Problem 1.4

At what absolute temperature do the Celsius and Fahrenheit temperature scales give the same numerical value? What is the value?

Solution:

Easy Method: Write a function for converting degrees C into degrees F. Set this equal to degrees F. Solve for the unknown.

In[1]:=
```
Solve[x * 9/5 + 32 == x]
```

Out[1]= $\{\{x \to -40\}\}$

You can also convert deg F into deg C and set this equal to deg C, giving the same answer.

In[2]:=
```
Solve[x == (x - 32) * 5/9]
```

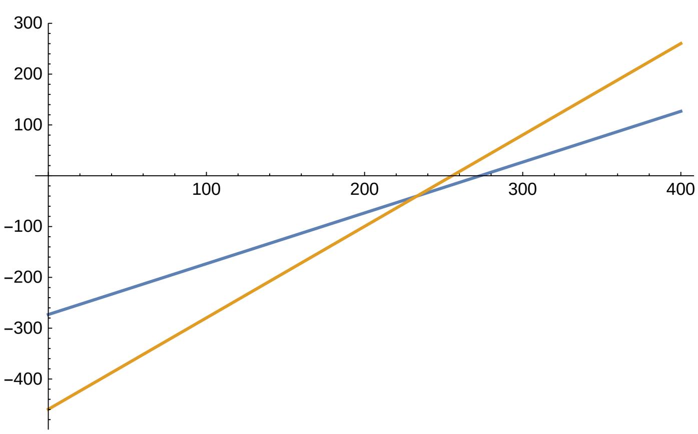
Out[2]= $\{\{x \to -40\}\}$

```
(*x=-40 degC or degF //ANS*)
```

To visualize this, write a function for converting Kelvins into deg C. Then write a second function converting Kelvins into deg F. Plot the two functions with Kelvins as the independent variable. The plot shows the intersection. Setting the two functions equal to each other and solving for the intersection gives -40 as before.

In[3]:=
```
(*Calculate deg C and F from Kelvins *)
f1[x_] = x - 273.15;
f2[x_] = (x - 273.15) * 9/5 + 32;
```

In[5]:=
```
Plot[{f1[x], f2[x]}, {x, 0, 400}]
```

Out[5]=


In[6]:=
```
Solve[f1[x] == f2[x]]
```

Out[6]= $\{\{x \to 233.15\}\}$

In[7]:=
```
233.15 - 273.15
```

Out[7]= -40.

```
(*ans: -40 deg C or 233.15 K //ANS*)
```

Problem 1.6

Pressures up to 3,000 bar are measured with a dead-weight gauge. The piston diameter is 4 mm. What is the approximate mass in kg of the weights required?

Solution:

Calculate the area of the piston.

$$\frac{\pi}{4}\left(4.\ \text{mm} * \frac{1\ \text{m}}{1000\ \text{mm}}\right)^2$$

$$0.00001256637061\ \text{m}^2$$

Calculate the force from the pressure and the area, knowing that pressure is force per unit area.

$$3000\ \text{bar}\ \frac{\frac{10^5\ \text{N}}{\text{m}^2}}{\text{bar}} * .0000125664\ \text{m}^2$$

$$3769.92\ \text{N}$$

Equate force to mass*g and solve for mass. (We retain units for illustrative purposes only. They can be dropped in this case for a quick calculation.)

In[ ]:= $$\text{eq1} = 3769.92\ \text{N} * \frac{\frac{1\ \text{kg}*\text{m}}{\text{s}^2}}{1\ \text{N}} == \text{mass} * \frac{9.80665\ \text{m}}{\text{s}^2}$$

Out[ ]= $$\frac{3769.92\ \text{kg m}}{\text{s}^2} == \frac{9.80665\ \text{m mass}}{\text{s}^2}$$

In[ ]:= `Solve[eq1, mass]`

Out[ ]= $\{\{\text{mass} \to 384.4248546\ \text{kg}\}\}$

Therefore, the mass is 384.425 kg //ANS.

It is a good idea to check the answer. This can be done quickly by converting the mass back to a force (in Newtons) and then into a pressure (in Pa) and then converting to pressure in bar.

$$\frac{384 * 9.8}{\pi * .004^2 / 4} \Big/ 10^5$$

$$2994.659409$$

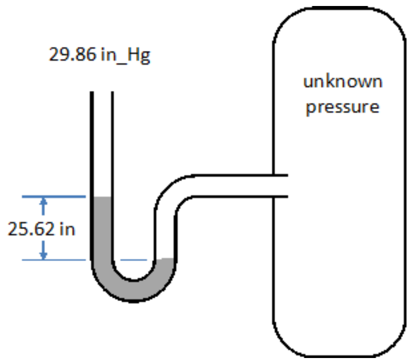
Note that this is about 3,000 bar, as expected.

Problem 1.9

The reading on a mercury manometer at 70 degF (open to the atmosphere at one end) is 25.62 inches. The local acceleration of gravity is 32.243 $\frac{ft}{s^2}$. Atmospheric pressure is 29.86 inches of mercury (in_Hg). What is the absolute pressure in psia being measured? The density of mercury at 70 degF is 13.543 $\frac{gm}{cm^3}$.

Solution:

A sketch of the manometer is shown below. The sketch shows how the different pressures and mercury height are related.



The absolute pressure in the vessel is the sum of the manometer pressure and the atmospheric pressure.

The manometer pressure is given by ρgh, where h is the difference in height between the two mercury levels. In English units, we need the conversion factor g_c, so the pressure difference is $\frac{1}{g_c}\rho gh$. First, though, convert desnity of mercury to English units:

$$\left(\frac{13.543\ \mathrm{gm}}{\mathrm{cm}^3}\right) * \left(\frac{2.20462\ \mathrm{lb_m}}{1000\ \mathrm{gm}}\right) * \left(\frac{10^6\ \mathrm{cm}^3}{35.3147\ \mathrm{ft}^3}\right)$$

$$\frac{845.4600679\ \mathrm{lb_m}}{\mathrm{ft}^3}$$

To get absolute pressure, add the guage pressure to the atmospheric pressure (25.62in+29.86in), then apply the manometer equation:

In[24]:=
$$\frac{\left(\left(\frac{845.46\ \mathrm{lb_m}}{\mathrm{ft}^3}\right) * \left(\frac{32.243\ \mathrm{ft}}{\mathrm{s}^2}\right) * (25.62\ \mathrm{in} + 29.86\ \mathrm{in}) * \left(\frac{1\ \mathrm{ft}}{12\ \mathrm{in}}\right)\right)}{\left(\frac{\frac{32.1740\ \mathrm{ft} * \mathrm{lb_m}}{\mathrm{s}^2}}{1\ \mathrm{lb_f}}\right)} * \left(\frac{1\ \mathrm{ft}}{12\ \mathrm{in}}\right)^2$$

Out[24]=
$$\frac{27.20296015\ \mathrm{lb_f}}{\mathrm{in}^2}$$

The absolute pressure in the vessel is 27.23 psia //ANS.

Problem 1.11

Liquids that boil at relatively low temperatures are often stored as liquids under their vapor pressures, which at ambient temperature can be quite large. Thus, n-butane stored as a liquid/vapor system is at a pressure of 2.581 bar for a temperature of 300 K. Large-scale storage (> 50 m^3) of this kind is sometimes done in spherical tanks. Suggest two reasons why.

Solution:

Reason 1:

For a given volume, the surface area to volume ratio is minimized in a sphere. (Examples of volume and area calculations follow below.) What does surface area to volume ration mean in terms of tank design? For a unit volume, the surface area for a sphere is lower than for other shapes. Since heat transfer is proportional to surface area, the same volume of fluid experiences less heat transfer when contained inside a sphere as opposed to a cube or rectangle. Less heat transfer means less evaporation, which means the evaporative losses should be lower. Since the vapor has to be captured and re-compressed, and recompression has energy costs, storage costs will be lower in the spherical vessel. This is generally verified industrial practice.

Reason 2:

A sphere is inherently a very strong structure. The reason for this is the symmetrical and even distribution of stresses on the sphere's surfaces. Generally, this means that there are fewer weak points than in cylindrical vessels. Of course, this reasoning is true only for a "theoretical" sphere. In an actual spherical vessel, there will be imperfections and stress points at the welds between the plates used to fabricate the vessel, but all things being equal, the spherical vessel should be somewhat stronger.

Area per volume examples:

The following are examples of area per volume calculations for a sphere, a cube, three different cylinders, one with h/D=1, one with h/D=2 (tall and narrow), and the other with h/D=1/2 (short and wide), and a triangular pyramid with b=h. We assume the same volume of 50 m^3 for all shapes.

Results

(m^2 per 50 m^3):		(m^2 per 1 m^3):
Sphere	65.6348	1.3127
Cylinder, h/D=1	75.1346	1.5027
Cylinder, h/D=2	78.8840	1.5777
Cylinder, h/D=1/2	79.5104	1.5902
Cube	81.4325	1.6287
Tri. Pyramid, b=h	89.6128	1.7923

In[4]:=
```
(*Example 1 - sphere - calculate sphere radius from volume*)
```
$$\text{Solve}\left[\frac{4}{3}\pi * r^3 == 50., r, \text{Reals}\right]$$

Out[4]= {{r → 2.28539}}

```
(*Calculate sphere area from radius*)
```
$$4 * \pi * 2.2854^2$$

65.6348

In[5]:=
```
(*Example 2 - cube - calculate cube edge length from volume*)
Solve[r^3 == 50., r, Reals]
```
Out[5]=
```
{{r → 3.68403}}
```

```
(*Calculate cube area from edge length *)
6 * 3.68403^2
```
```
81.4325
```

In[6]:=
```
(*Example 3 - Cylinder with h/D=1*)
(*calculate radius from volume *)
Solve[π * r^2 * 2 * r == 50., r, Reals]
```
Out[6]=
```
{{r → 1.99647}}
```

```
(*Calculate cylinder area from radius *)
2 * π * 1.9965^2 + 2 * π * 1.9965 * 2 * 1.9965
```
```
75.1346
```

In[7]:=
```
(*Example 4 - Cylinder with h/D=2*)
(*calculate radius from volume *)
Solve[π * r^2 * (4 * r) == 50., r, Reals]
```
Out[7]=
```
{{r → 1.5846}}
```

```
(*Calculate cylinder area from radius *)
2 * π * 1.5846^2 + 2 * π * 1.5846 * (4 * 1.5846)
```
```
78.884
```

In[8]:=
```
(*Example 5 - Cylinder with h/D=1/2*)
(*calculate radius from volume *)
Solve[π * r^2 * r == 50., r, Reals]
```
Out[8]=
```
{{r → 2.5154}}
```

```
(*Calculate cylinder area from radius *)
2 * π * 2.5154^2 + 2 * π * 2.5154 * (2.5154)
```
```
79.5104
```

In[9]:=
```
(*Example 6 - Triangular pyramid with b=h=H*)
(*calculate b from volume *)
Solve[1/6 b^3 == 50., b, Reals]
```
Out[9]=
```
{{b → 6.69433}}
```

```
(*Calculate pyramid area from base *)
4 * 1/2 * 6.69433 * 6.69433
```
```
89.6281
```

Problem 1.12

The first accurate measurements of the properties of high-pressure gases were made by E.H. Amagat in France between 1869 and 1893. Before developing the dead-weight gauge, he worked in a mine shaft, and used a mercury manometer for measurements of pressure to more than 400 bar. Estimate the height of the manometer required.

Solution:

Since this is an estimate, we do not need highly precise constants. We can assume a density of mercury of about 13.5 $\frac{\text{gm}}{\text{cm}^3}$, which corresponds to a temperature near 25 degC. The acceleration of gravity is about 9.8 $\frac{m}{s^2}$.

(*Convert the pressure to base units. *)

$$\mathbf{400.\ bar * \frac{\frac{100\,000\ kg}{m*s^2}}{1\ bar}}$$

$$\frac{4.\times 10^7\ \text{kg}}{\text{m s}^2}$$

(*The pressure is given by ρgh*)

$$\mathbf{eq1 = \frac{4.*10^7\ kg}{m*s^2} == \frac{13.5\ gm * \frac{1\ kg}{1000\ gm}}{cm^3 * \left(\frac{1\ m}{100\ cm}\right)^3} * \frac{9.8\ m}{s^2} * (h)}$$

$$\frac{4.\times 10^7\ \text{kg}}{\text{m s}^2} == \frac{132\,300.\ \text{h kg}}{\text{m}^2\ \text{s}^2}$$

Solve[eq1, h]

$\{\{h \to 302.343\ \text{m}\}\}$

Therefore the height of the manometer was more than 302 m or 992 ft. That is more than 3 football fields in length!

Problem 1.18

A gas is confined in a 1.25-ft-diameter cylinder by a piston, on which rests a weight. The mass of the piston and weight together is 250 lb_m. The local acceleration of gravity is 32.169 $\frac{ft}{s^2}$,and the atmospheric pressure is 30.12 inches of Hg (in_Hg).

(a) What is the force in lb_f exerted on the gas by the atmosphere, the piston, and the weight, assuming no friction between the piston and the cylinder?

(b) What is the pressure of the gas in psia?

(c) If the gas in the cylinder is heated, it expands, pushing the piston and weight upward. If the piston and weight are raised 1.7 ft, what is the work done by the gas in $ft * lb_f$? What is the change in potential energy of the piston and the weight?

Solution:

Part (a)

Calculate the force due to the piston and the weight:

$$250\ lb_m * \left(32.169\ ft / s^2\right) * \frac{1\ lb_f}{\frac{32.174\ ft*lb_m}{s^2}}$$

$$249.961\ lb_f$$

Calculate the atmospheric pressure in psia using the conversion factors from Appendix A. Additional conversion factor: 1 Torr = 1 mmHg.

$$30.12\ in\_Hg * \frac{100\ cm\_Hg}{39.3701\ in\_Hg} * \frac{10\ mm\_Hg}{1\ cm\_Hg} * \frac{1\ torr}{1\ mm\_Hg} * \frac{14.5038\ psia}{750.061\ torr}$$

$$14.7936\ psia$$

Calculate the piston area:

$$area = \pi * \left(1.25\ ft * \frac{12\ in}{ft}\right)^2 / 4$$

$$176.715\ in^2$$

Now calculate the force due to atmospheric pressure:

$$\frac{14.7936\ lb_f}{1\ in^2} * area$$

$$2614.24\ lb_f$$

Now calculate the total force due to weight, piston, air atmosphere:

$$force = 249.961\ lb_f + 2614.24\ lb_f$$

$$2864.2\ lb_f$$

The total force is 2864.2 lbf //ANS

Part (b)

The pressure of the gas in psia is the force divided by the piston area:

$$\frac{2864.2\ \mathrm{lb_f}}{176.715\ \mathrm{in}^2}$$

$$\frac{16.208\ \mathrm{lb_f}}{\mathrm{in}^2}$$

The pressure of the gas is 16.208 psia //ANS

Part (c)

The system is defined as the gas in the cylinder. The system (gas) performs work by lifting the piston/weight and by expanding against the constant-pressure of the atmosphere. By equation 1.3 expansion work is given by -Δ(PV) which is -PΔV in this case because the surrounding pressure is constant. The total pressure pushing on the gas was calculated in part (b) which accounts for the atmosphere and the piston/weight. The volume change is given by the displacement multiplied by the area.

$$\frac{-16.2081\ \mathrm{lb_f}}{\mathrm{in}^2} * 176.7\ \mathrm{in}^2 * 1.7\ \mathrm{ft}$$

$$-4868.75\ \mathrm{ft\ lb_f}$$

Therefore, the system did -4868.75 ft*lbf of work on the surroundings. //ANS Work is **negative** since the total force and displace-ment are opposite in direction.

Change in potential energy is given by m*g*h:

$$250\ \mathrm{lb_m} * 32.169\ \frac{\mathrm{ft}}{\mathrm{s}^2} * 1.7\ \mathrm{ft} * \frac{1\ \mathrm{lb_f}}{\frac{32.174\ \mathrm{ft}*\mathrm{lb_m}}{\mathrm{s}^2}}$$

$$424.934\ \mathrm{ft\ lb_f}$$

The change in potential energy is 424.934 ft*lbf. //ANS

Problem 1.20

Verify that the SI unit of kinetic and potential energy is the joule.

Solution:

This problem deals with converting energy units. Students must know how to convert kinetic and potential energy from base units into Joules.

(*for kinetic energy start with $\frac{1}{2}mv^2$*)

$$kg * \left(\frac{m}{s}\right)^2 * \frac{1\,N}{\frac{1\,kg*m}{s^2}} * \frac{1\,J}{1\,N*m}$$

J

(*for potential energy start with m*g*h*)

$$kg * \frac{m}{s^2} * m * \frac{1\,N}{\frac{1\,kg*m}{s^2}} * \frac{1\,J}{1\,N*m}$$

J

Problem 1.22

The turbines in a hydroelectric plant are fed by water falling from a 50-m height. Assuming 91% efficiency for conversion of potential to electrical energy, and 8% loss of the resulting power in transmission, what is the mass flow rate of water required to power a 200-watt light bulb?

Solution:

Students must know how to convert potential energy into *energy flow rate*. The following conversion factors are important:

$$\frac{\text{kg} * \text{m}}{\text{s}^2} \text{(*N*)} \quad \frac{\text{kg} * \text{m}^2}{\text{s}^2} \text{(*Nm or joule*)} \quad \frac{\text{kg} * \text{m}^2}{\text{s}^3} \text{(*Nm/s or Watt*)} \quad \frac{\text{kg}}{\text{m} * \text{s}^2} \text{(*N/m}^2 \text{ or pascal*)}$$

$$\text{LightBulbPower} = 200\,\text{W} * \frac{\frac{\text{kg}*\text{m}^2}{\text{s}^3}}{\text{W}} \quad \text{(*Light bulb power*)}$$

$$\frac{200\,\text{kg}\,\text{m}^2}{\text{s}^3}$$

$$\text{HydrostaticPressure} = \frac{1000\,\text{kg}}{\text{m}^3} * \frac{9.8\,\text{m}}{\text{s}^2} * 50\,\text{m} \quad (*\rho*\text{g}*\text{h}*)$$

(*This is pressure head, not power power, but they are interconvertible*)

$$\frac{490\,000.\,\text{kg}}{\text{m}\,\text{s}^2}$$

By comparison to the units for Watts, these two terms differ by multiplication of ρgh by volumetric flow in $\frac{m^3}{s}$. To illustrate, divide them:

$$\frac{\text{LightBulbPower}}{\text{HydrostaticPressure}}$$

$$\frac{0.000408163\,\text{m}^3}{\text{s}}$$

Now add the efficiencies, noting that any losses must increase the flow rate to account for the lost energy. We do this by dividing by the efficiencies.

$$\frac{\text{LightBulbPower}}{0.91 * (1 - .08) * \text{HydrostaticPressure}}$$

$$\frac{0.000487534\,\text{m}^3}{\text{s}}$$

$$\frac{0.000487534\,\text{m}^3}{\text{s}} * \frac{1000\,\text{kg}}{\text{m}^3}$$

$$\frac{0.487534\,\text{kg}}{\text{s}}$$

The mass flow rate required is $0.4875\ \frac{kg}{s}$ or $1{,}755\ \frac{kg}{h}$.

Problem 1.27

Energy costs vary greatly with energy source: coal @ \$35.00/ton, gasoline @ a pump price of \$2.75/gallon, and electricity @ \$0.1000/kWhr. Conventional practice is to put these on a common basis by expressing them in \$/GJ. For this purpose, assume gross heating values of 29 MJ/kg for coal and 37 GJ $/ m^3$ for gasoline.

(a) Rank order the three energy sources with respect to energy cost in \$/GJ.

(b) Explain the large disparity in the numerical results of Part (a). Discuss the advantages and disadvantages of the three energy sources.

Solution:

Part a.

In[ ]:= (*Coal*)

$$\frac{35\ \text{dollars}}{\text{ton}} * \frac{1\ \text{ton}}{2000\ \text{lbs}} * \frac{2.20462\ \text{lbs}}{\text{kg}} * \frac{1\ \text{kg}}{29\ \text{MJ}} * \frac{1000\ \text{MJ}}{\text{GJ}}$$

Out[ ]=
$$\frac{1.33037\ \text{dollars}}{\text{GJ}}$$

In[ ]:= (*Gasoline*)

$$\frac{2.75\ \text{dollars}}{\text{gal}} * \frac{264.172\ \text{gal}}{1\ \text{m}^3} * \frac{1\ \text{m}^3}{37\ \text{GJ}}$$

Out[ ]=
$$\frac{19.6344\ \text{dollars}}{\text{GJ}}$$

(*Electricity*)

$$\frac{0.1000\ \text{dollars}}{\text{kWhr}} * \frac{2.77778 * 10^{-7}\ \text{kWhr}}{1\ \text{J}} * \frac{10^9\ \text{J}}{\text{GJ}}$$

$$\frac{27.7778\ \text{dollars}}{\text{GJ}}$$

Coal < Gasoline < Electrcitiy. Ans.

Part b.

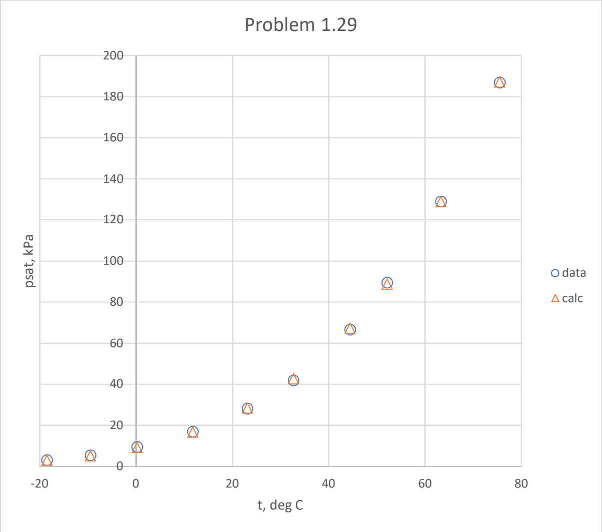
Gasoline and electricity are more expensive because they are more highly refined forms of energy requiring more infrastructure. Converting coal to electricity requires a power plant plus a train line plus and electrical power grid. Burning coal directly to produce heat energy requires only a fire box. To convert coal to mechanical energy requires a fire box and a heat engine such as a steam engine. Steam engines are mechanically very simple. Ans.

Problem 1.29 Solved in deg C

Andrew Biaglow

A	13.33896
B	2248.247
D	201.818

$t/^oC$	data p^{sat}/kPa	Ant eq ln(psat)	calc p^{sat}/kPa		dev^2
-18.5	3.18	1.0748	2.929		0.06284
-9.5	5.48	1.6487	5.200		0.07828
0.2	9.45	2.2100	9.116		0.11165
11.8	16.9	2.8143	16.682		0.04742
23.1	28.2	3.3431	28.307		0.01144
32.7	41.9	3.7523	42.618		0.51622
44.4	66.6	4.2078	67.211		0.37324
52.1	89.5	4.4847	88.653		0.71664
63.3	129	4.8588	128.868		0.01755
75.5	187	5.2319	187.139		0.01932
55.99	101.325	4.6183	101.325	SSQ	1.955
				ERR	0.442



Answers to questions:

The average error is 0.442 and the fit is good.

The predicted normal boiling point is 55.99 deg C.

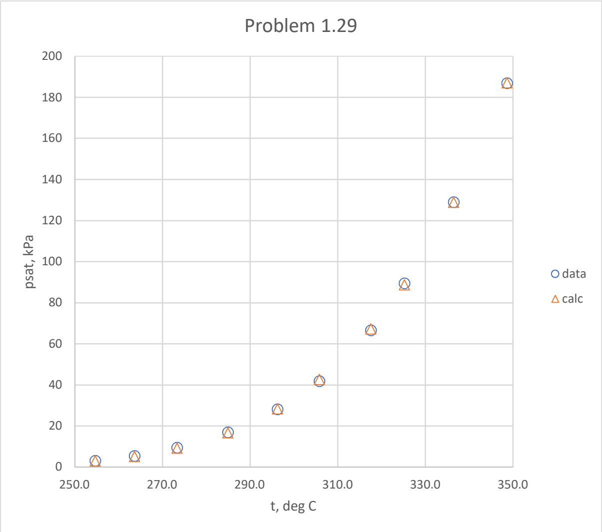
This compound does not appear in Table B.2

Problem 1.29 Solved in deg K

Andrew Biaglow

E	13.33894
F	2248.243
G	-71.332

$t/^oC$	T/K	data p^{sat}/kPa	Ant eq ln(psat)	calc p^{sat}/kPa		dev^2
-18.5	254.7	3.18	1.0748	2.929		0.06283
-9.5	263.7	5.48	1.6487	5.200		0.07826
0.2	273.4	9.45	2.2100	9.116		0.11163
11.8	285.0	16.9	2.8143	16.682		0.04740
23.1	296.3	28.2	3.3431	28.307		0.01145
32.7	305.9	41.9	3.7523	42.618		0.51623
44.4	317.6	66.6	4.2078	67.211		0.37316
52.1	325.3	89.5	4.4847	88.653		0.71688
63.3	336.5	129	4.8588	128.867		0.01764
75.5	348.7	187	5.2318	187.138		0.01914
329.14	101.325		4.6183	101.325	SSQ	1.955
					ERR	0.442



Notes:

The average error is 0.442 and the normal boiling point is 329.14 K.

This compound does not appear in Table B.2