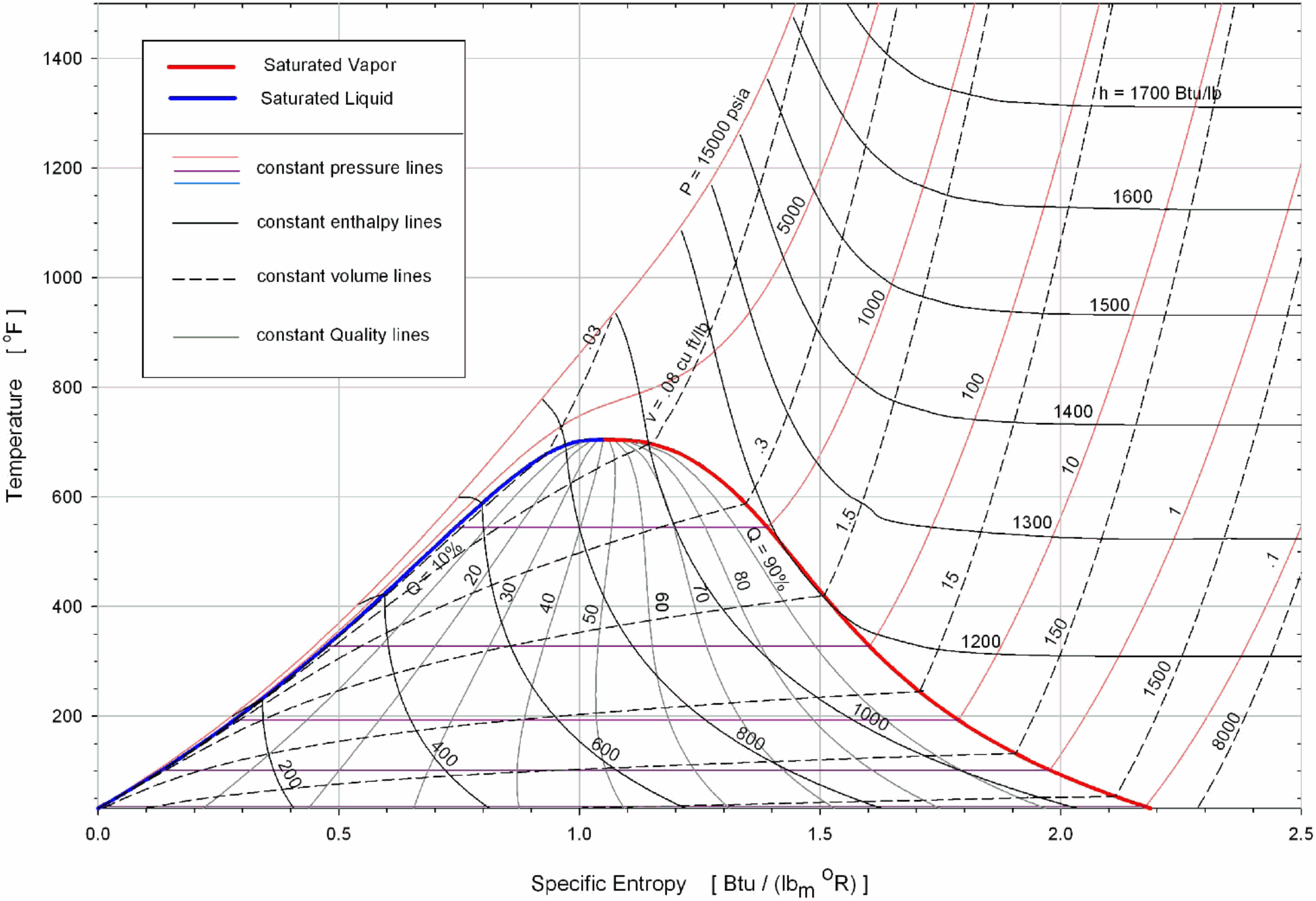


Chart 2a. Specific Enthalpy vs. Specific Entropy - SI units

LIVE GRAPH

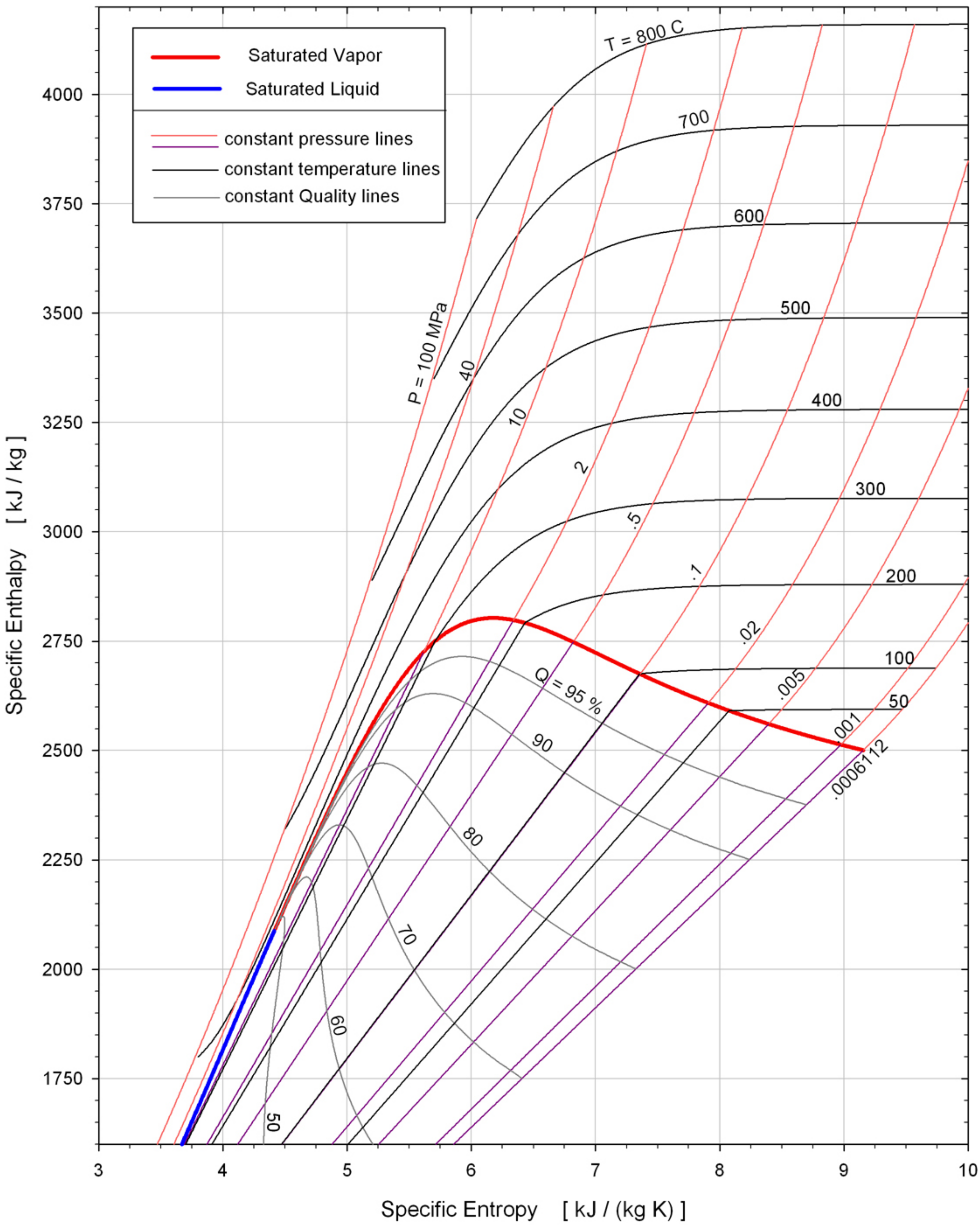


Chart 2b. Specific Enthalpy vs. Specific Entropy - English Units

LIVE GRAPH

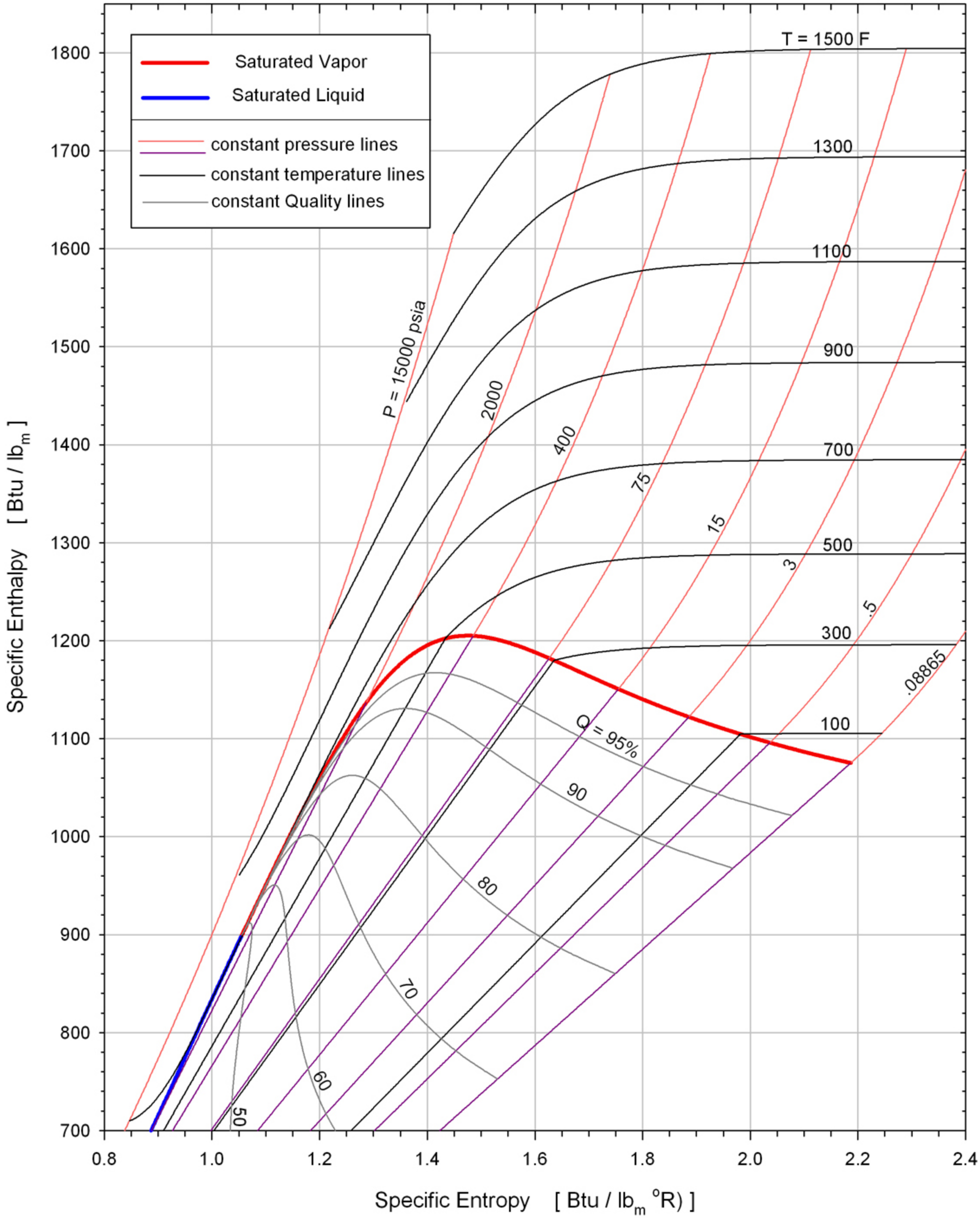


Chart 3a. Reciprocal Isobaric Heat Capacity vs. Temperature - SI units

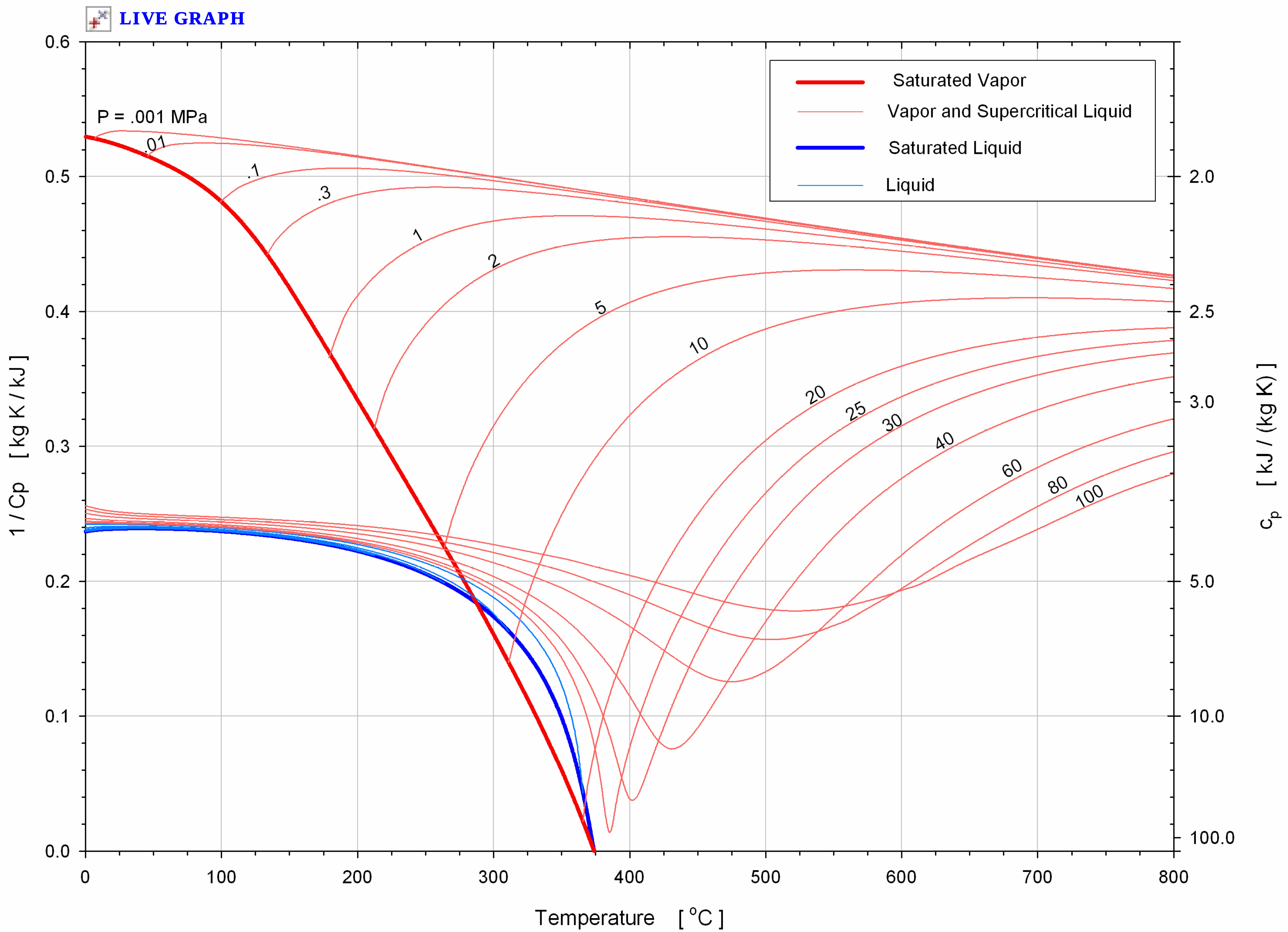


Chart 3b. Reciprocal Isobaric Heat Capacity vs. Temperature - English units

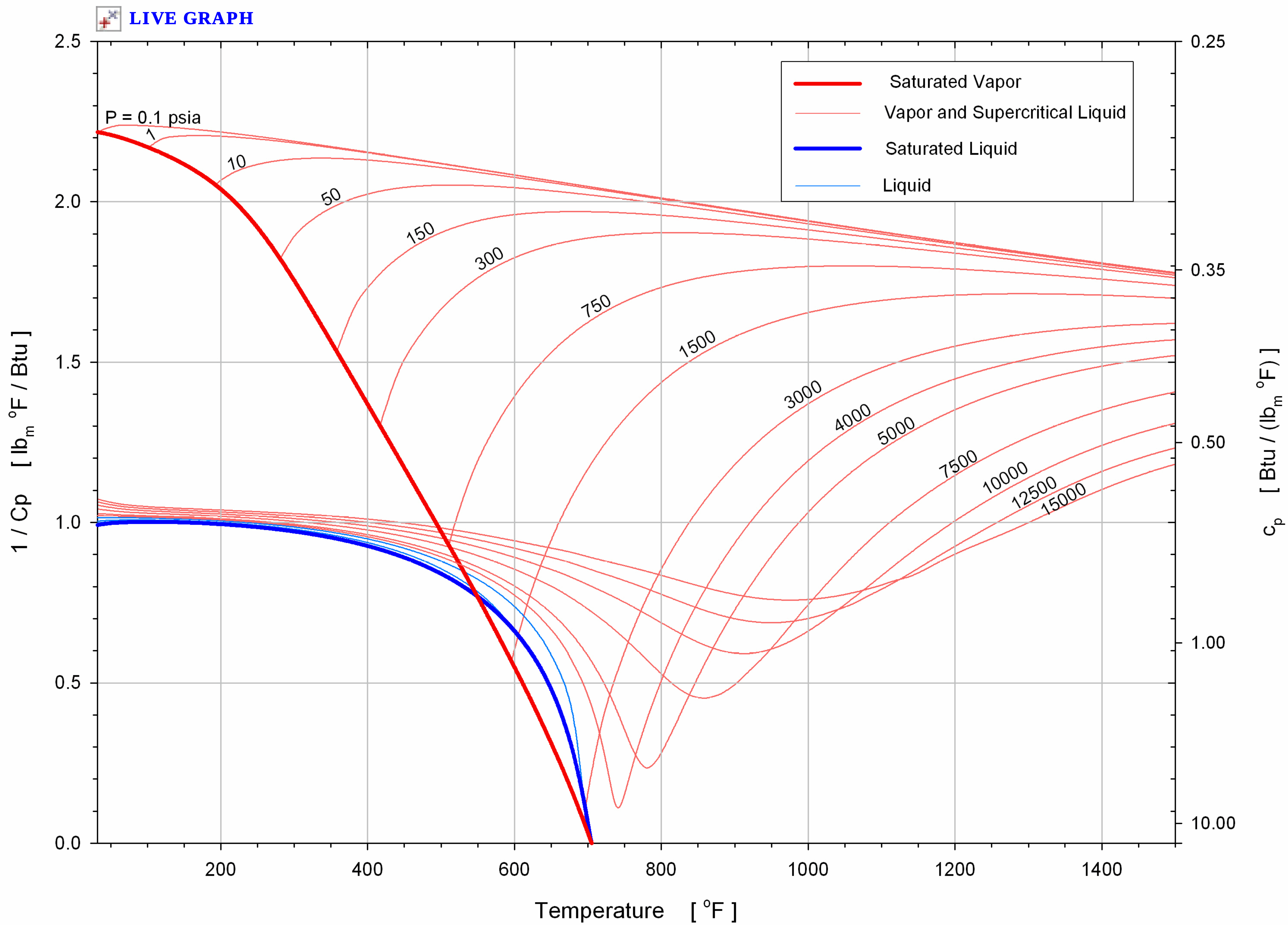


Chart 3c. Reciprocal Isochoric Heat Capacity vs. Temperature - SI units

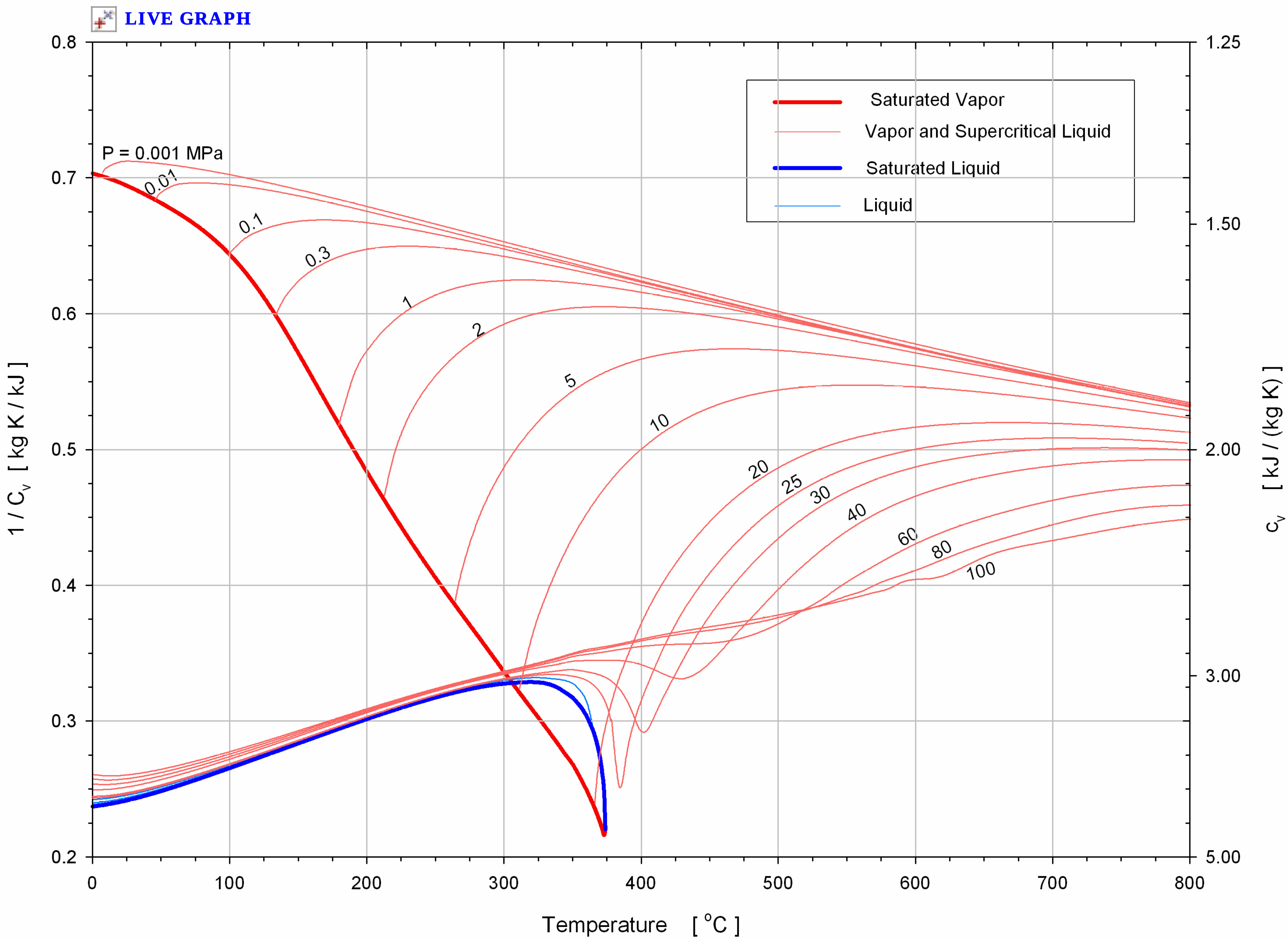


Chart 3d. Reciprocal Isochoric Heat Capacity vs. Temperature - English units

LIVE GRAPH

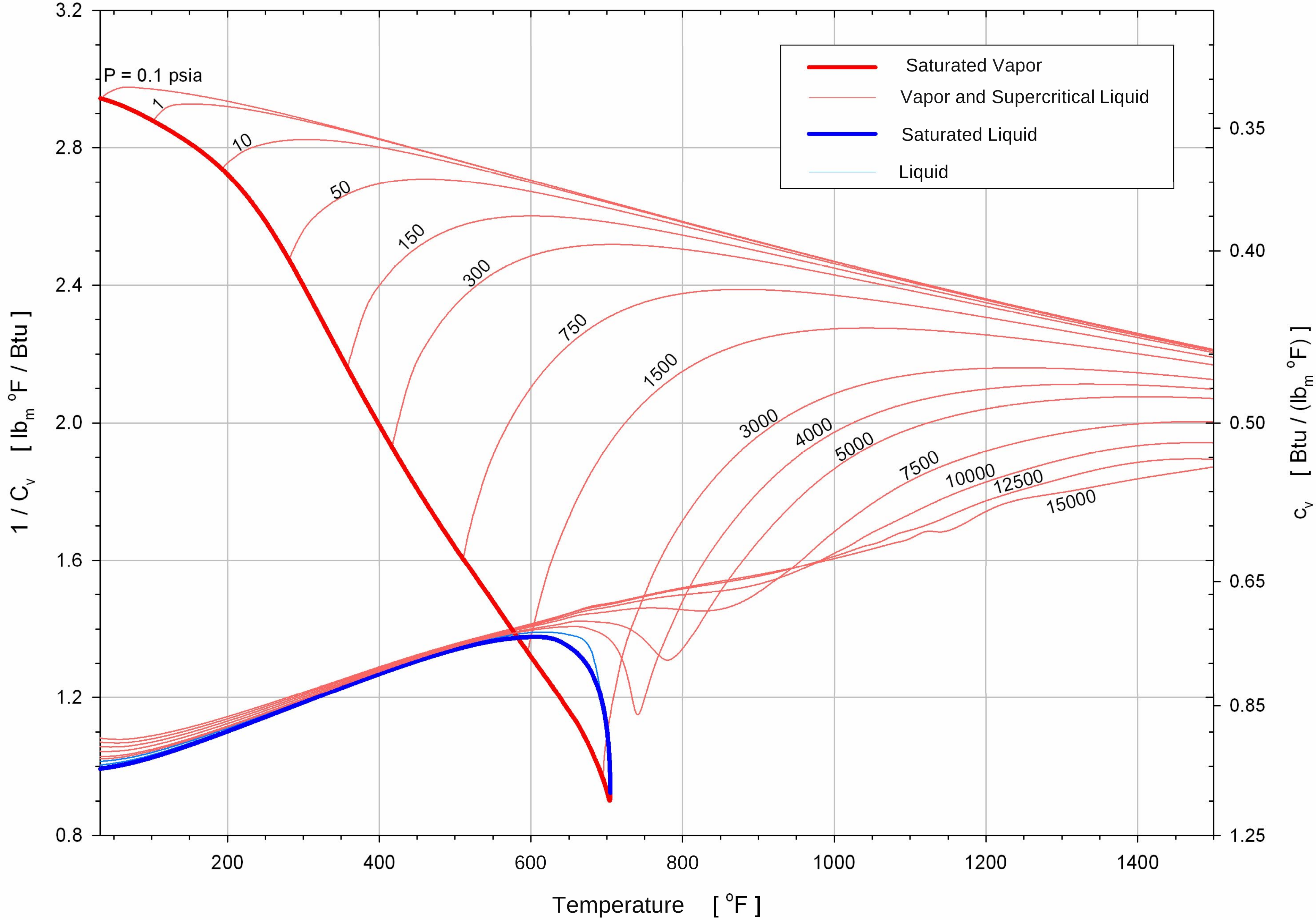


Chart 4a. Speed of Sound vs. Temperature - SI units

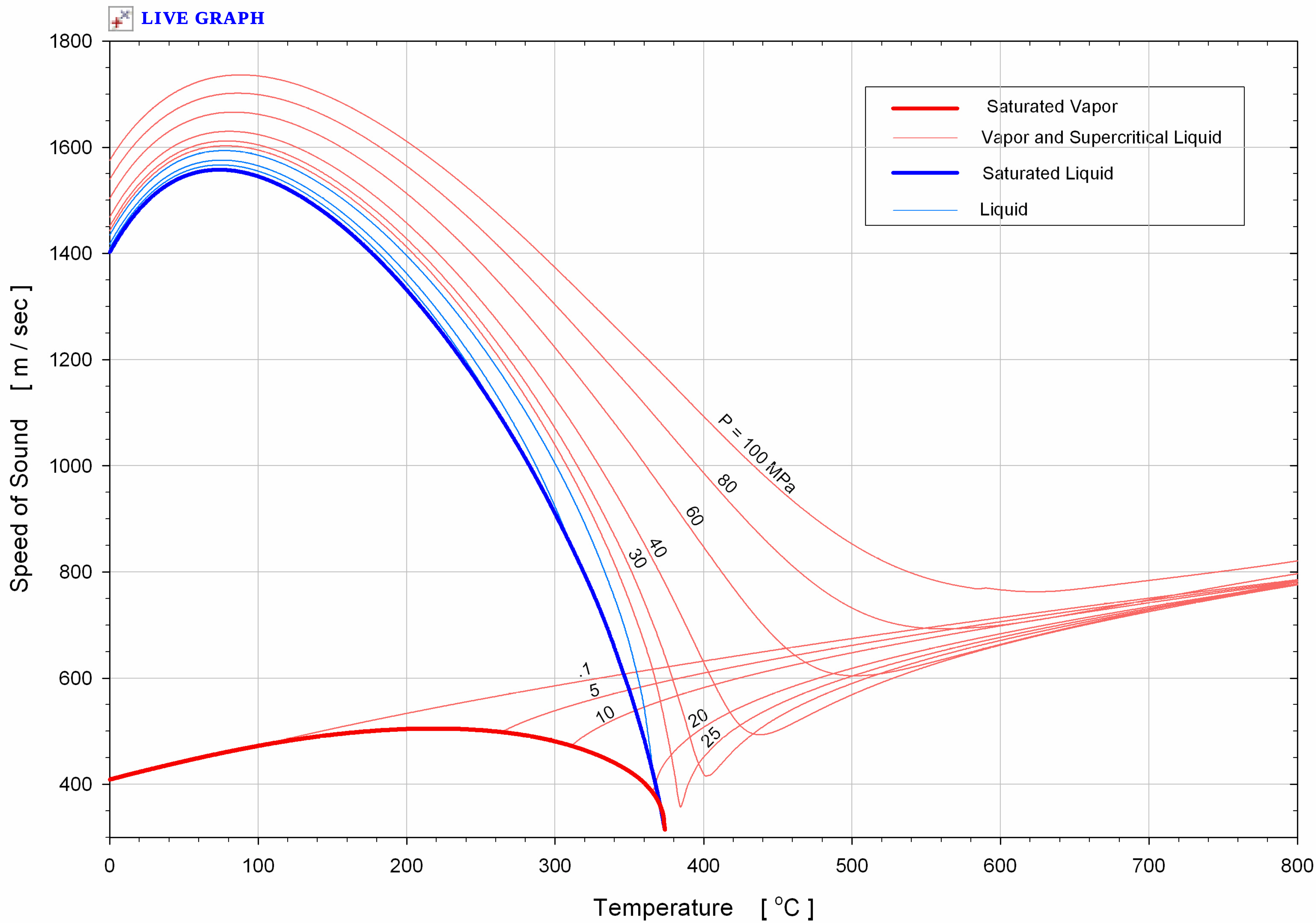


Chart 4b. Speed of Sound vs. Temperature - English units

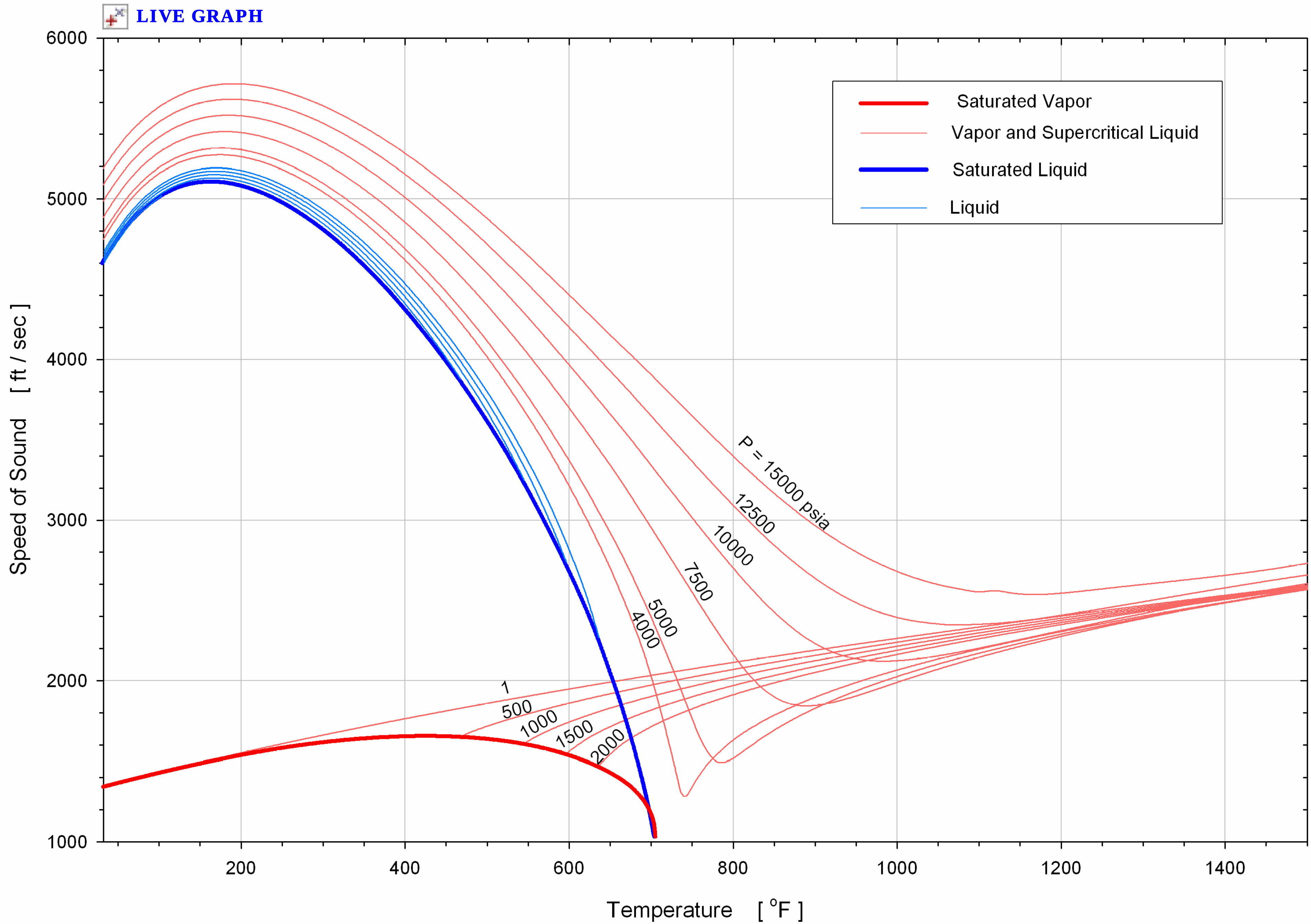


Chart 5a. Dynamic Viscosity vs. Temperature - SI units (liquid region)

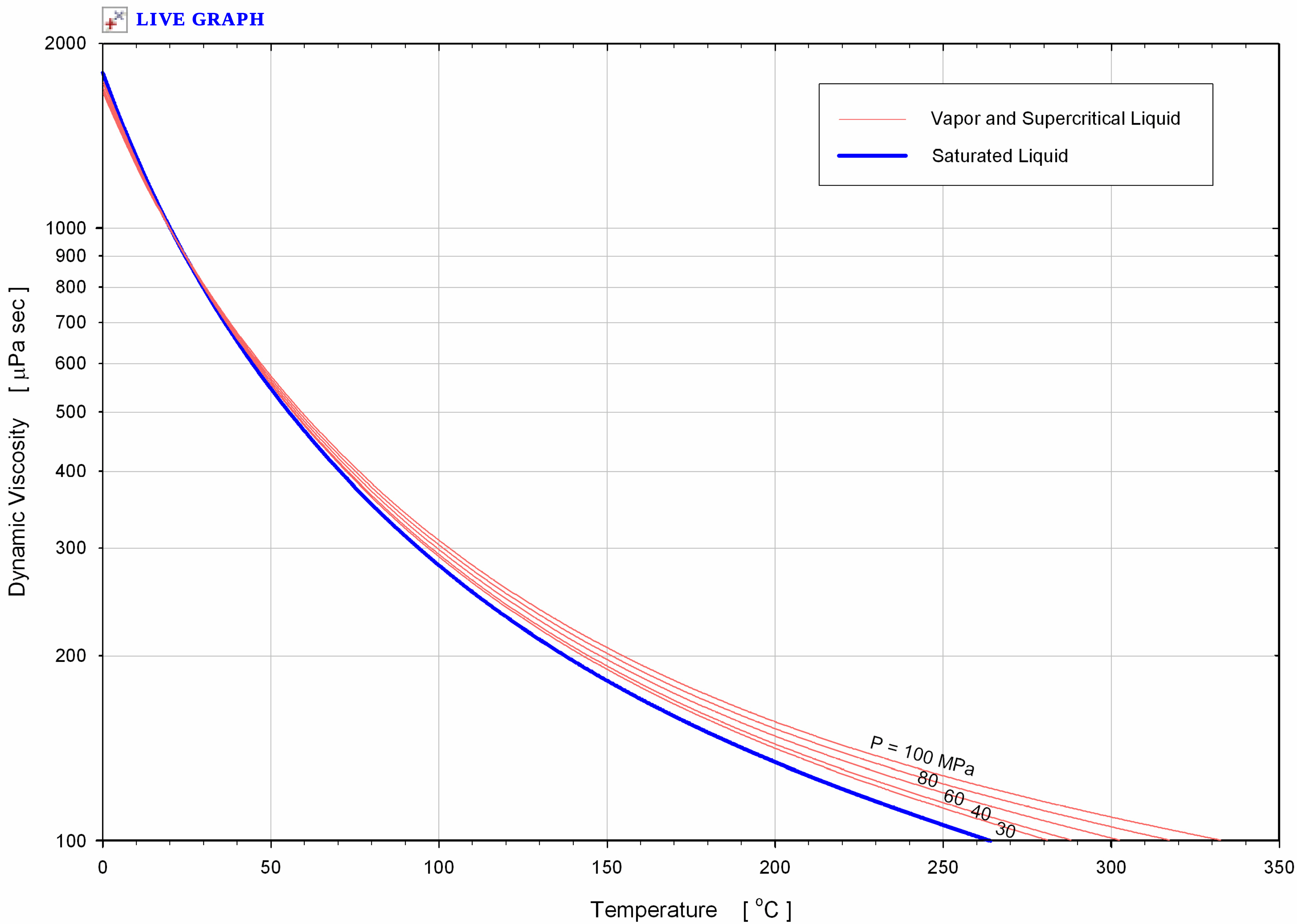


Chart 5a. Dynamic Viscosity vs. Temperature - SI units (vapor region)

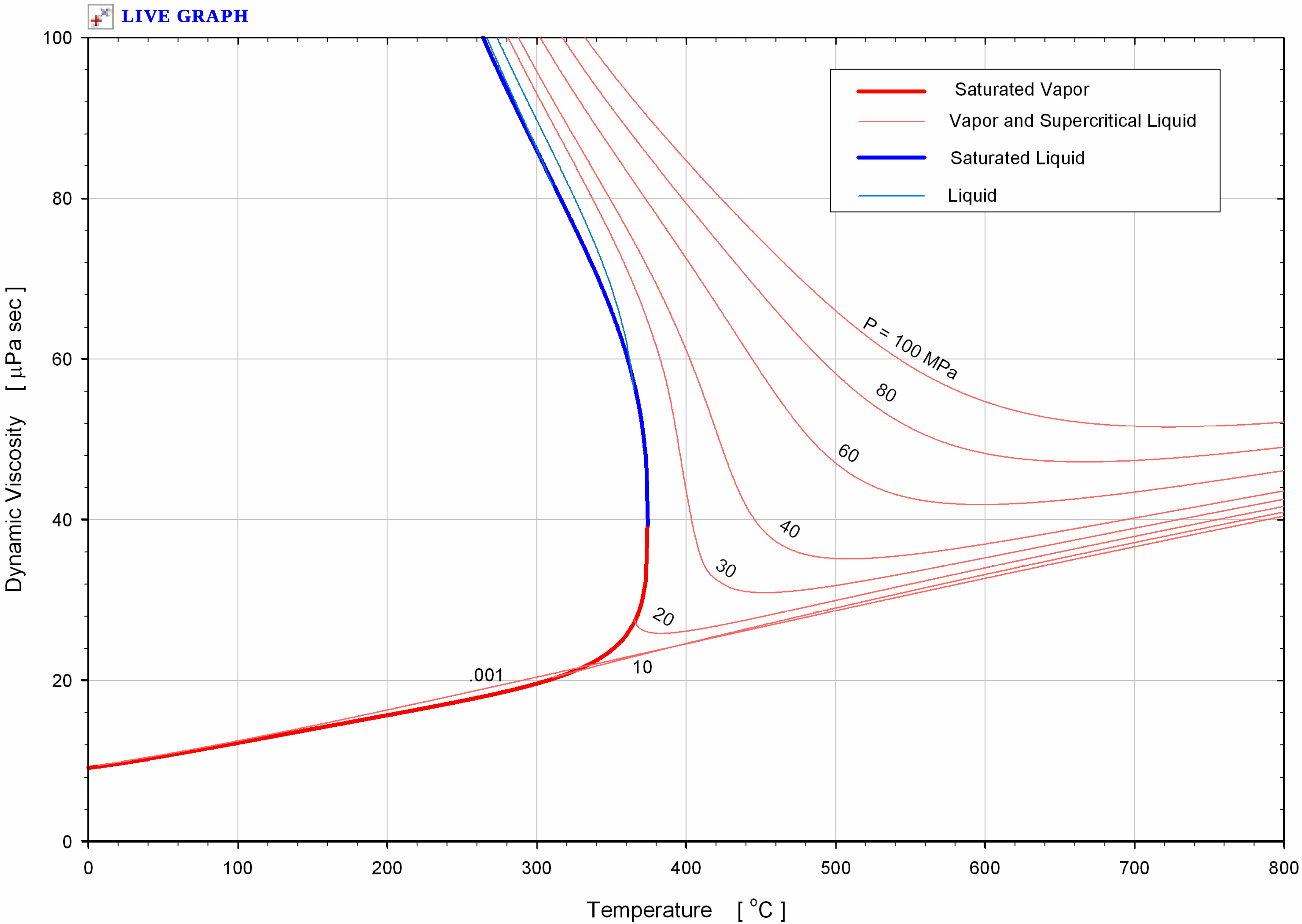


Chart 5b. Dynamic Viscosity vs. Temperature - English units (liquid region)

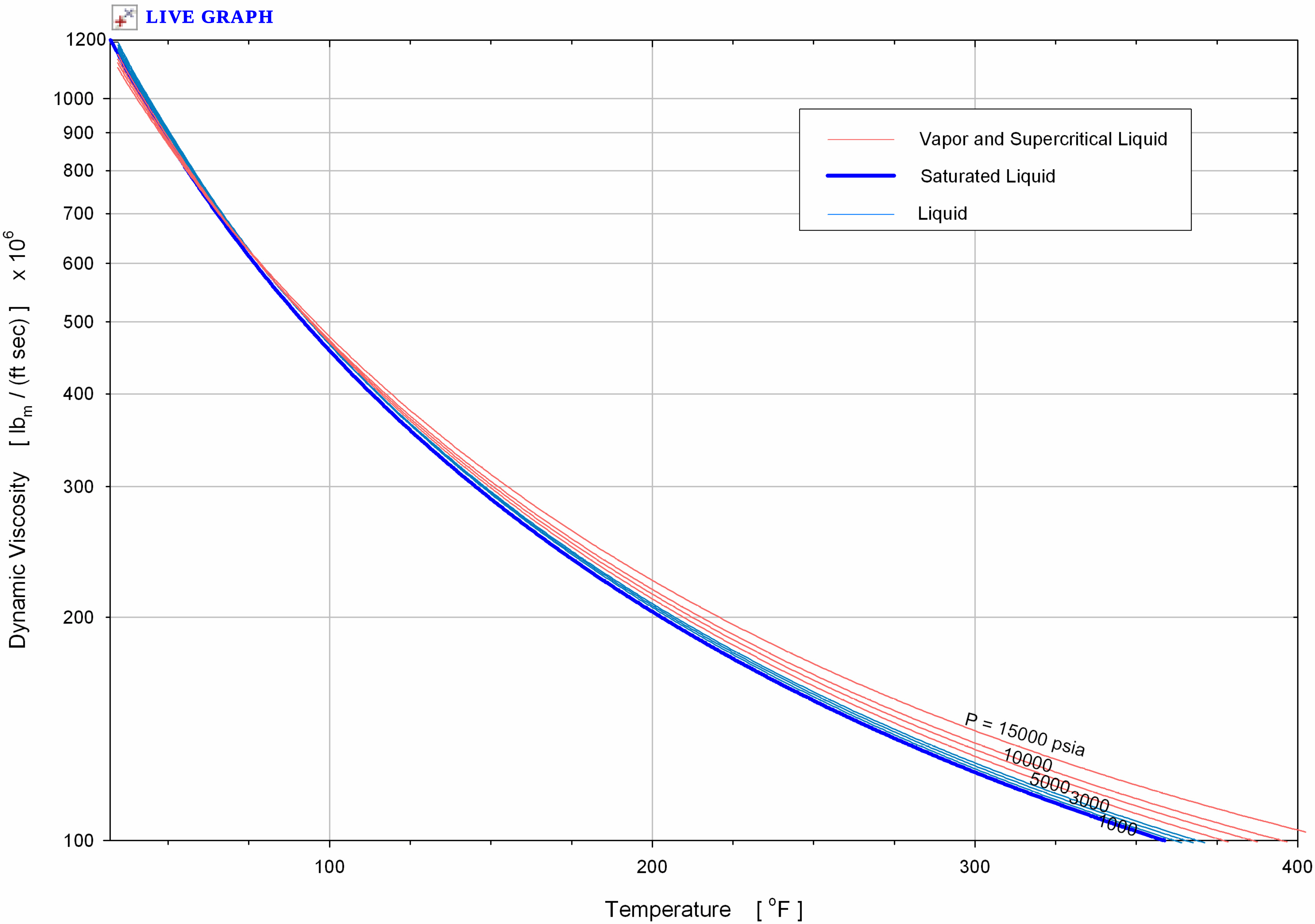


Chart 5b. Dynamic Viscosity vs. Temperature - English units (vapor region)

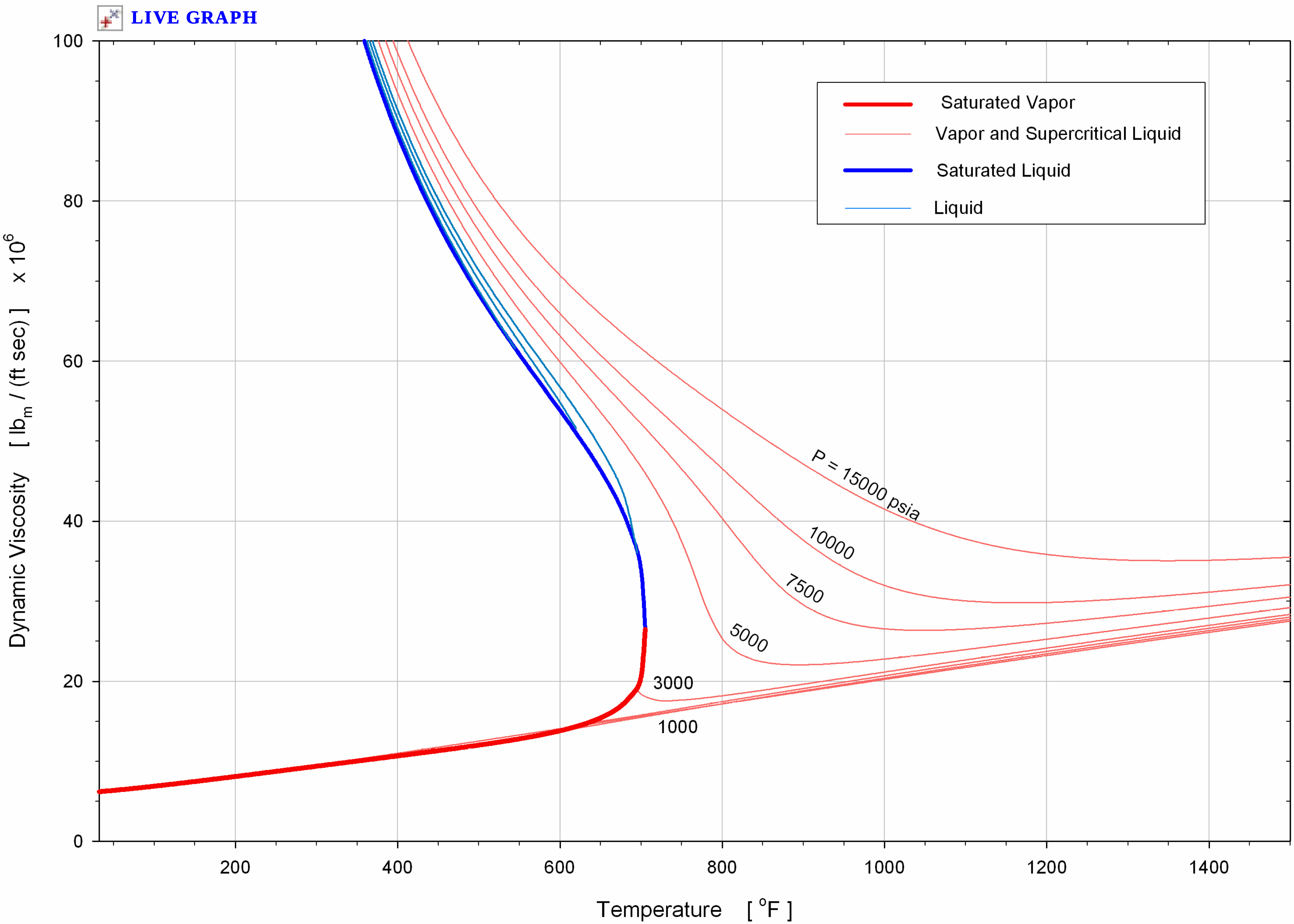


Chart 6a. Thermal Conductivity vs. Temperature - SI units

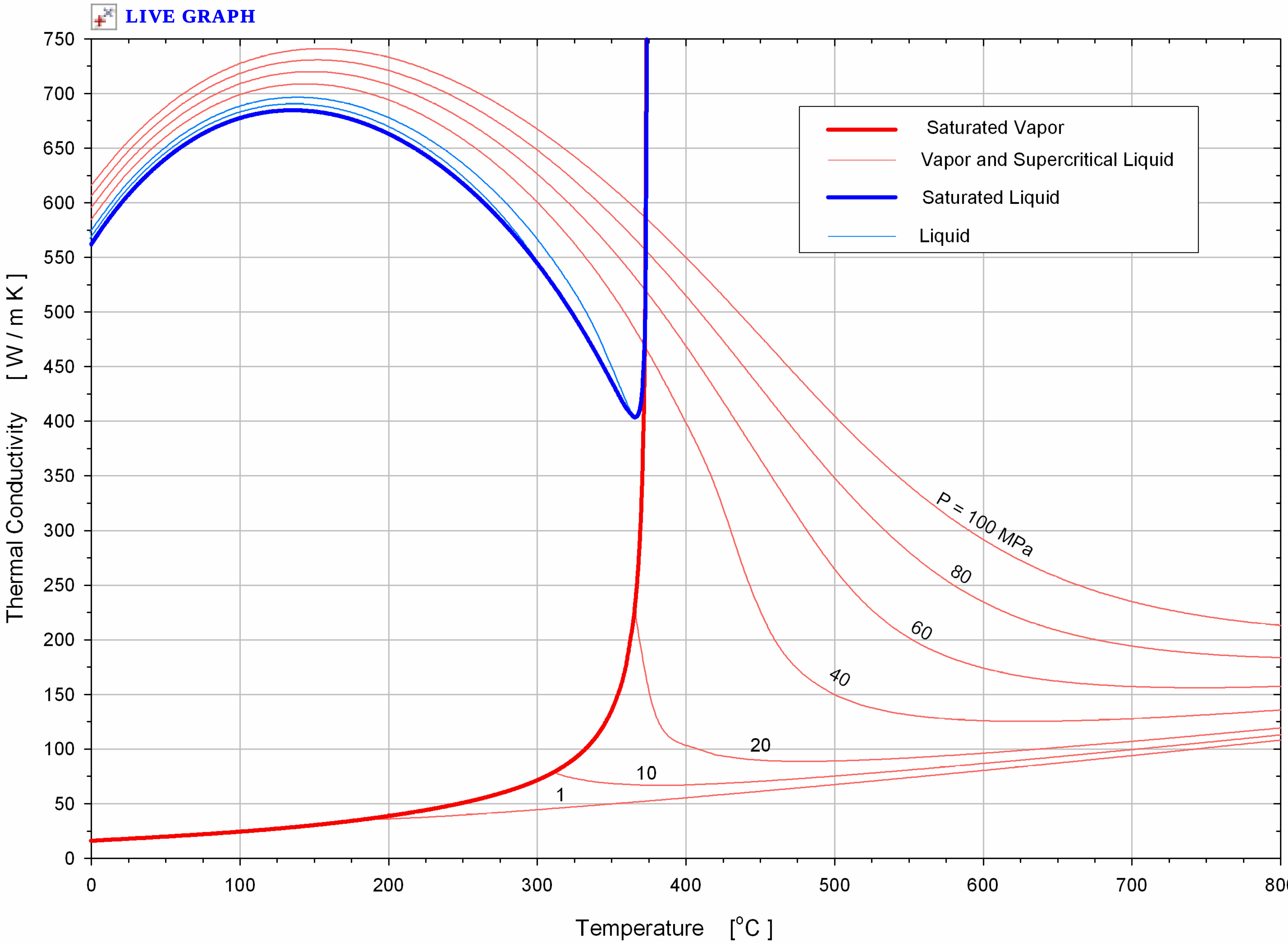


Chart 6b. Thermal Conductivity vs. Temperature - English units

LIVE GRAPH

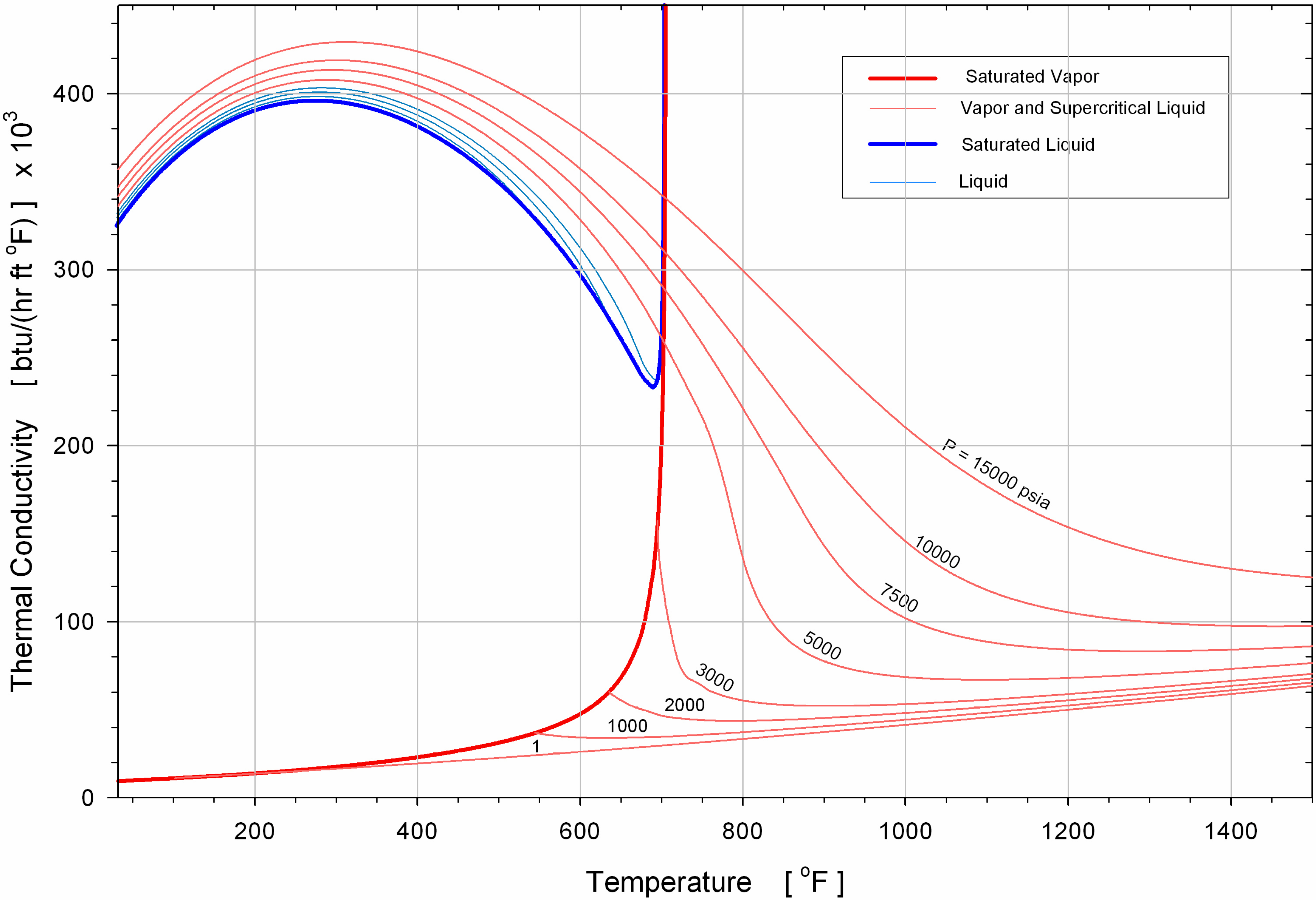


Chart 7a. Surface Tension vs. Temperature - SI units

LIVE GRAPH

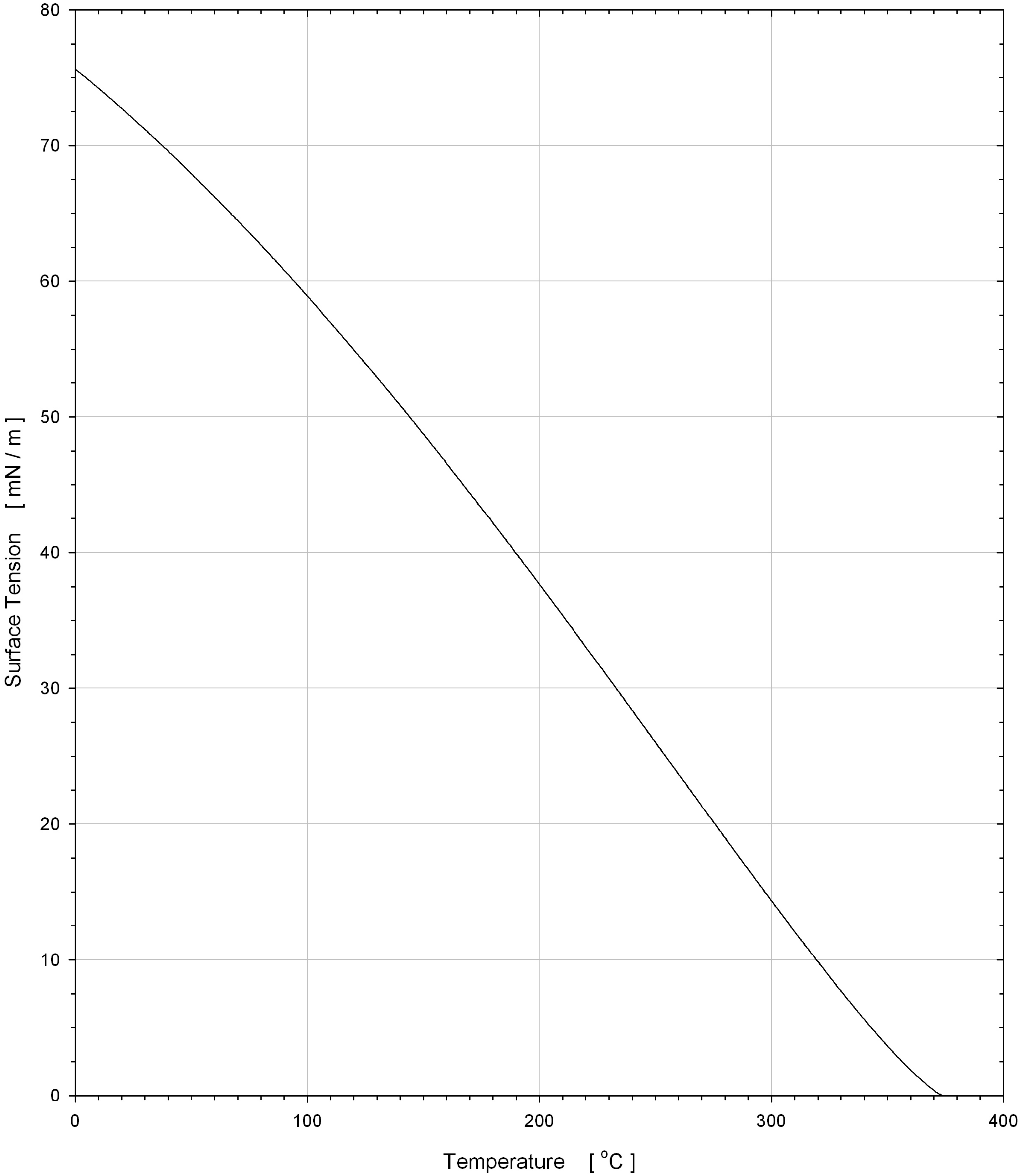
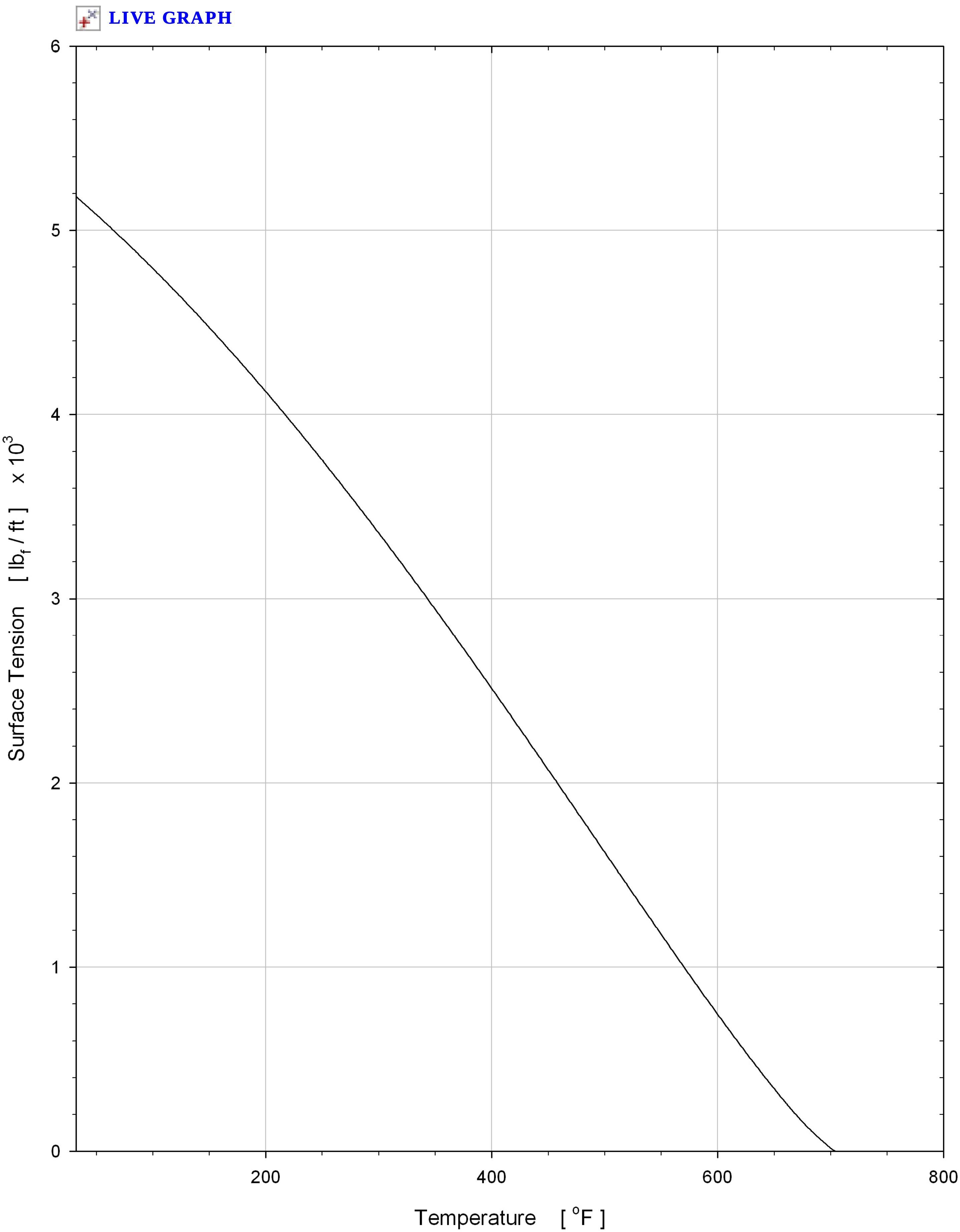


Chart 7b. Surface Tension vs. Temperature - English units



Introduction to the Knovel Steam Tables

1. General Considerations

1.1 Acknowledgements

This databook contains a full implementation of the industrial formulation of the thermodynamic properties, transport properties, and surface tension of water and steam contained in the 1997 release of the International Association for the Properties of Water and Steam (IAPWS) [ref. 1], related documents [ref. 2 - 4] and supplementary releases [ref. 5 - 7]. Use has also been made of the summaries of the IAPWS equations prepared by Bernhard Spang [ref. 8 -9].

In addition use has been made of the ASME International Steam Tables for Industrial Use [ref. 10], which is based on the same IAPWS formulation, especially its excellent tables of conversion factors. Its steam tables have often been used as a convenient source of test data while debugging the programs that implement the calculators and graph digitizers developed for this databook.

A final source is the extensive summary of power cycles contained in chapter 8 of reference 11. This has been used in developing the Power Cycle Efficiency Calculator and its planned extensions.

1.2 Description of the implementation

The industrial formulation equations provided by the IAPWS have been used in all the calculations for this databook. This includes the tables and their associated calculators, the charts and their associated digitizers, and the Power Cycle Efficiency Calculator. These equations are based on polynomial approximations to the Gibbs and Helmholtz free energies for the thermodynamic properties and polynomial fits to experimental data for the transport properties and surface tension. The use of polynomials has the great advantage of providing computational speed, and, for the thermodynamic properties, it leads to immediate, simple expressions for the required derivatives of the free energy.

The IAPWS has done extensive work on its formulations in order to insure that computed results obtained from the various equations always meet internationally agreed requirements for accuracy and numerical consistency. These are generally in the range of tenths to hundredths of a percent or better, except near the critical point where they may be a few percent. For specific information on tolerances, accuracies, and consistency of the computed results reference should be made to the relevant IAPWS documents and references contained therein. All of the IAPWS releases and supplemental releases can be downloaded from the IAPWS web site at http://www.iapws.org.

2. Nomenclature and Units

The tables, charts, calculators, and graph digitizers contained herein are all presented in both SI and English units. The nomenclature and units of the different variables are detailed in the table below:

variable	name	SI unit	English unit
T	temperature	^oC	^oF
P	pressure	MPa	psia
Q	quality	% vapor	% vapor
v	specific volume	m^3 / kg	ft^3 / lb_m
u	specific internal energy	kJ / kg	Btu / lb_m
h	specific enthalpy	kJ / kg	Btu / lb_m
s	specific entropy	kJ /(kg K)	Btu /(lb_m ^oR)
c_p	specific isobaric heat capacity	kJ /(kg K)	Btu /(lb_m ^oR)
c_v	specific isochoric heat capacity	kJ /(kg K)	Btu /(lb_m ^oR)
w	speed of sound	m / sec	ft / sec
μ	dynamic viscosity	μPa / sec	10^{-6} lb_m / (ft sec)
λ	thermal conductivity	mW / (m K)	10^{-3} Btu / (hr ft ^oF)
σ	surface tension	mN / m	10^{-3} lb_f / ft

3. Interactive Tables

There are seven tables included in this databook, each with two or more variations, and each accompanied by a calculator. Together they cover the entire range of variables and parameters of the IAPWS formulation. However, these tables are of relatively low resolution and should be used for purposes of orientation only. For higher resolution in specific ranges the associated calculators should be employed.

The tables generally have temperature as their independent variable, with each page containing data for a specific pressure, with the pressure value for the page indicated in green at the top of the page. The only exceptions to this are table 1 which has a temperature and a pressure version, and table 7 where saturation temperature is the sole variable.

Where the data on a page span the liquid-vapor phase boundary points for the saturated liquid and the saturated vapor are included. These are highlighted in blue for the saturated liquid and red for the saturated vapor.

The included tables are as follows:

Table 1. Saturation Thermodynamic Properties of Water and Steam

contains data for saturation pressure, specific volume, specific internal energy, specific enthalpy, and specific entropy as a function of temperature in the range

$$0 \le T \le T_{crit} = 373.946\ ^{o}C \qquad \text{(table 1a)}$$

or

$$32 \le T \le T_{crit} = 705.1028\ ^{o}F \qquad \text{(table 1b)}$$

or

contains data for saturation temperature, specific volume, specific internal energy, specific enthalpy, and specific entropy as a function of pressure in the range

$$0 < P \le P_{crit} = 22.064 \text{ MPa} \qquad \text{(table 1c)}$$

or

$$0 < P \le P_{crit} = 3200.11 \text{ psia} \qquad \text{(table 1d)}$$

Table 2. Thermodynamic Properties of Compressed Water and Superheated Steam

contains data for specific volume, specific internal energy, specific enthalpy, and specific entropy as a function of temperature and pressure in the range

$0 \leq T \leq 800\ ^{o}C$ and $0 < P \leq 100$ MPa (table 2a)

or

$32 \leq T \leq 1500\ ^{o}F$ and $0 < P \leq 15000$ psia (table 2b)

Table 3. Thermodynamic Properties of Metastable Steam

contains data for equilibrium quality factor, Q, temperature, specific volume, specific internal energy, specific enthalpy, and specific entropy as a function of pressure in the range of Q from 95 – 100 % vapor and

$.001 \leq P \leq 16$ MPa (table 3a)

or

$.145 \leq P \leq 2400$ psia (table 3b)

Table 4. Thermodynamic Properties of High Temperature Steam

contains data for specific volume, specific internal energy, specific enthalpy, specific entropy, specific isobaric heat capacity, specific isochoric heat capacity, and speed of sound as a function of temperature and pressure in the range

$800 \leq T \leq 2000\ ^{o}C$ and $0 < P \leq 10$ MPa (table 4a)

or

$1475 \leq T \leq 3625\ ^{o}F$ and $0 < P \leq 1450$ psia (table 4b)

Table 5. Heat Capacity and Speed of Sound of Compressed Water and Superheated Steam

contains data for specific isobaric heat capacity, specific isochoric heat capacity, and speed of sound as a function of temperature and pressure in the range

$0 \leq T \leq 800\ ^oC$ and $0 < P \leq 100$ MPa (table 5a)

or

$32 \leq T \leq 1500\ ^oF$ and $0 < P \leq 15000$ psia (table 5b)

Table 6. Transport Properties of Compressed Water and Superheated Steam

contains data for dynamic viscosity and thermal conductivity as a function of temperature and pressure in the range

$0 \leq T \leq 800\ ^oC$ and $0 < P \leq 100$ MPa (table 6a)

or

$32 \leq T \leq 1500\ ^oF$ and $0 < P \leq 15000$ psia (table 6b)

Table 7. Surface Tension at the Water - Steam Interface

contains data for surface tension as a function of saturation temperature from the triple point to the critical point

$.01 \leq T \leq 373.946\ ^oC$ (table 7a)

or

$32.018 \leq T \leq 705.1028\ ^oF$ (table 7b)

4. Calculators

Each table has an associated calculator which can be accessed from the table itself or independently from the Table of Contents for the databook. The calculators have selectable precision and allow the computation of any single point or any desired range within the range of the tables with selectable resolution up to a limit of 101 points (21 points for calculator 3). The range output is in the form of a table which is identical to the standard Knovel tables with all their features.

In addition to the calculators associated with the tables there is the Power Cycle Efficiency Calculator. This calculator accepts input of a pump inlet pressure or temperature, a pump outlet pressure, and a boiler outlet temperature. The output is the efficiency for an ideal Rankine cycle according to the input parameters, including isentropic pump work. The output also includes the temperature and pressure of the turbine outlet and the quality factor, Q, which is the percent of vapor at the turbine outlet. The efficiency of a Carnot cycle operating between the same upper and lower temperatures is output for comparison purposes.

5. Charts

There are seven charts included in this databook, each occurring in two or more versions. There are always SI and English unit versions of a given chart and, in addition, for Chart 3 there are separate versions for c_p and c_v , and for Chart 5, dynamic viscosity, there are separate versions for the liquid and vapor regions due to the wide range of the viscosity values. The charts cover generally the same range of temperature and pressure as for the corresponding tables (see above), with some minor variations.

The included charts are as follows:

Chart 1. Temperature – Entropy

graphs temperature versus specific entropy with families of curves for pressure, specific enthalpy, specific volume, and quality factor (% vapor) in the two phase region

Chart 2. Enthalpy – Entropy (Mollier diagram)

graphs specific enthalpy versus temperature with families of curves for temperature, pressure, and quality factor (% vapor) in the two phase region

Chart 3. Heat Capacity

graphs $1/c_p$ and $1/c_v$ versus temperature with a family of curves for pressure

Chart 4. Speed of Sound

graphs speed of sound versus temperature with a family of curves for pressure

Chart 5. Dynamic Viscosity

graphs dynamic viscosity versus temperature with a family of curves for pressure

Chart 6. Thermal Conductivity

graphs thermal conductivity versus temperature with a family of curves for pressure

Chart 7. Surface Tension

graphs surface tension versus temperature

6. Chart Digitizers

Each chart is accompanied by a digitizer which can be accessed either from the chart page or independently from the Table of Contents for the databook. The digitizer for chart number seven is of the standard type which allows the user to click on a point on the chart to obtain output of the coordinates of the selected point. The other six have additional capabilities. For them, clicking on a point on the chart will yield output to the text boxes in the left hand pane of the digitizer of values for the axes and also for any families of curves displayed on the chart.

Additionally, the user may enter a value for the x-axis and a second variable which may be either the y-axis or any of the other parameters displayed as families of curves on the chart. This will result in the relevant point being plotted on the chart and the values of all the other variables being displayed in the text boxes.

For example, if a value is entered for specific entropy (x-axis) and pressure (curve family) in digitizer 2, a point will be plotted corresponding to the entered entropy and pressure and values will be output to the test boxes in the left hand pane of the digitizer for specific enthalpy, temperature, and also quality factor if the point falls in the two phase region.

For certain combinations of input pairs there are multiple points which correspond to the pair of entered values. For charts 3 – 5 this occurs for pairs of x and y axis points where the pressure curves on the chart cross each other. This results in two values of pressure satisfying the input. Both of these will be plotted on the chart and output to the text boxes.

For charts 1 and 2 there is the possibility of up to three solutions satisfying an entered entropy and quality factor for quality factors near 50%. All of them will be output to the text boxes. For chart 1 all the computed points will also be plotted on the chart. In the case of chart 2 one or two of the points may lie outside the region included in the plot. Those that are within the axis ranges will be plotted.

7. References

1. "Release on the IAPWS Industrial Formulation 1997 for the Thermodynamic Properties of Water and Steam", Erlangen, Germany, September 1997

2. "Revised Release on the IAPWS Formulation 1985 for the Thermal Conductivity of Ordinary Water Substance", London, England, September 1998

3. "Revised Release on the IAPWS Formulation 1985 for the Viscosity of Ordinary Water Substance", Vejle, Denmark, August 2003

4. "IAPWS Release on Surface Tension of Ordinary Water Substance", September 1994

5. "Supplementary Release on Backward Equations for Pressure as a Function of Enthalpy and Entropy $p(h,s)$ to the IAPWS Industrial Formulation 1997 for the Thermodynamic Properties of Water and Steam", Gaithersburg, Maryland, USA, September 2001

6. Supplementary Release on Backward Equations $p(h,s)$ for Region 3, Equations as a Function of h and s for the Region Boundaries, and an Equation $T_{sat}(h,s)$ for Region 4 of the IAPWS Industrial Formulation 1997 for the Thermodynamic Properties of Water and Steam", Kyoto, Japan, September 2004

7. "Revised Supplementary Release on Backward Equations for the Functions $T(p,h)$, $v(p,h)$, and $T(p,s)$, $v(p,s)$ for Region 3 of the IAPWS Industrial Formulation 1997 for the Thermodynamic Properties of Water and Steam", Kyoto, Japan, September 2004

8. Bernhard Spang, "Equations of IAPWS-IF97", available at http://www.cheresources.com.

9. Bernhard Spang, "IAPWS Equations for Transport Properties and Surface Tension of Water and Steam", available at http://www.cheresources.com.

10. "ASME International Steam Tables for Industrial Use", ASME Press, New York, N.Y., 2000

11. Merle C. Potter and Craig W. Somerton, "Thermodynamics for Engineers", Schaum's Outline Series, McGraw-Hill, 1993