Cryogenics – The Basics

or
Pre-Basics

Lesson 1

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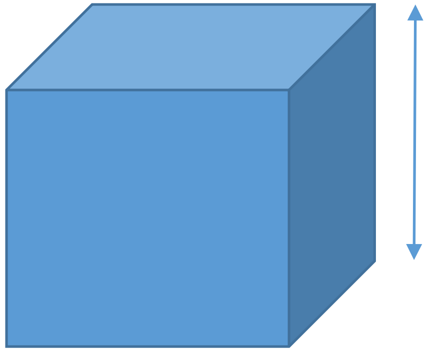
Version 3

Lesson 1 - Objectives

- Look at common liquids and gases to get a feeling for their properties
- Look at Nitrogen and Helium
- Discuss Pressure and Temperature Scales
- Learn more about different phases of these fluids
- Become familiar with some cryogenic fluids properties

Liquids – Water (a good reference)



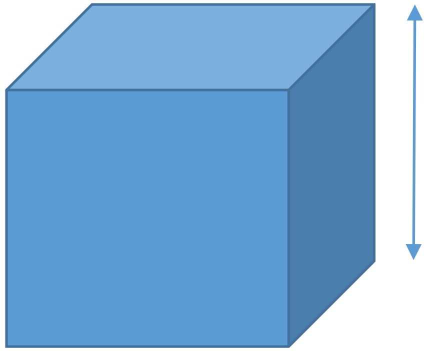
10cm

H2O density is 1 g/cc

Total weight 1000g or 1kg (2.2lbs)

Cube of water – volume 1000cc
= 1 liter

Liquids – Motor Oil

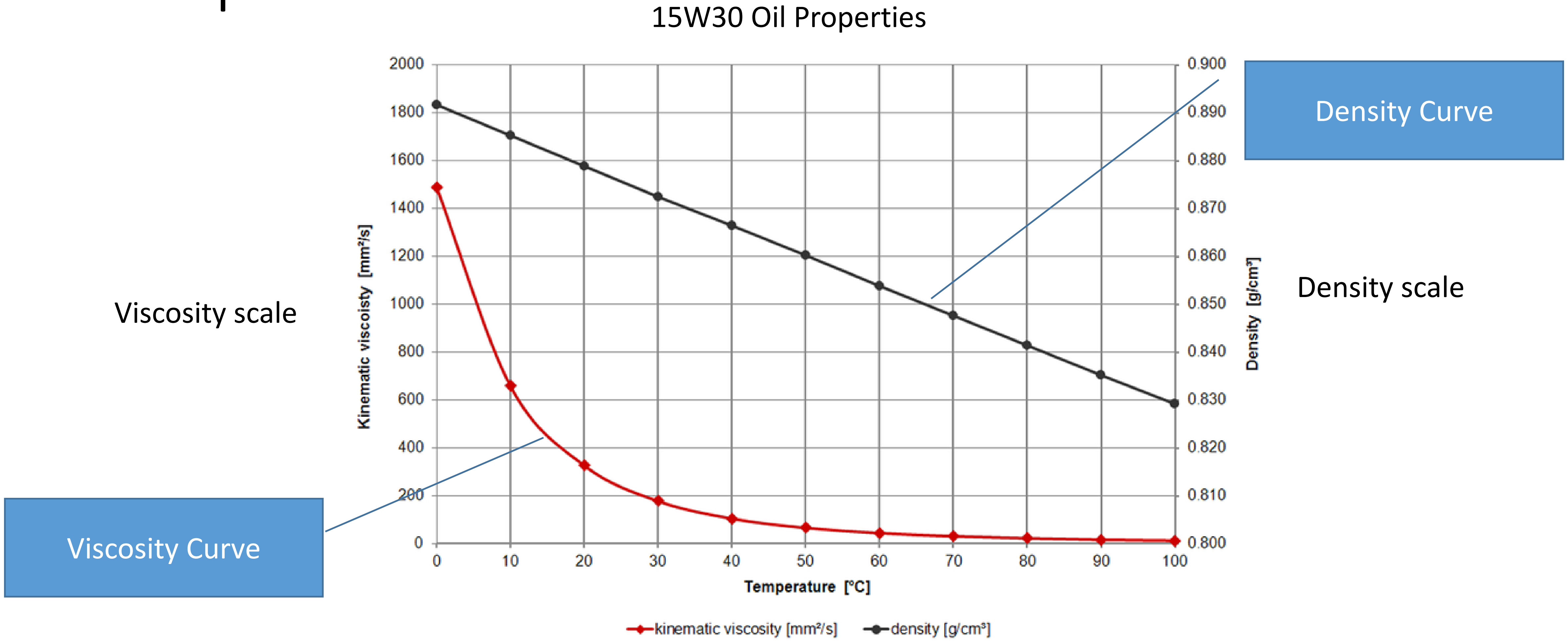


15W30 density is 0.9 g/cc

Total weight 900g or 0.9 kg (2lbs)

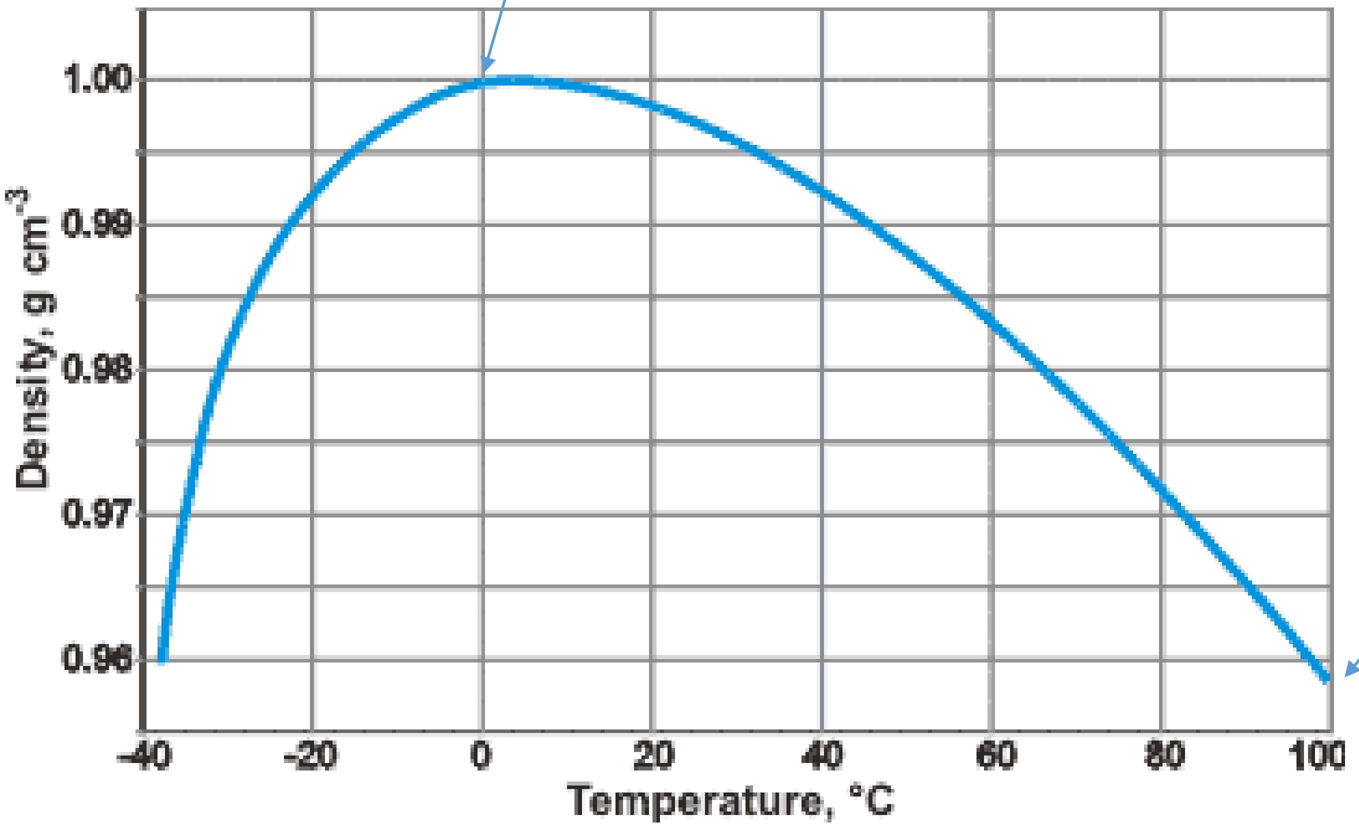
Cube of motor oil – volume
1000cc = 1 liter

Density can and usually does change with temperature



Water density vs temperature

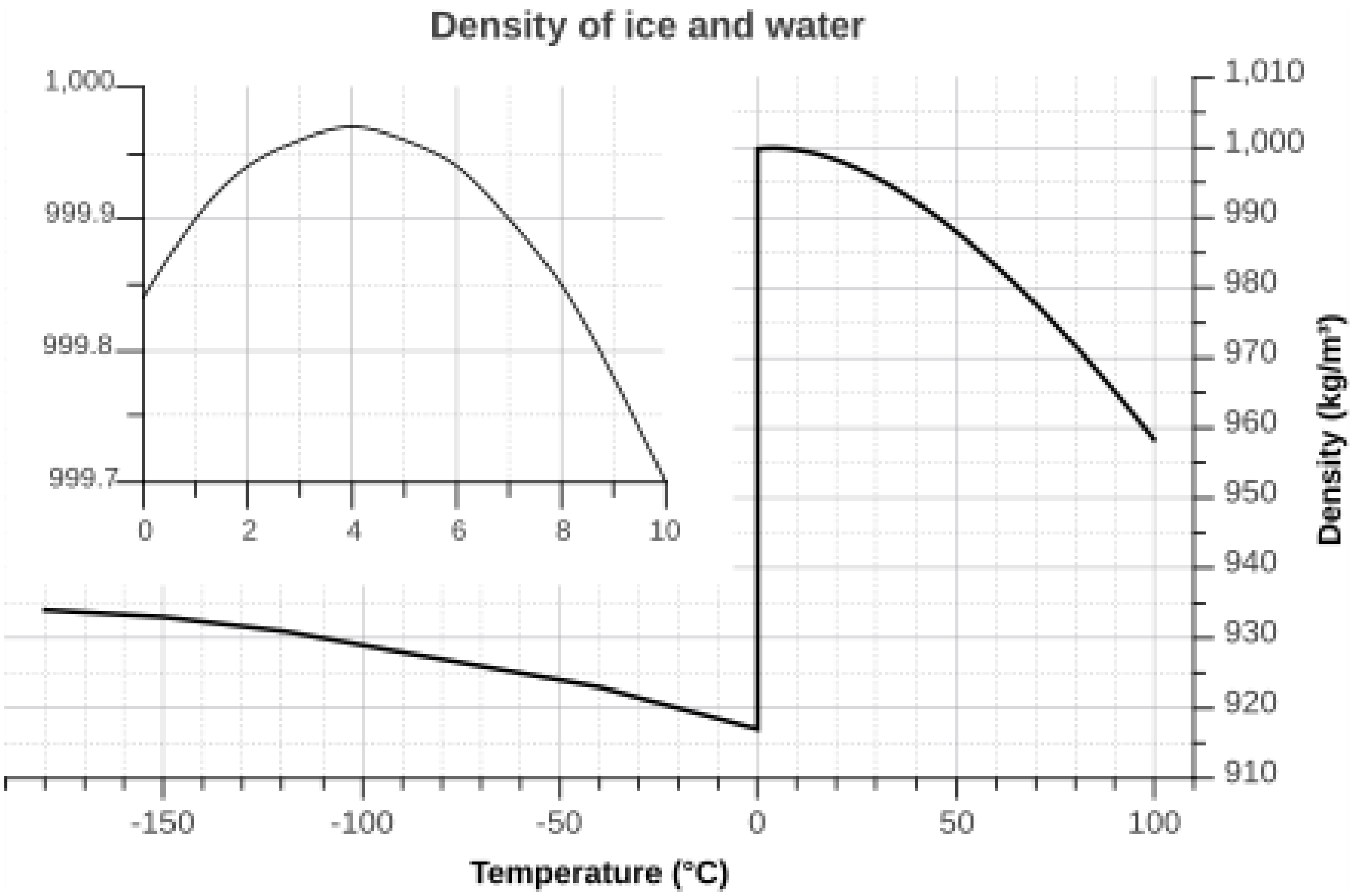
What happens here?



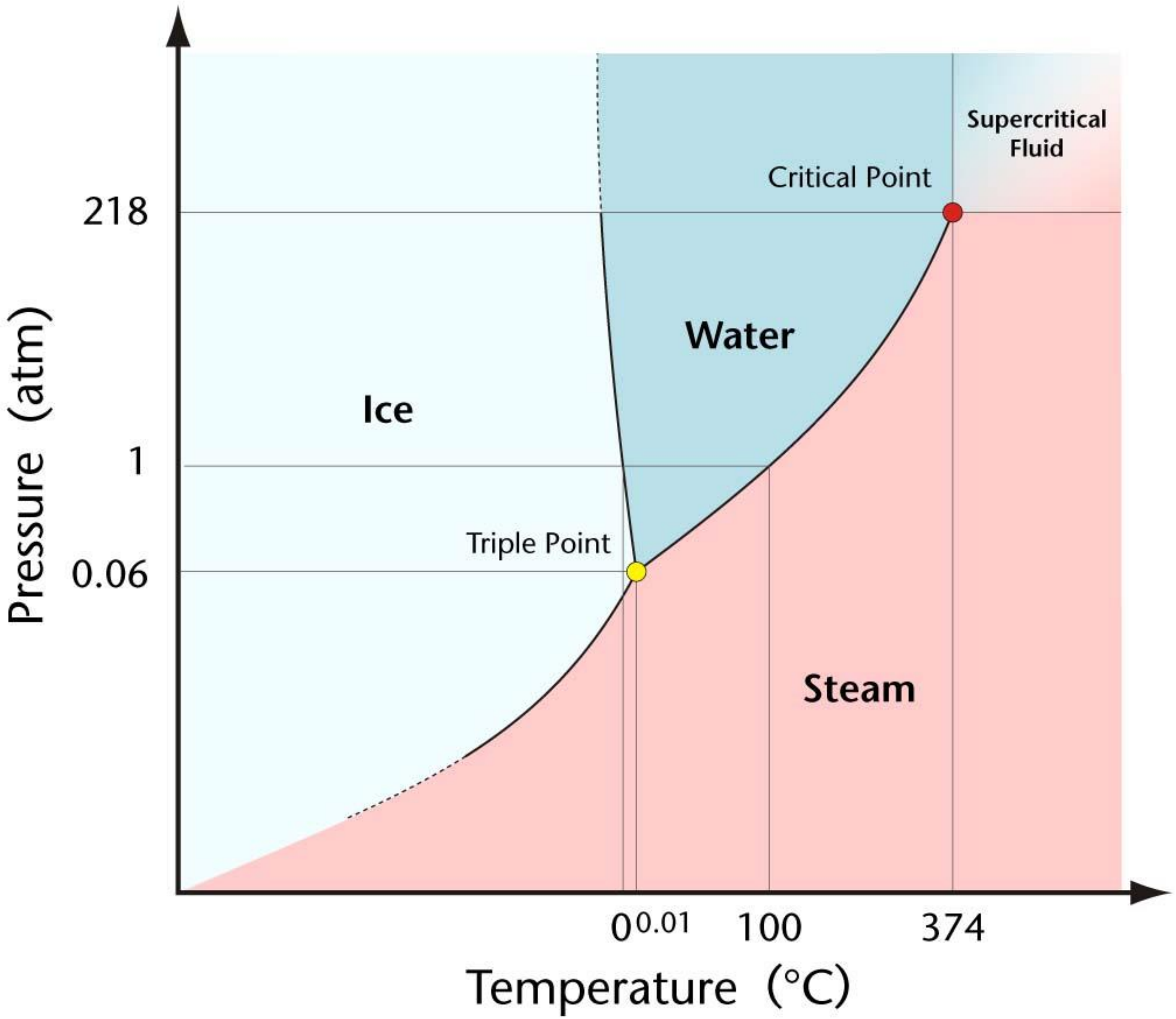
What happens here?

Note: This plot is for SATURATED Water – Discussed soon

Water and Ice



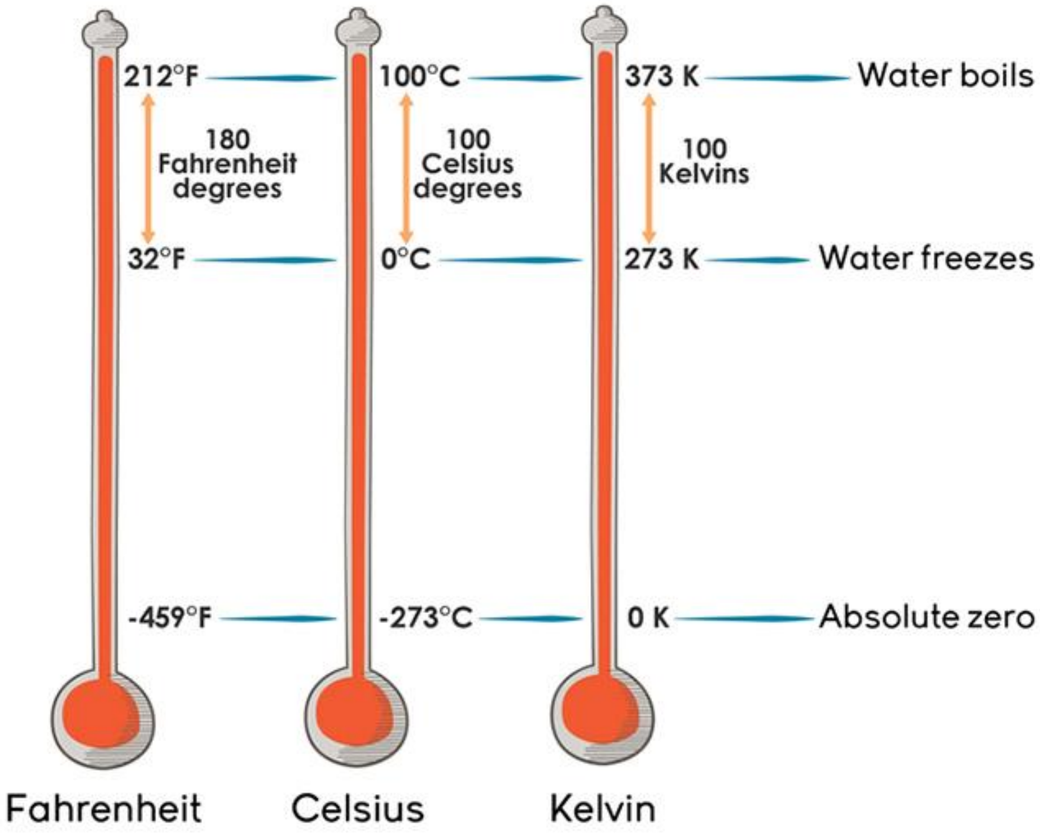
Water Phase Diagram



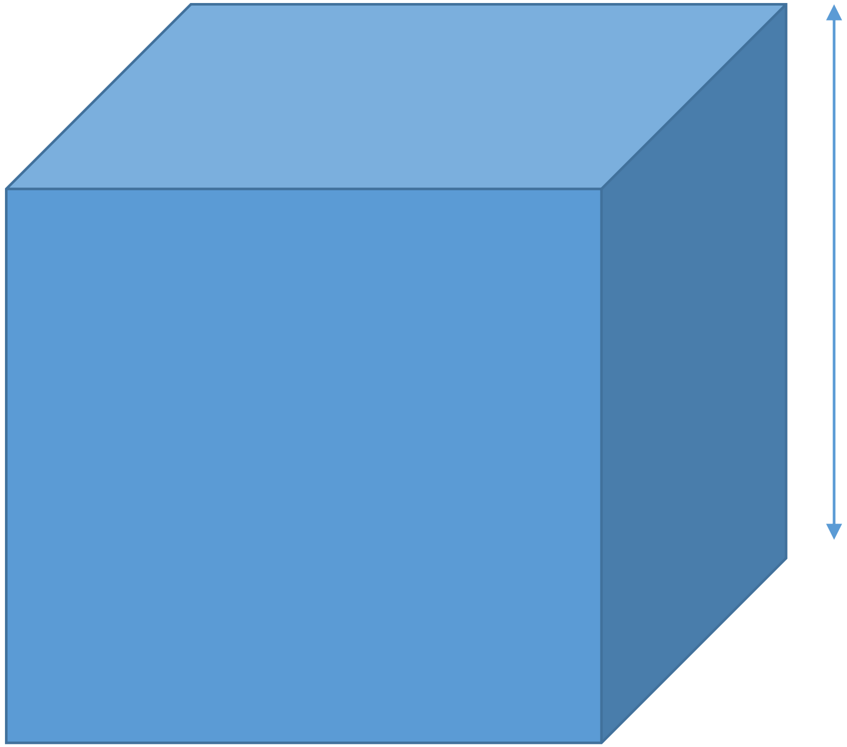
Temperature and Pressure scales

- Fahrenheit: 32F water freezes 212 water boils (at atmospheric pressure)
- Celsius: 0C water freezes and 100C water boils (again at atmospheric pressure)
- Kelvin: 273.15 water freezes and 373.15 water boils (0K is absolute zero – All motion would stop even electrons around a nucleus)
- psi (pounds per square in) one can reference absolute pressure or “gage” pressure (psia or psig)
- 14.7psia is one Atmosphere
- 0 Atmosphere is absolute vacuum, and 0psia and -14.7psig
- Standard Temperature and Pressure (STP) is 20C (68F) and 1 atm

Temperature Scales



Gases– Air



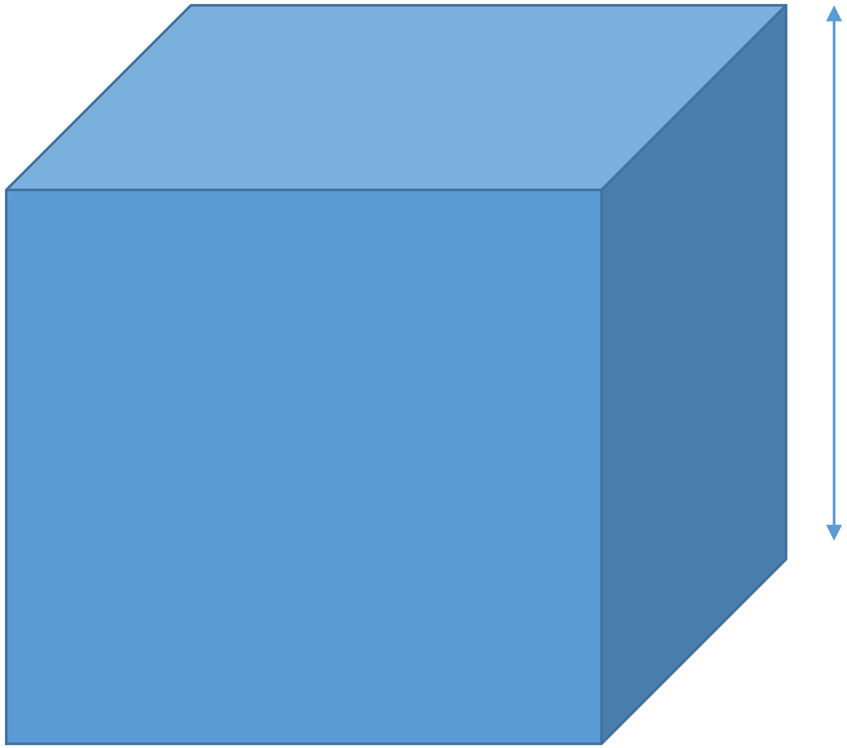
100cm =1m

Air density is 1.2kg/m^3 => **NO Kidding!**

Total weight 1200g or 1.2kg (2.6lbs)

Cube of air – volume 1cu meter

Gases– Nitrogen (at room temperature)



100cm =1m

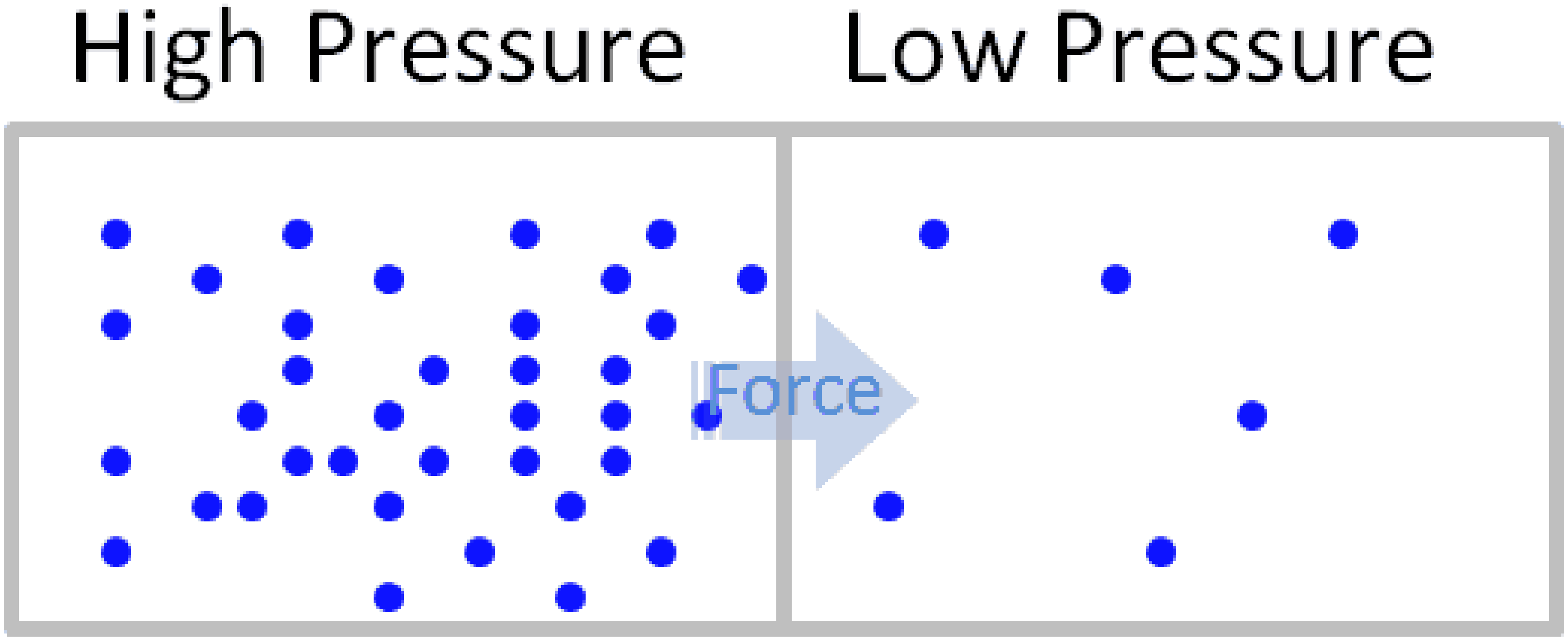
Cube of N2 – volume 1cu meter

N2 density is 1.12 kg/m^3

Total weight 1120g or 1.12kg
(2.4lbs)

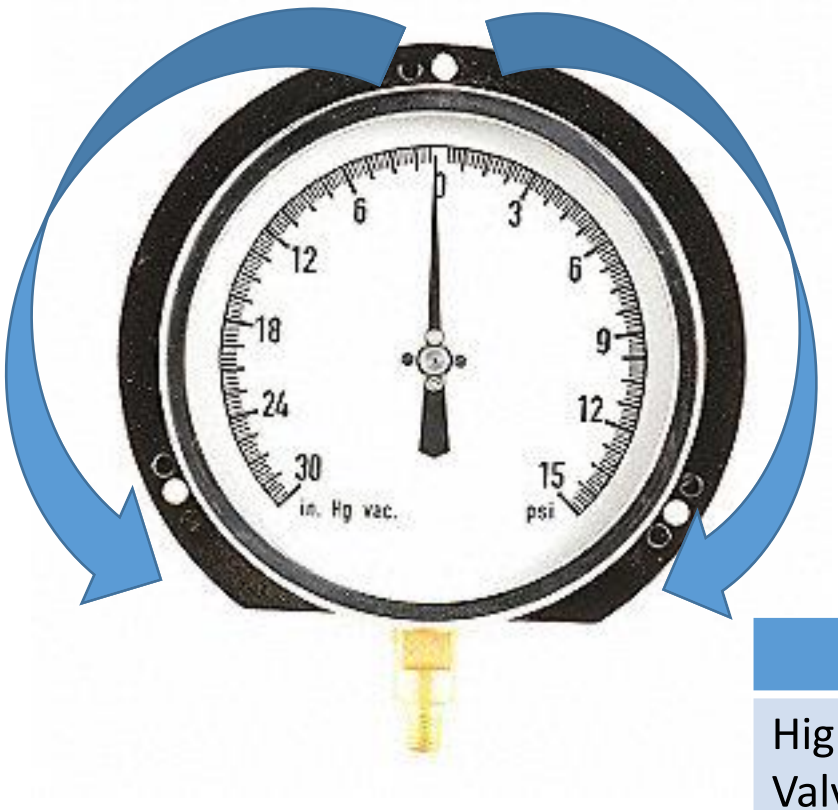
Should make sense as Air is mostly N2 gas (N_2 is 28 and O_2 is 32)

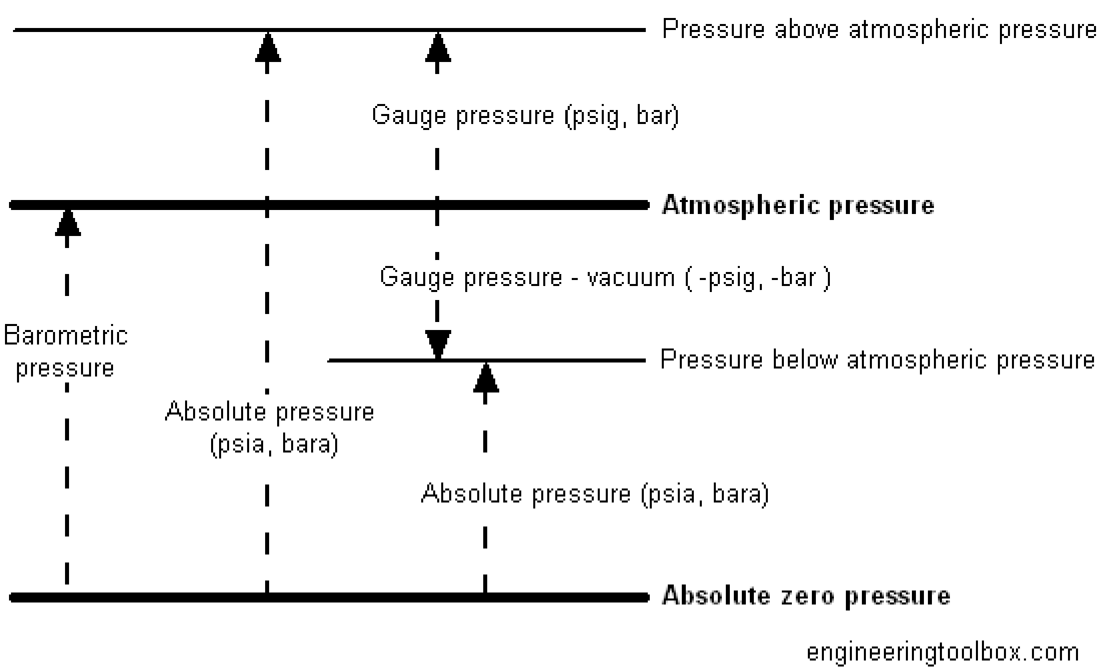
What is/causes pressure



More molecules = more pressure

Pressure Scales

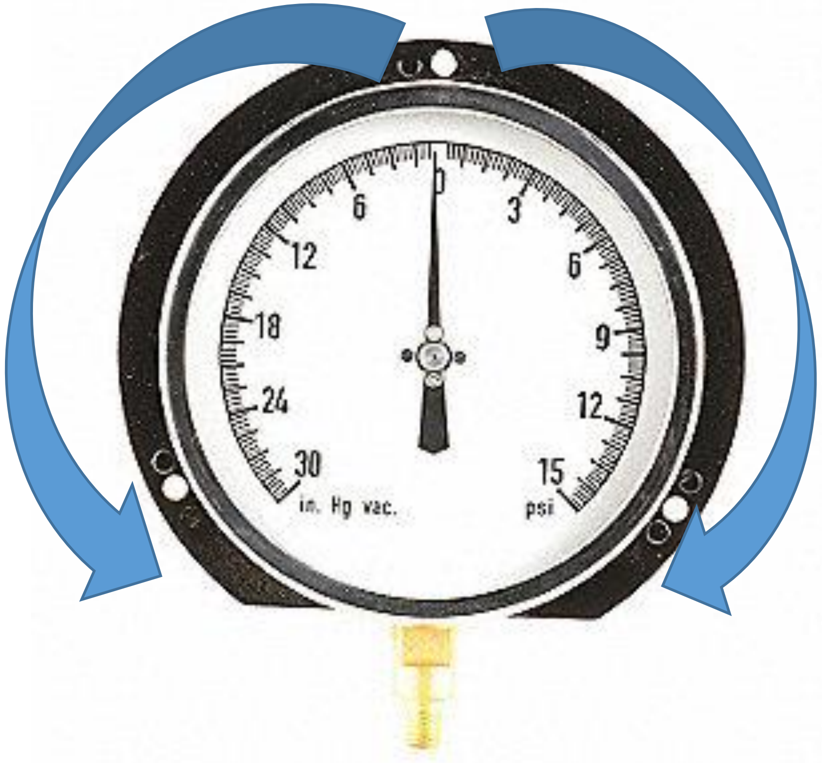




	Atm	PSIG	PSIA
High Pressure Relief Valve on Torus	5.4	65	79.7
Typical Refrigerator 4K supply pressure	3	29.4	44.1
Air Pressure at Earths surface	1	0	14.7
Absolute Vacuum	0	-14.7	0

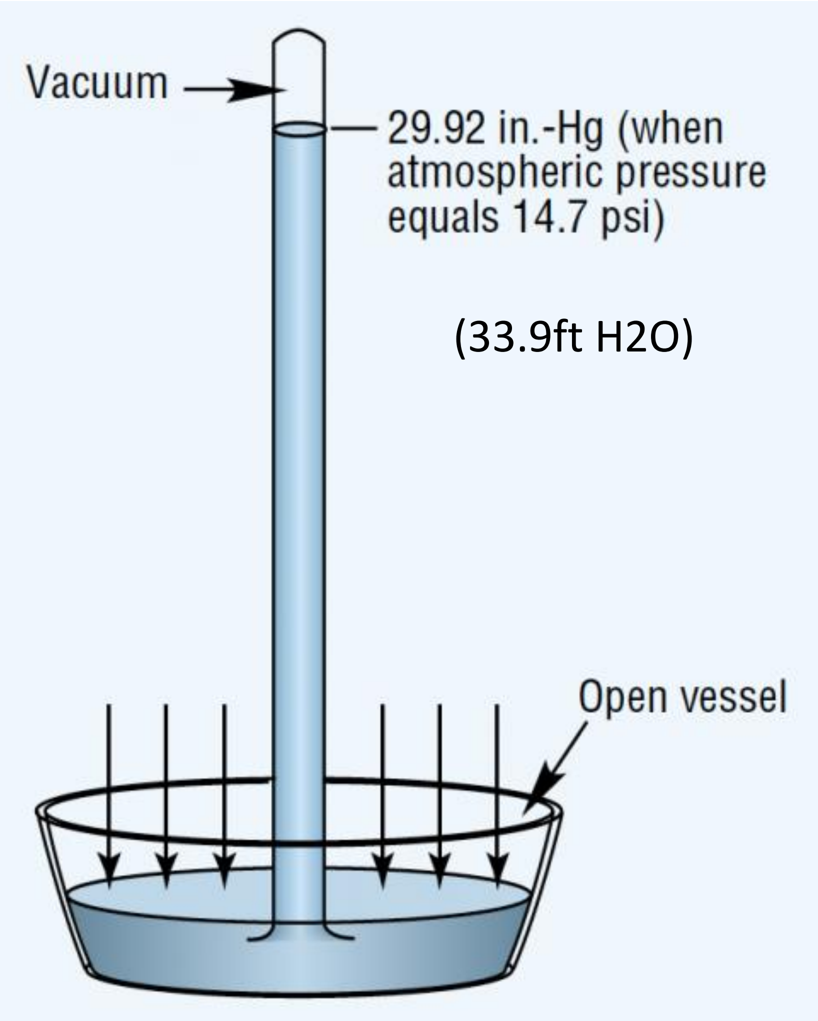
In gage above notice that the distance from 0 to 30in Hg is about the same as from 0 to 15psi

Compound Gages



NOTE: There is a g missing at the end of psi!

Pressure Scales



Pressure Unit Conversion Table

Nominal unit	Mpa	kPa	Pa	Psi	0℃mmHg	0℃inHg	15℃mmH_2O	15℃inH_2O	kgf/cm^2	atm	bar	mbar	Torr
Mpa	1	1000	1000000	145. 03725	7500. 61682	295. 28744	102047. 865	4018. 75154	10. 19718	9. 86923	10	10000	7500. 61682
kPa	0. 001	1	1000	0. 14503	7. 50061	0. 29528	102. 04786	4. 01875	0. 01019	0. 00986	0. 01	10	7. 50061
Pa	0. 000001	0. 001	1	0. 00014	0. 0075	0. 00029	0. 10204	0. 00401	0. 00001	0. 0000098	0. 00001	0. 01	0. 0075
Psi	0. 00689	6. 89478	6894. 78017	1	51. 7151	2. 03594	703. 5976	27. 7084	0. 0703	0. 06804	0. 06894	68. 9478	51. 7151
0℃mmHg	0. 00013	0. 13332	133. 32236	0. 01933	1	0. 03936	13. 60526	0. 53578	0. 00135	0. 00131	0. 00133	1. 33322	1
0℃inHg	0. 00338	3. 38653	3386. 53074	0. 49117	25. 40106	1	345. 58823	13. 60962	0. 03453	0. 03342	0. 03386	33. 8653	25. 40106
15℃mmH_2O	0. 0000098	0. 00979	9. 79932	0. 00142	0. 0735	0. 00289	1	0. 03938	0. 00009	0. 00009	0. 00009	0. 09799	0. 0735
15℃inH_2O	0. 00024	0. 24883	248. 83349	0. 03609	1. 8664	0. 07347	25. 39292	1	0. 00253	0. 00245	0. 00248	2. 48833	1. 8664
kgf/cm^2	0. 09806	98. 06625	98066. 2582	14. 22326	735. 55742	28. 95773	10007. 4523	394. 10392	1	0. 96783	0. 98066	980. 66258	735. 55742
atm	0. 10132	101. 325	101325	14. 6959	760	29. 92	10340	407. 2	1. 03323	1	1. 01325	1013. 25	760
bar	0. 1	100	100000	14. 50372	750. 06168	29. 52874	10204. 7865	401. 87515	1. 01971	0. 98692	1	1000	750. 06168
mbar	0. 0001	0. 1	100	0. 0145	0. 75006	0. 02952	10. 20478	0. 40187	0. 00101	0. 00098	0. 001	1	0. 75006
Torr	0. 00013	0. 13332	133. 32236	0. 01933	1	0. 03936	13. 60526	0. 53578	0. 00135	0. 00131	0. 00133	1. 33322	1

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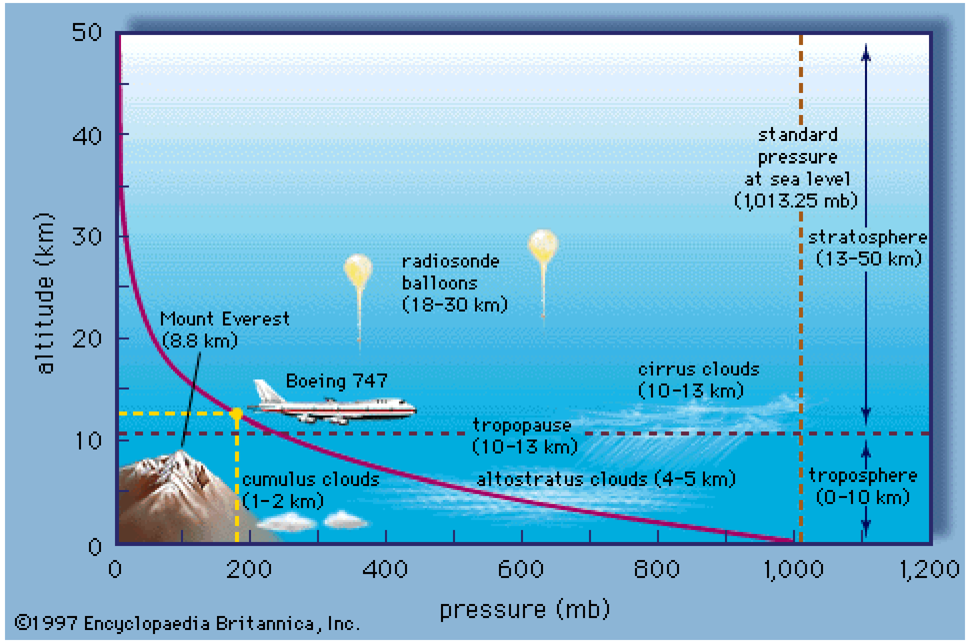
Double check on manometer and Air Density

Fluid		Air	Water	Hg
Density	kg/cuM	1.2	1000	13600
	kg/liter	0.0012	1	13.6
	g/cc	0.0012	1	13.6
	lb/in^3	4.32621E-05	0.036052	0.490304
Pressure of the atmosphere	psi	14.7	14.7	14.7
Height of column	in	339789	408	29.97
	ft	28316	34.0	2.5
	mile	5.4	0.0	0.0

Coin floating in a jar of Mercury (Hg)


50
40
30
20
10
0
altitude (km)
0
200
400
600
800
1,000
1,200
pressure (mb)
standard pressure at sea level (1,013.25 mb)
stratosphere (13-50 km)
troposphere (0-10 km)
radiosonde balloons (18-30 km)
Mount Everest (8.8 km)
Boeing 747
cirrus clouds (10-13 km)
tropopause (10-13 km)
cumulus clouds (1-2 km)
altostratus clouds (4-5 km)
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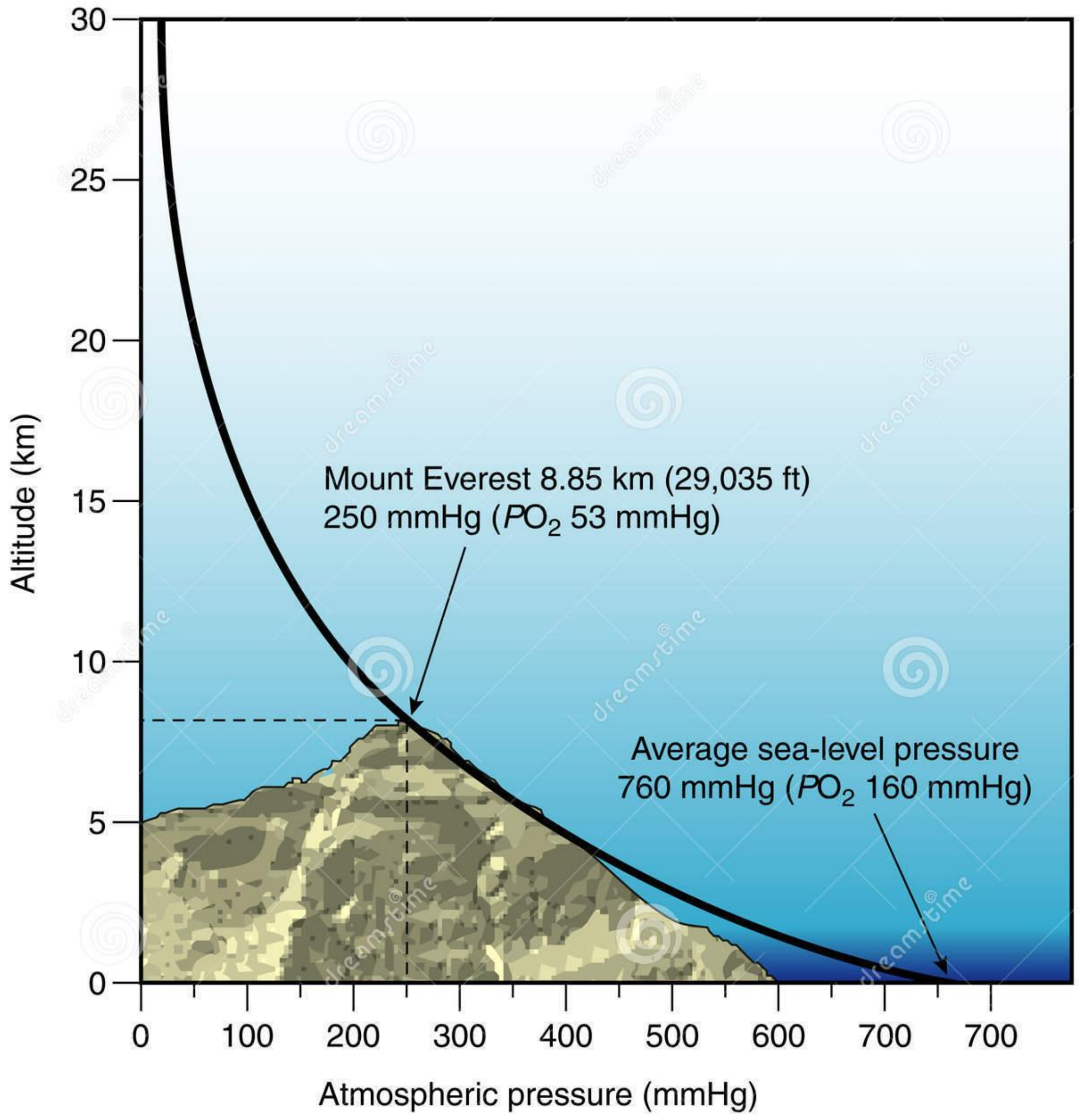

30
25
20
15
10
5
0
Altitude (km)
0
100
200
300
400
500
600
700
700
Atmospheric pressure (mmHg)
Mount Everest 8.85 km (29,035 ft)
250 mmHg (PO_2 53 mmHg)
Average sea-level pressure
760 mmHg (PO_2 160 mmHg)

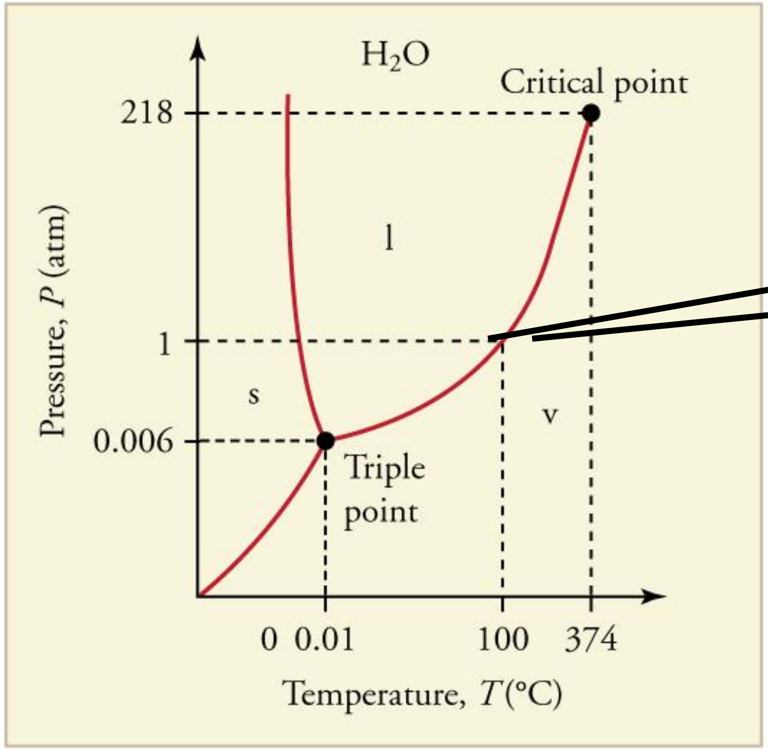
Hurricane Wilma

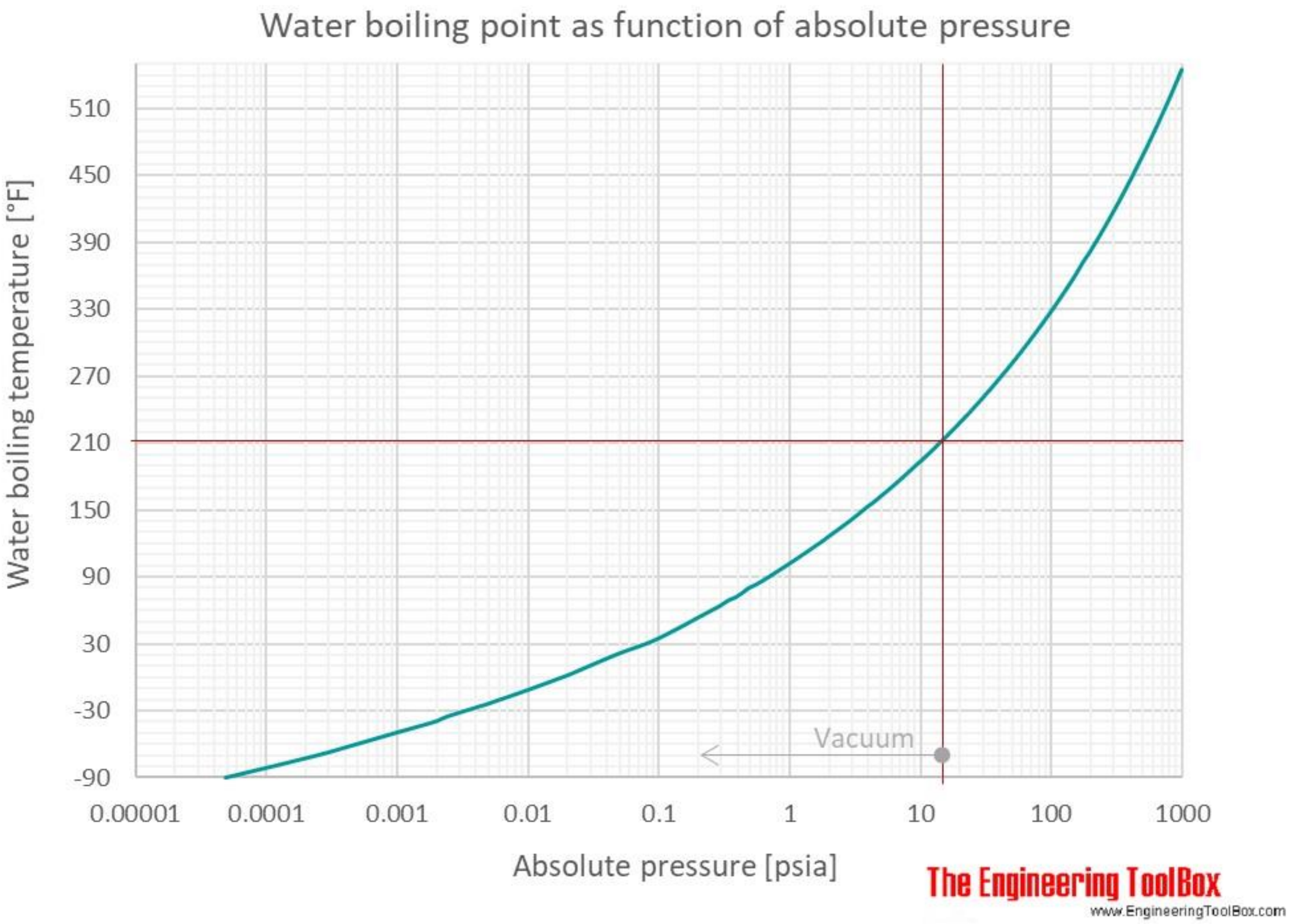
- Lowest pressure of a hurricane ever = 882mbar

Fluid		Water
Density	kg/cuM	1000
	kg/liter	1
	g/cc	1
	lb/in^3	0.036051757
Atmospheric pressure	mbar	1013.25
Hurricane Wilma	mbar	882
Differential pressure Wilma	mbar	131.25
	psi	1.90
Height of column	in	53
	ft	4.4

Definition – Saturated condition

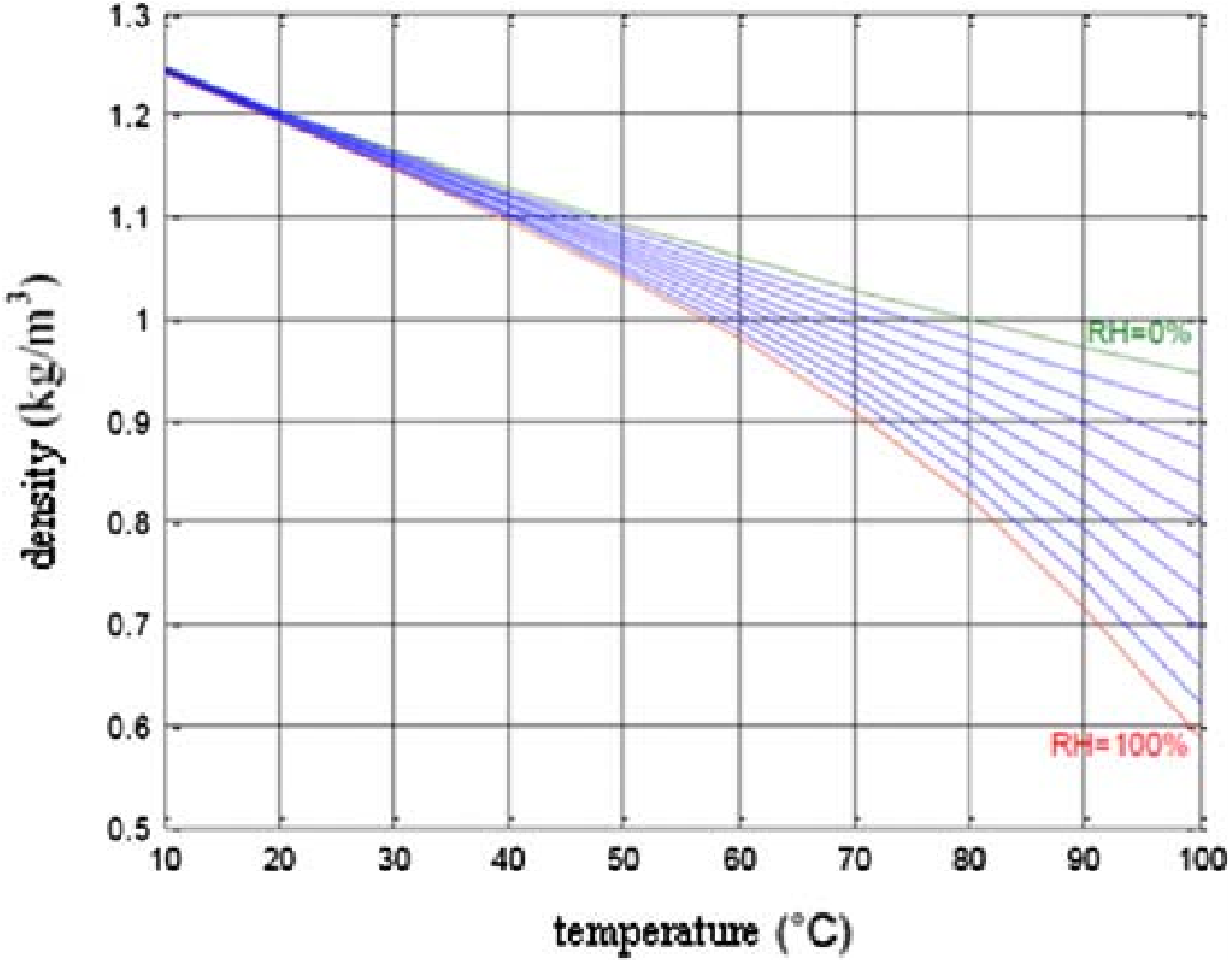
SATURATED LIQUID: about to vaporize
e.g., water at 100ºC and 1 atmosphere
SATURATED VAPOR: about to condense
e.g., water vapor (steam) at 100ºC and 1 atm.





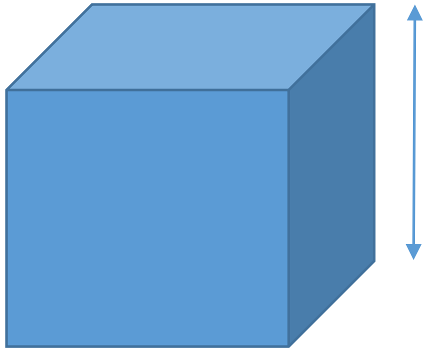
Water boiling point as function of absolute pressure
Water boiling temperature [°F]
510
450
390
330
270
210
150
90
30
-30
-90
Vacuum
0.00001
0.0001
0.001
0.01
0.1
1
10
100
1000
Absolute pressure [psia]
The Engineering ToolBox
www.EngineeringToolBox.com

Effect of humidity on Air density



Liquids – Liquid Nitrogen (at 1.0atm)

Nitrogen boils at 77.4K at 1 atm –
(saturation condition)

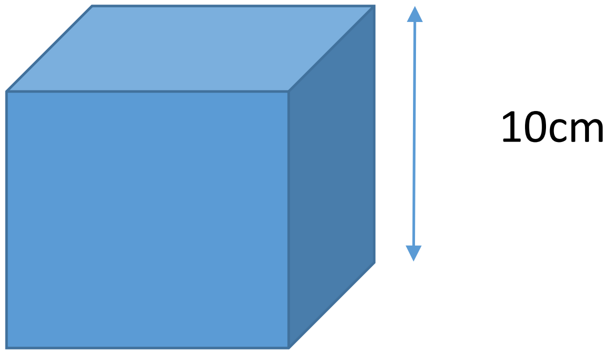


LN2 density is 0.81 g/cc at 77.4K and 1.0 ATM

Total weight 0.81kg or 1.8lbs

Cube of nitrogen liquid –
volume 1 liter

Liquids – Liquid Helium (at 1.2Atm)

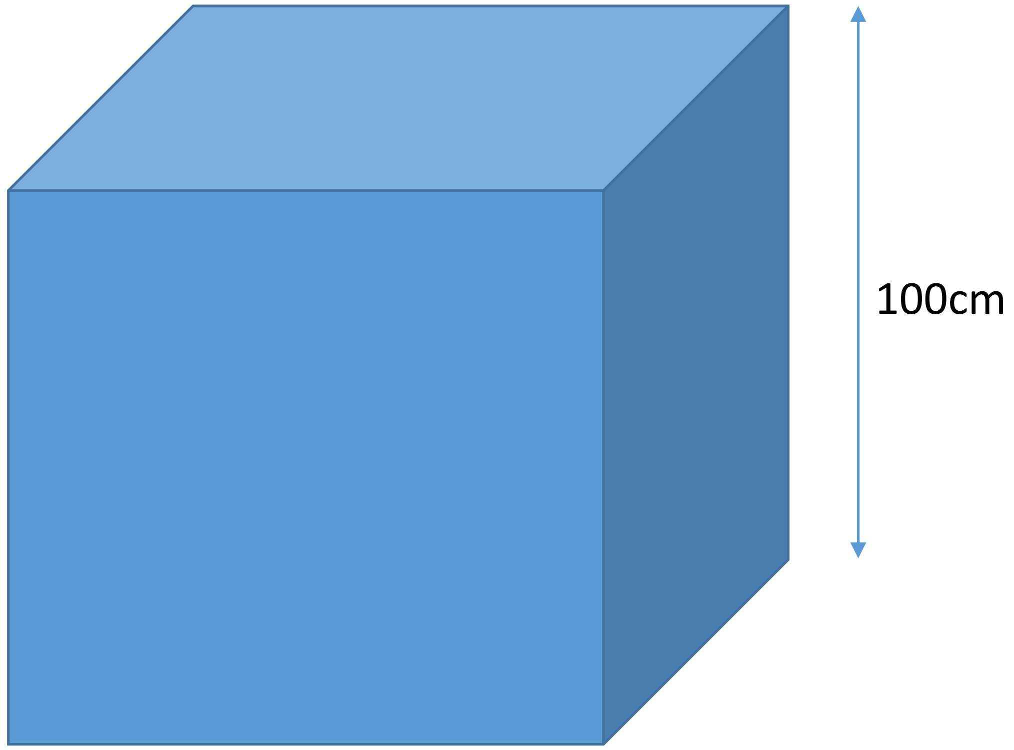


Cube of helium liquid – volume 1 liter

Helium liquid density is .121 g/cc at 4.42K and 1.2 ATM

Total weight 121g or 0.27lbs

Gases– Helium (at STP)



Helium gas density is .166 kg/m^3 293K and 1 ATM

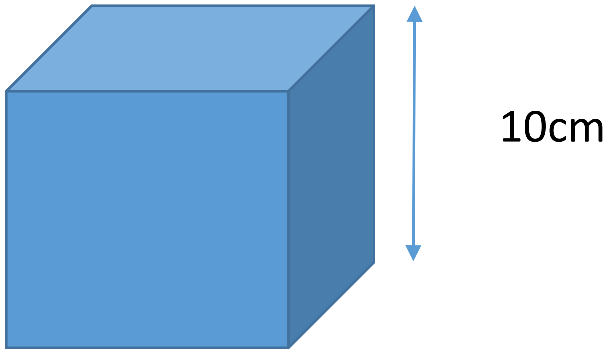
Total weight 166 g or .37lbs

Cube of helium gas – volume 1m^3

Look at Helium vs Air

- Helium is an atom with Molecular weight of 4 (2 Protons and 2 Neutrons)
- Air is a mix of N_2 and O_2 (Molecular weight 28 and 32 ratio is ~4 to 1)
- So the MW of air is about 29
- 29/4 = 7.3
- 1.2/.166 = 7.3

Gases– Cold Helium (at 1.2Atm 4.42K)



Helium gas density is .021 g/cc at 4.42K and 1.2 ATM

Total weight 21g or .035lbs

Cube of cold helium gas –
volume 1 liter

Review

- Mass of:
  - Liter of water 1000g
  - Liter of motor oil 900g
  - Liter of LN2 810g
  - Liter of liquid helium 121g (1.2atm 4.4K)
  - Liter of gas helium 21g (1.2atm and 4.4K)
  - Cubic meter of air 1200g (STP)
  - Cubic meter of helium 166g (STP)

- Density ratios at saturation condition
  - Water vs steam at 1 atm/373K
    - 958g/l ÷ .59 g/l = 1623
  - Liquid nitrogen density /cold gas nitrogen density (@1.0atm & 78K)
    - 810g/l ÷ 4.6 g/l = 176
  - Liquid helium density /cold gas helium density (@1.2 atm & 4.4K)
    - 121g/l ÷ 21 g/l = 5.8

Why is helium used here?

- Superconductivity occurs in some metals below 9K
  - Niobium: used for cavities in cryomodules
  - Niobium / Titanium used in conductors for some SC magnets
  - https://en.wikipedia.org/wiki/List_of_superconductors
- Helium is the only substance that remains liquid below ~14K
  - Nitrogen solidifies at ~ 64K
  - Neon solidifies at ~25K
  - Hydrogen solidifies at ~14K
  - Helium can be solidified but it takes very high pressure and low temperature

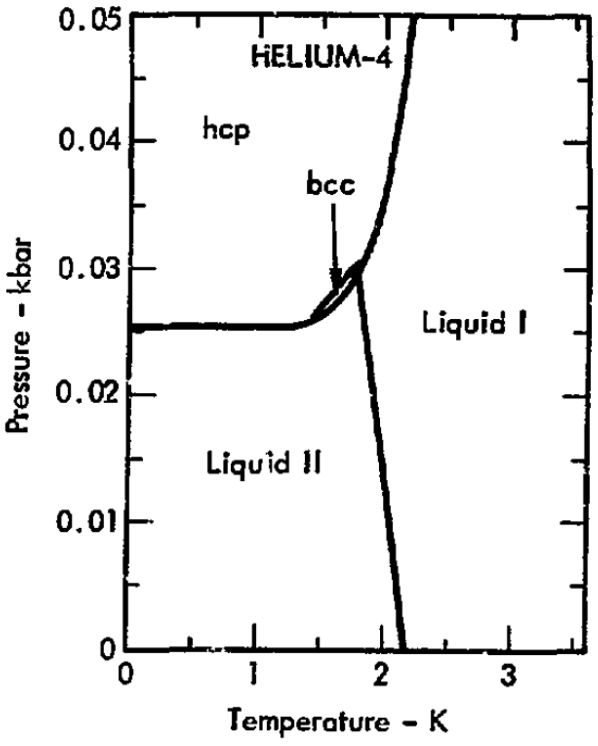
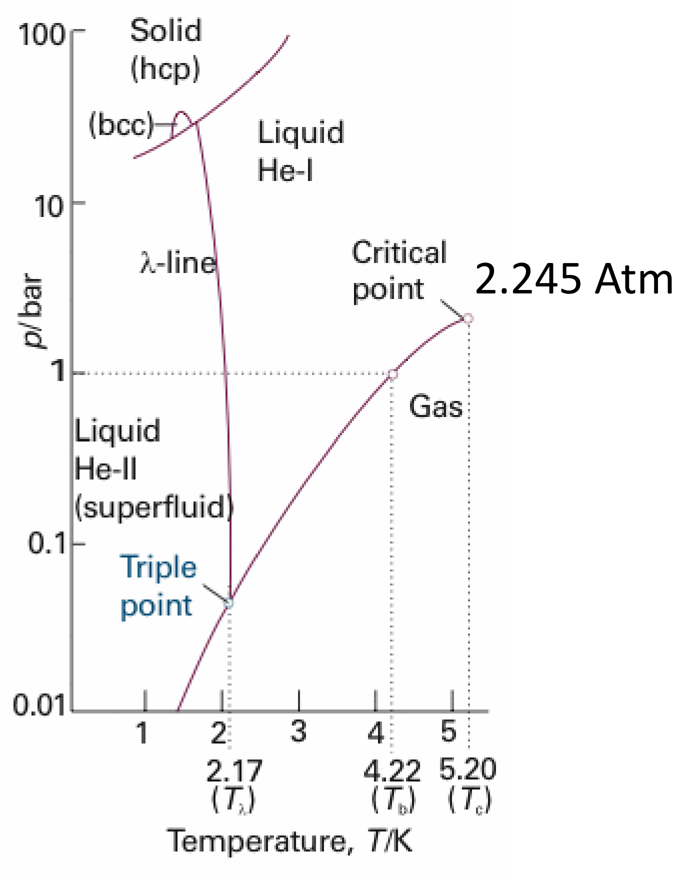


Fig. 6. The phase diagram of helium - 4.

More on Helium properties

Helium Phase Diagram



- Helium is the element that liquefies at the lowest temperature

Basic Properties of Helium needed for Cryogenic Engineering

- Density (discussed in detail earlier)
- Enthalpy (Amount of energy per unit mass, *a function its "internal energy" and its temperature and pressure*)
- Heat Capacity (Amount of energy it takes to change its temperature)
- Thermal Conductivity (ability to transfer heat)
- Viscosity (how difficult it is to make it flow)

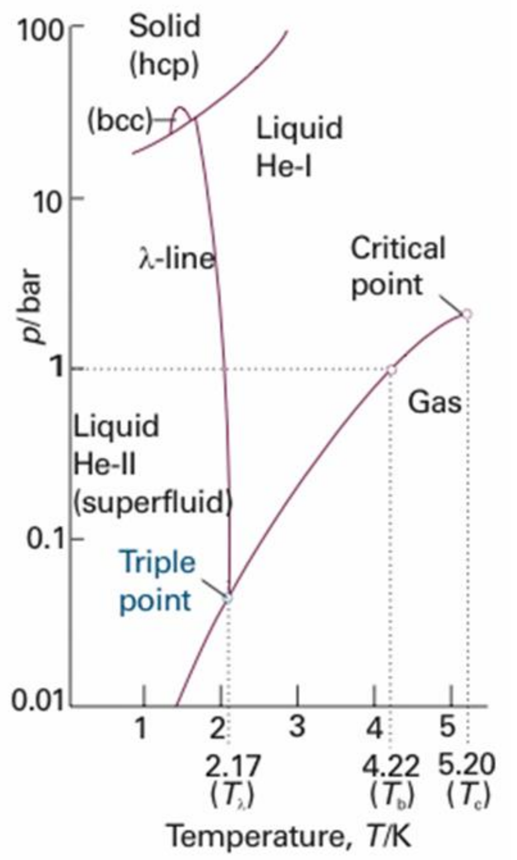
Lets focus on Enthalpy for now because with that understanding we can discuss liquid and gas phases of helium in our normal range of use

Helium and Enthalpy

- Most magnets run with Liquid helium in them at 1.2 to 1.4atm
- The space above the liquid is normally cold gas at the same pressure and temperature
- This means the liquid/gas are in the “saturated” condition-
  - Cool it a little colder or raise the pressure and the gas becomes liquid
  - Add a little heat to the liquid and it boils and makes gas, or pump on it and it boils…
- Enthalpy units are J/g (Joules/gram)
- Enthalpy of liquid helium at 1.2atm is 10.8J/g and of gas helium at 1.2atm it is 29.94 J/g (T=4.424K) Difference is 29.94-10.8 = 19.15 J/g
- Enthalpy of liquid helium at 1.4atm is 11.91J/g and of gas helium at 1.4atm it is 29.57 J/g (T=4.602K) Difference is 17.67 J/g

Helium and Enthalpy continued

- Super-Critical Helium
  - The pressure is above 2.245atm
  - Temperature is above 5.2K
  - Our refrigerators usually run with outlet pressures of ~3.0atm
  - Typically after the refrigerator gets the gas down to 3.0atm the gas flows through a final cooling heat exchanger in a bath of saturated liquid helium so it is cooled down to near 4.5K
  - Enthalpy of gas at 3.0atm and 4.5K is 11.41J/g
  - Enthalpy of supercritical helium at 3 atm and 5.9K is 30.3J/g and at 3 atm and 5.0K it is 14.2J/g



The physical meaning of a supercritical fluid is that as long as a fluid is in the supercritical region, it will not undergo a phase transition between liquid and gas and no meniscus separating liquid and gas will be observed. Technically speaking, a substance in its supercritical state is neither a liquid nor a gas, but rather a fluid.
The technological advantage of a supercritical fluid is that it cannot turn into a two-phase mixture of liquid and gas. This eliminates the possibility of increased pressure drops, flow instabilities or possible vibrations associated with two-phase systems. As a result, many cryogenic systems are designed to operate with supercritical fluids.
* https://www.cryogenicsociety.org/resources/defining_cryogenics/supercritical_fluids/

JT process (Joule Thompson)

- To run most gases through a valve (or orifice) with out adding heat, and have its pressure drop
  - Causes the gas to cool
  - If the conditions are right the JT effect will allow some of the gas to turn to liquid and the rest to gas (or it could all turn to liquid – {not common})
- Typically vales are considered constant enthalpy devices (assuming no heat load)
- Thus the enthalpy in must equal the enthalpy out

Example

- 10g/s of 3 atm 4.5K helium enters a JT valve and exhausts into a dewar that is at 1.2 atm

$Hi = H_0$

$Hi = 10g/s *$ 11.41J/g = 114.1 J/s

$Ho =$ ml *hl +mg*hg

Mt= 10 g/s = ml + mg

Solving these equations gives:

Mg=0.32g/s and ml=9.68g/s, **thus most of the supercritical gas turns to liquid**

Next lessons –

- Where do we get cryogens for the Halls
- ESR and Hall B systems and PID control
- Effect of Heat load and more