Lecture 2 of 4 (27:$_1$)

Heat exchangers (1)

Example of a "perfect" (full contact, not full jacket) heat exchanger
in which all 3 phases of matter interact (no intermediate surfaces):

solid fresh water ➔ sea water (water with around 35 kg/tonne of salt,
which acts as a freezing point depressant);

solid fresh water ➔ air;
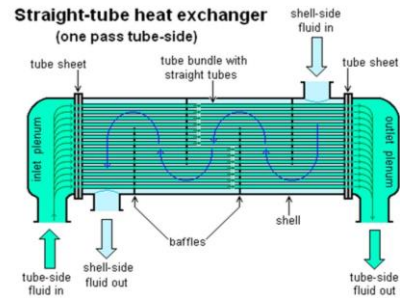*peripheral fresh meltwater ➔ sea water and air ;*

(Picture credit: 𝕿𝖍𝖊𝕽𝖎𝖉𝖊𝖗𝕻𝖔𝖘𝖙.𝖈𝖔𝖒:
https://www.theriderpost.com/lifestyle/environnement/iceberg-titanic-sechoue-cote-canada/)
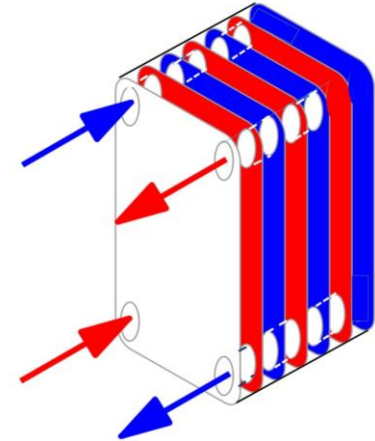*Beautiful but something perhaps you would rather wish you were not witnessing*
on a Sunday afternoon bike ride along the coast.

Heat exchangers (2)

Hot liquid ➜ cold liquid
(can also be used in evaporators and condensers)

Straight-tube heat exchanger
(one pass tube-side)

tube sheet
tube bundle with straight tubes
shell-side fluid in
tube sheet
inlet plenum
outlet plenum
tube-side fluid in
shell-side fluid out
baffles
shell
shell-side fluid out
tube-side fluid out

Parallel Plate Heat Exchanger

Hot liquid ➜ Cold gas (air)
the humble automobile radiator

Heat exchangers (3): and in your refrigerator…

Gas (air in closed volume to be cooled)
to
(liquid ➜ vapor)
(refrigerator evaporator)

Evaporator

Gas (room air to be cooled)
to
(liquid ➜ vapor)
(A/C evaporator)

-22°

Hot (Vapor ➜ liquid)
to
cooler gas (room air)
(refrigerator condenser)

Condenser

Hot (Vapor ➜ liquid)
to
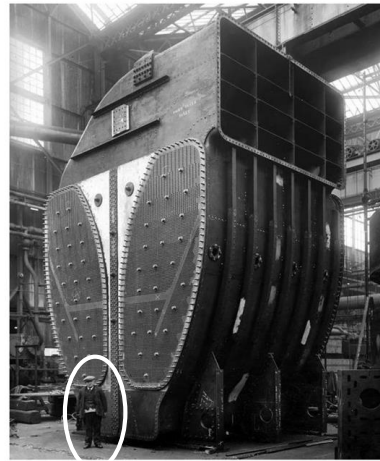*cooler gas (outside air)*
(A/C condenser)

Heat exchangers (4): …
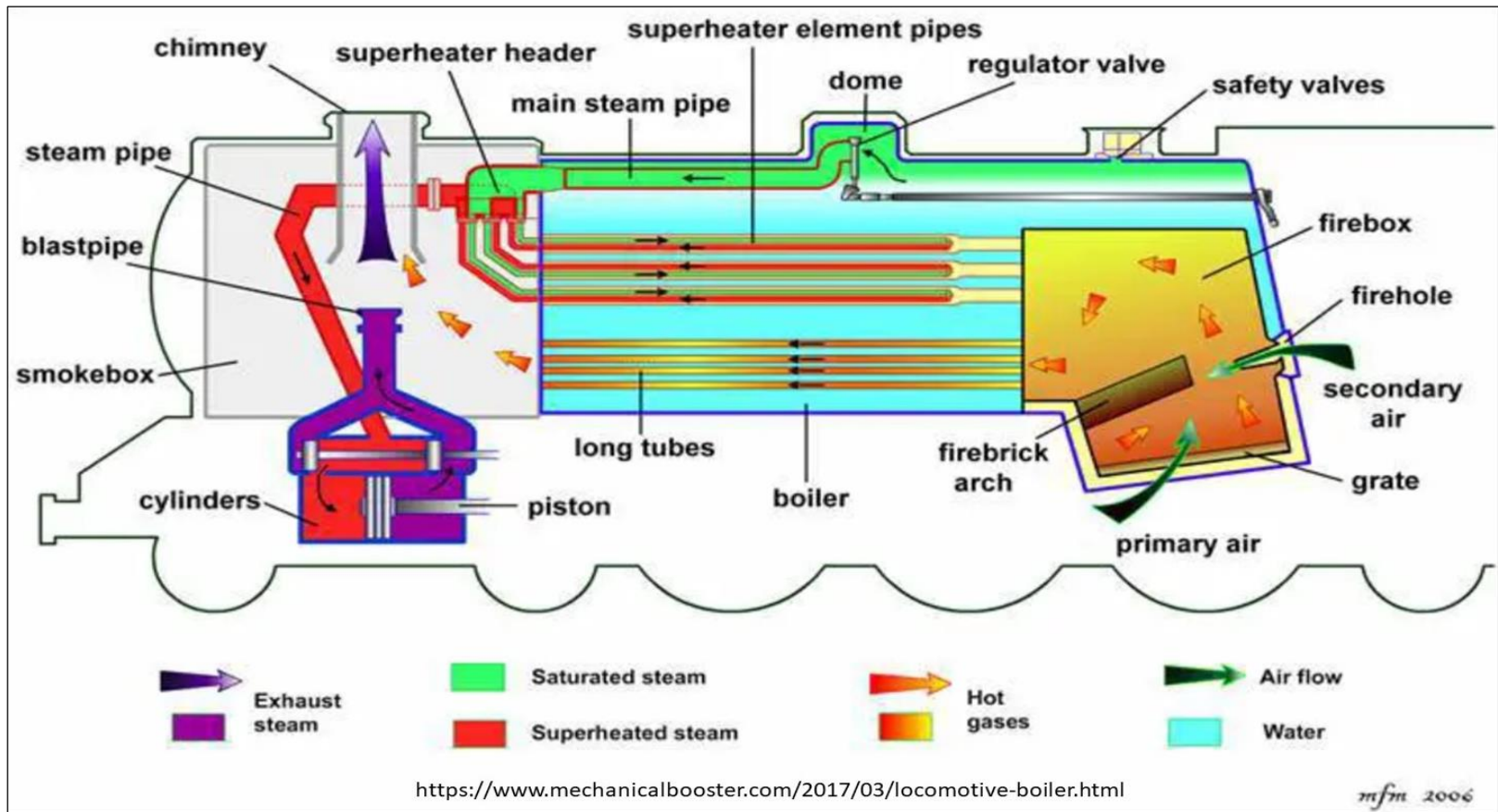
Another form of evaporative heat exchanger: the steam locomotive:
Boils water, then adds another thermodynamic step: superheating steam to reduce its saturation content and lessen the risk of compressive condensation in the cylinders

Heat exchangers (5): can be huge - like this condenser...

Hot (Steam ➡ liquid)
to
cooler liquid (sea water)
(Oil-fired boilers ➡
steam turbines ➡
condensers
(closed feedwater circuit))

Seawater coolant enters
& leaves condensers
through openings in hull.

RMS Queen Mary (Long Beach, CA)

Ship completed 1936, John Brown shipyard, Clydebank, Glasgow, Scotland
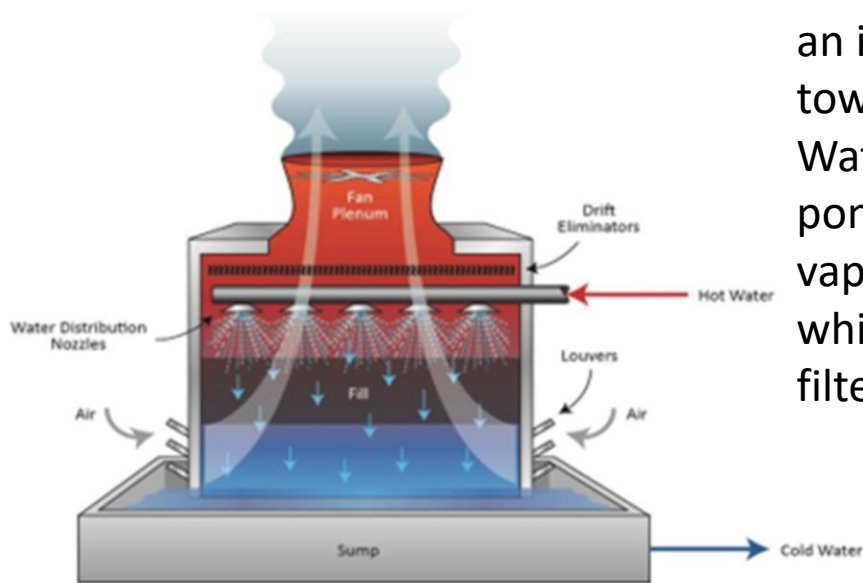*Displacement: 77,400 long tons (78,642 metric tons)*
Length: 1,019.4 ft (310.7 m): Beam: 118 ft (36.0 m), Height: 181 ft (55.2 m)
Draught: 38 ft 9 in (11.8 m), Decks: 12
Installed power: 24 × Yarrow boilers Propulsion: 4 × Parsons geared steam turbines,
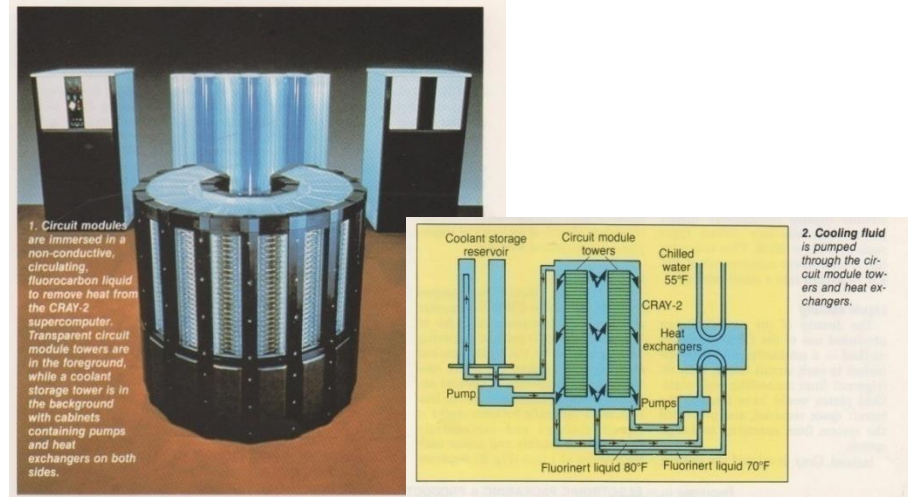*4 shafts, 200,000 shp (150,000 kW) Speed: 28.5 kts (52.8 km/h; 32.8 mph)*

Heat exchangers (6): can be huge - like this cooling tower…

Hot liquid to cooler gas (air):

Water cooling tower, typically used at power stations and big industrial plants & data centers.
Secondary hot water from a heat exchanger cooling an industrial process is pumped to the top of the tower and sprayed into a counter flow of air.
Water is thus cooled and collected in the bottom pond. The circuit is open, some water escapes as vapour and must be replenished,
while that collected in the bottom pond must be filtered on its way back to the heat exchanger


1. Circuit modules are immersed in a non-conductive, circulating, fluorocarbon liquid to remove heat from the CRAY-2 supercomputer. Transparent circuit module towers are in the foreground, while a coolant storage tower is in the background with cabinets containing pumps and heat exchangers on both sides.

2. Cooling fluid is pumped through the circuit module towers and heat exchangers.

Heat exchangers (7): and small too (100 Wattish) – like this overclocking (?) installation…

5.3 Phase Change Cooling

- We saw in the examples of some of the heat exchangers that a phase change can occur in one of the fluids.

- Changing the phase of a fluid requires the right combination of temperature & pressure, and requires a lot of energy transfer to achieve.

- Indeed: phase change is a very good way to achieve cooling with a much smaller flow of coolant than in a monophase system.

- We will now go on to explore the energy uptake capabilities of phase change cooling.

Attention: ye approach Isenthalp
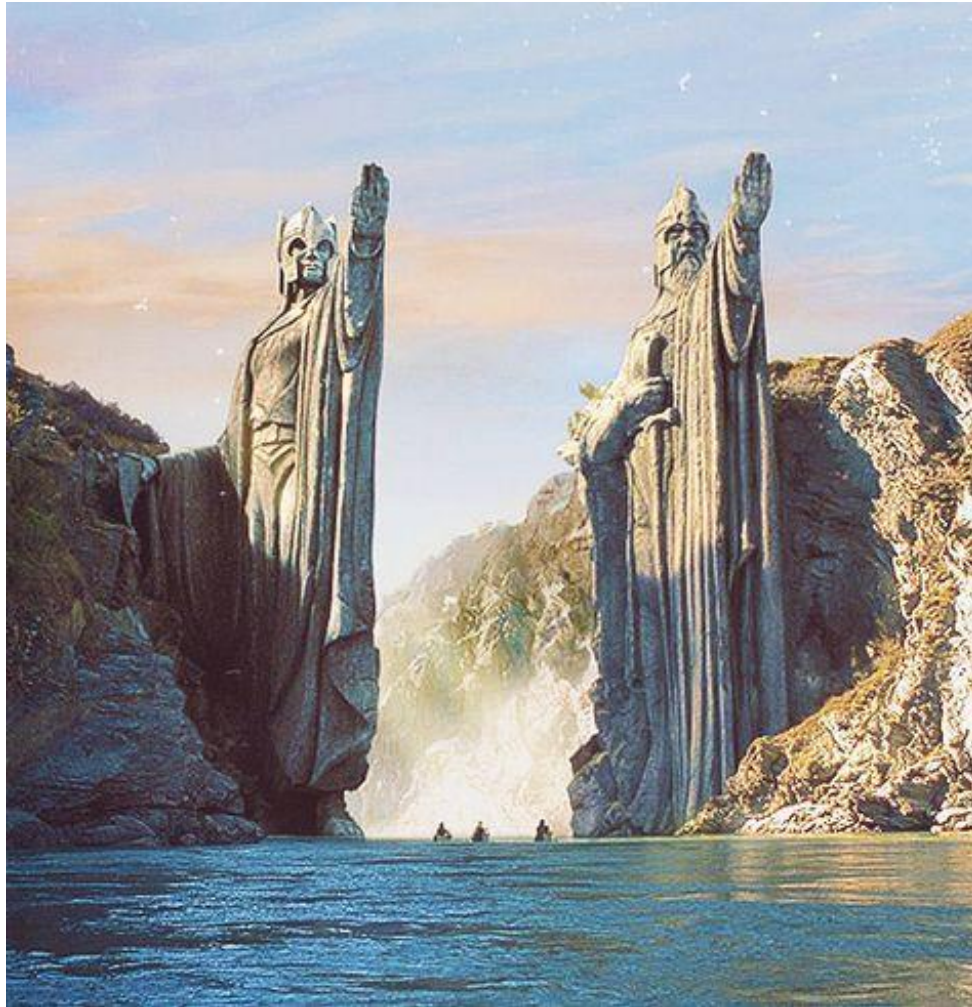
5.3 Phase Change Cooling (2)

A kitchen crisis…

Materials can contain a huge amount of energy, and we are not talking about E = mc² (we wont).

Your kitchen kettle holds 1 litre of water and has a power rating of 2000 Watts.
(You can ignore the loss of heat through the kettle wall to the kitchen for now).

- **You fill it and turn it on noticing that the kitchen temperature is 20 ˚C.**

- **In just under 3 minutes on the kitchen clock (167 seconds later) the water is boiling and bubbling nicely: 1 kg of water has been raised 80 ˚C for a total delivered electrical energy of 334.7 kilojoules**

(It already sounds like a lot: did you need all this energy just to boil water for one cup of mint tea?).

- **The bell rings: somebody's at the front door and you forget to switch off the kettle, which doesn't have an automatic cut out at 100 ˚C. Some time later you smell a nasty smell coming from the kitchen, which is full of steam. The kettle is empty and finally its thermal interlock trips. You look at the kitchen clock and see that almost 19 more minutes have passed!**

Q: How much extra energy was wasted boiling that water into steam at 100 ˚C while you were outside?

A: around 2.25 Mega Joules*! (or about 0.1% of the output of a typical 2GW electrical power station for 1 second). This is around eight times more than you used to raise the liter of water to its boiling temperature for that cup of tea.
*The amount is calculated from the 2250 kJ.kg⁻¹ latent heat (or "enthalpy") of evaporation, of water at atmospheric pressure (1 bar) where the evaporation temperature is 100 ˚C.

5.3 Phase Change Cooling (3)

So what is <u>enthalpy:</u> - in thermodynamic terms?

Well, the key here is in the "*dynamics*" of the word "thermodynamics".

Thermodynamics is the study of <u>*changes*</u> in key parameters of material systems: pressure, temperature and energy being carried, in response to <u>*perturbations*</u> applied to the system caused by the delivery of external heat energy, the extraction of energy from the system and by the application of mechanical work to the system, or indeed making the system perform mechanical work.

Enthalpy (*H*) is usually expressed in terms of the internal energy (*E*) of a system and its temperature *T, volume V,* and pressure *P*. for example:

$$H = E + P.V$$

The internal energy of a system is hard to measure directly. The energy carrying capability of fluids depends on factors including their chemical composition. Surprisingly, water (mol. wt. 18) has a much higher heat capacity (4181 $J.kg^{-1}.K^{-1}$ @25°C) than cooling fluids with higher molecular weights. Its <u>*enthalpy of evaporation*</u> is also much higher.

The *absolute* enthalpy, *H*, of a system can perhaps be thought of as containing a baseline energy on top of which *energetic changes* (*thermodynamic changes*) of interest occur. In terms of a particular material it can be expressed in $kJ.kg^{-1}$.

5.3 Phase Change Cooling (4)
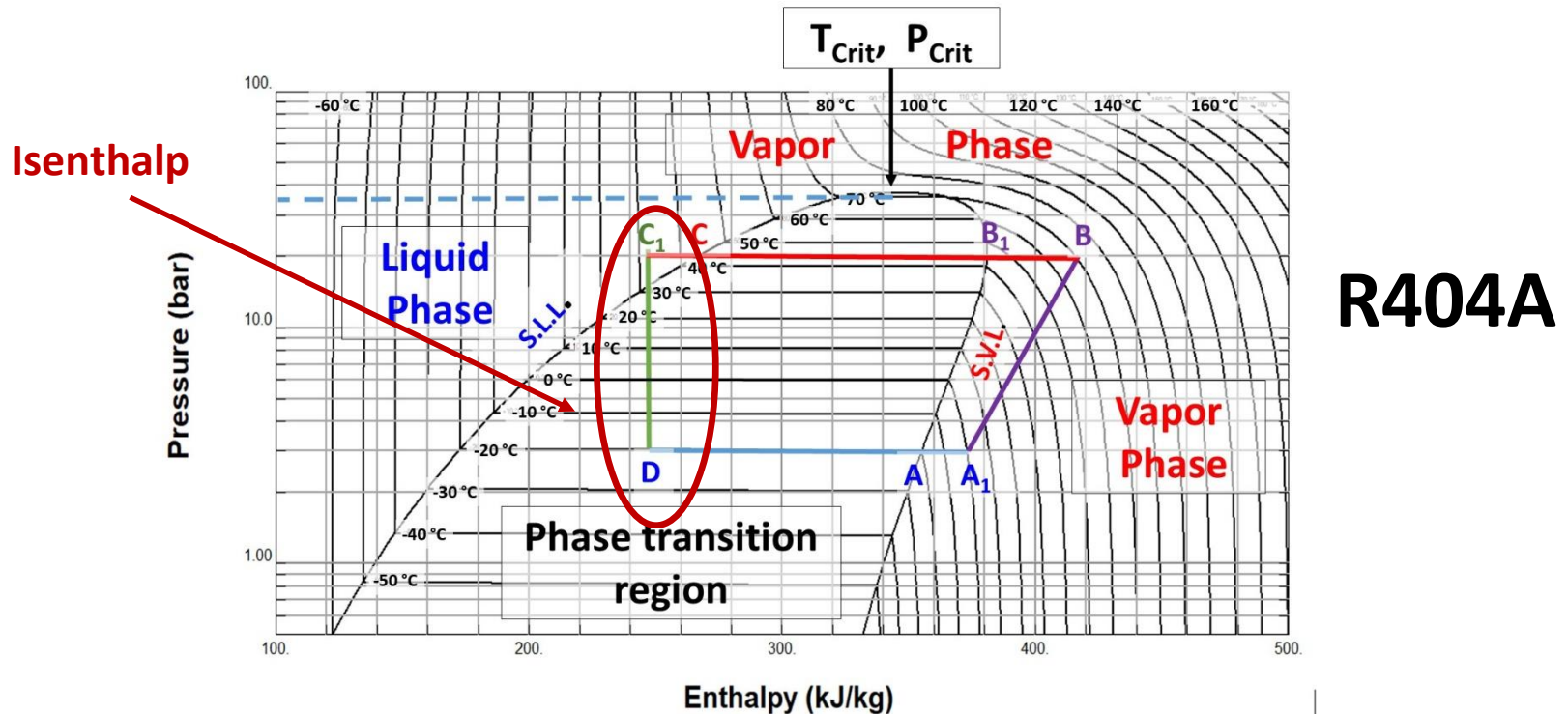
R404A

Pressure-enthalpy diagram: example: *for a domestic refrigerator closed-loop cycle (R404A):*
*(D➔A): heat extraction (**enthalpy increase**) - evaporation at -20 ˚C;*
*(A$_1$➔B) vapour compression (**temperature & pressure increase through mechanical work)**),*
*(B➔C) condensation (**enthalpy decrease**) at 43 ˚C (hot condenser radiator of refrigerator);*
*(C$_1$➔D) liquid "detent" (**Joule-Thompson cooling through forced pressure drop at constant enthalpy**) through a throttling element like an orifice, valve or thin tube (capillary).*
P-h diagram calculated with REFPROP Standard reference database 23, version 9.0 (2010):
E. Lemmon, M. Huber, & M. McLinden U.S. National Institute of Standards & Technology

5.3 Phase Change Cooling (5)

R404A
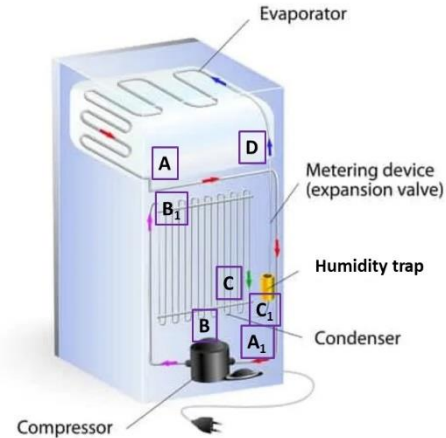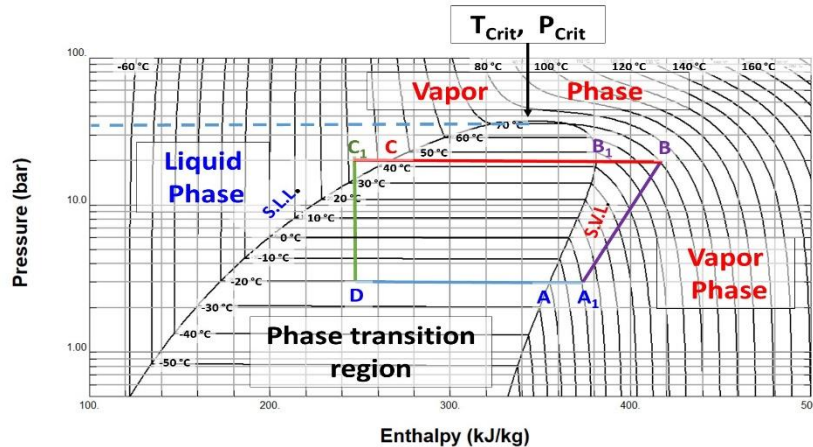
Path (D ➡ A): shows the that *difference in enthalpy* necessary to evaporate 1 kg of R404A between points D (245 kJ.kg^{-1}) & A (360 kJ.kg^{-1}) is 115 kJ.kg^{-1} on the enthalpy axis.

This *enthalpy difference* of tells us the refrigerative (here evaporative) power *ERP$_{P,T}$* (W) that a mass flow of 1 kg.s^{-1} of this fluid can remove at these conditions of (constant) temperature and pressure, as follows:

$$ERP = \delta H_{P,T} * \dot{m}$$
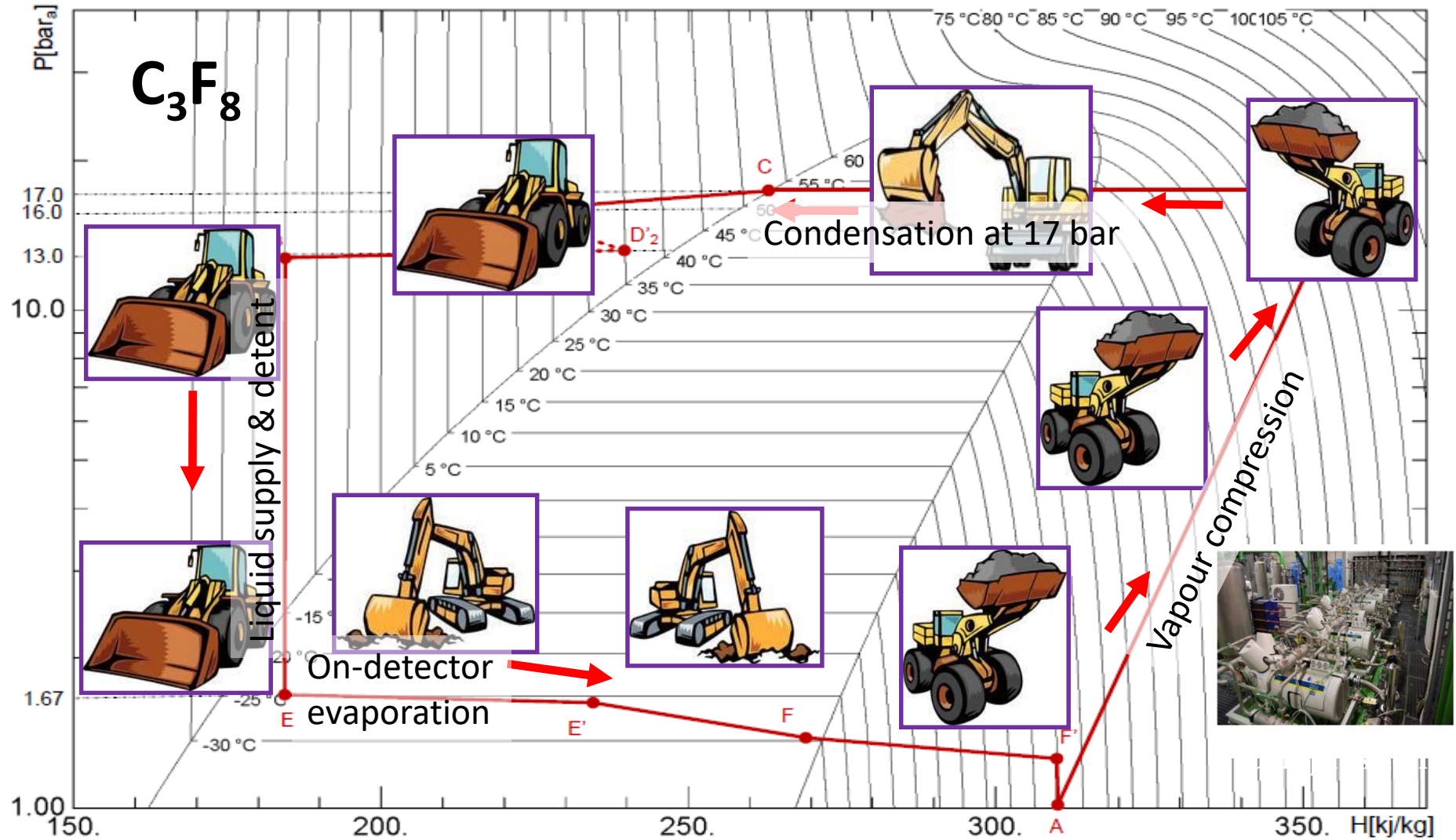
where $\dot{m}$ is the mass flow in kg.s^{-1}

·**The mass flow $\dot{m}$ of refrigerant necessary for required refrigerative power *ERP* is thus:**
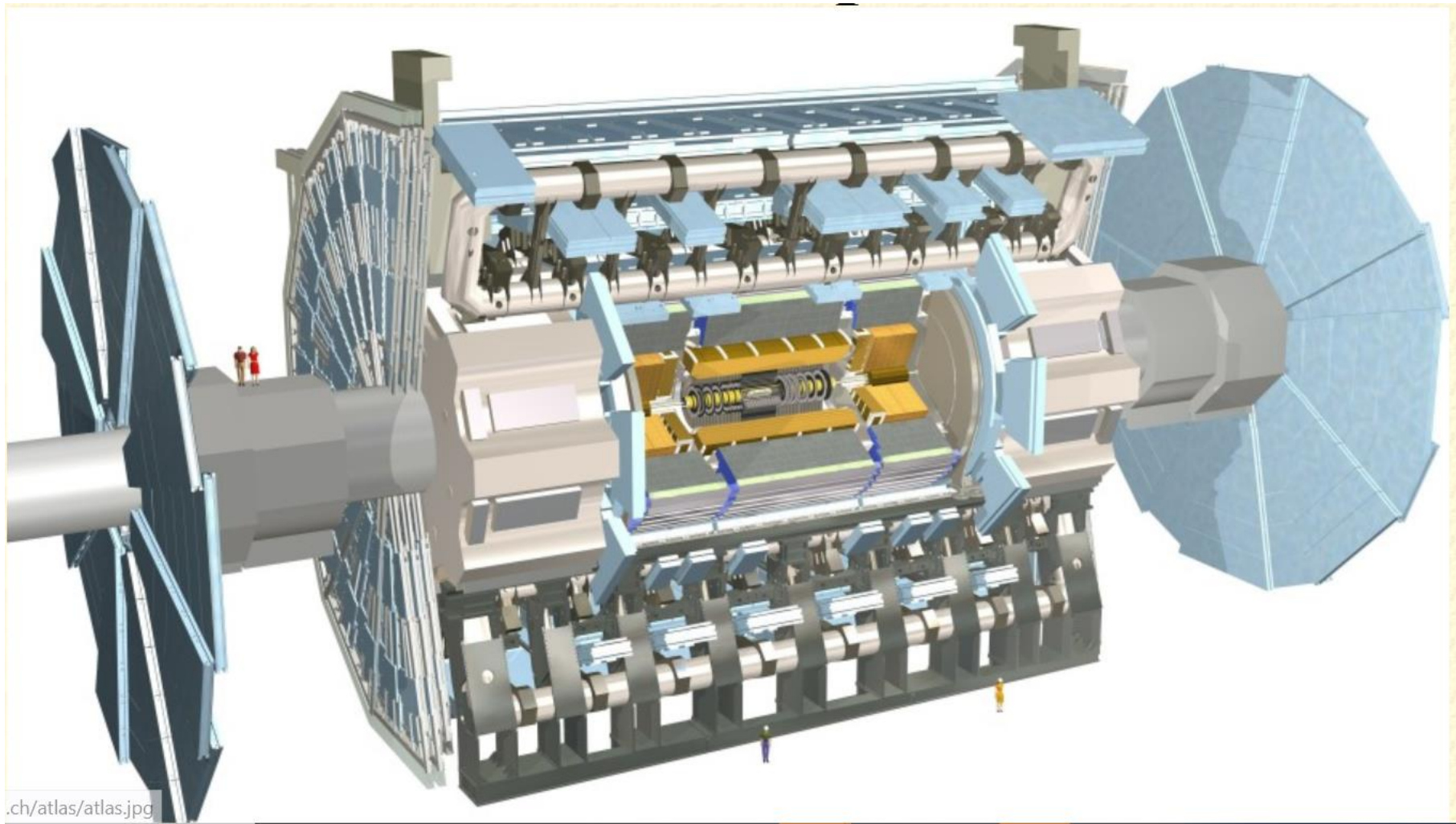
$$\dot{m} = ERP/\delta H_{P,T}$$

For example, a small domestic refrigerator must evaporate 2.6 grams per second of R404A for a refrigerative power of 300 Watts in the conditions of transition *D ➡ A* above.

Another way of looking at energy exchange: Digger = fluid; heat in vapour form = sand...

C_3F_8

Condensation at 17 bar

Liquid supply & detent

On-detector evaporation

Vapour compression

Let's digress!   Here is ATLAS at LHC

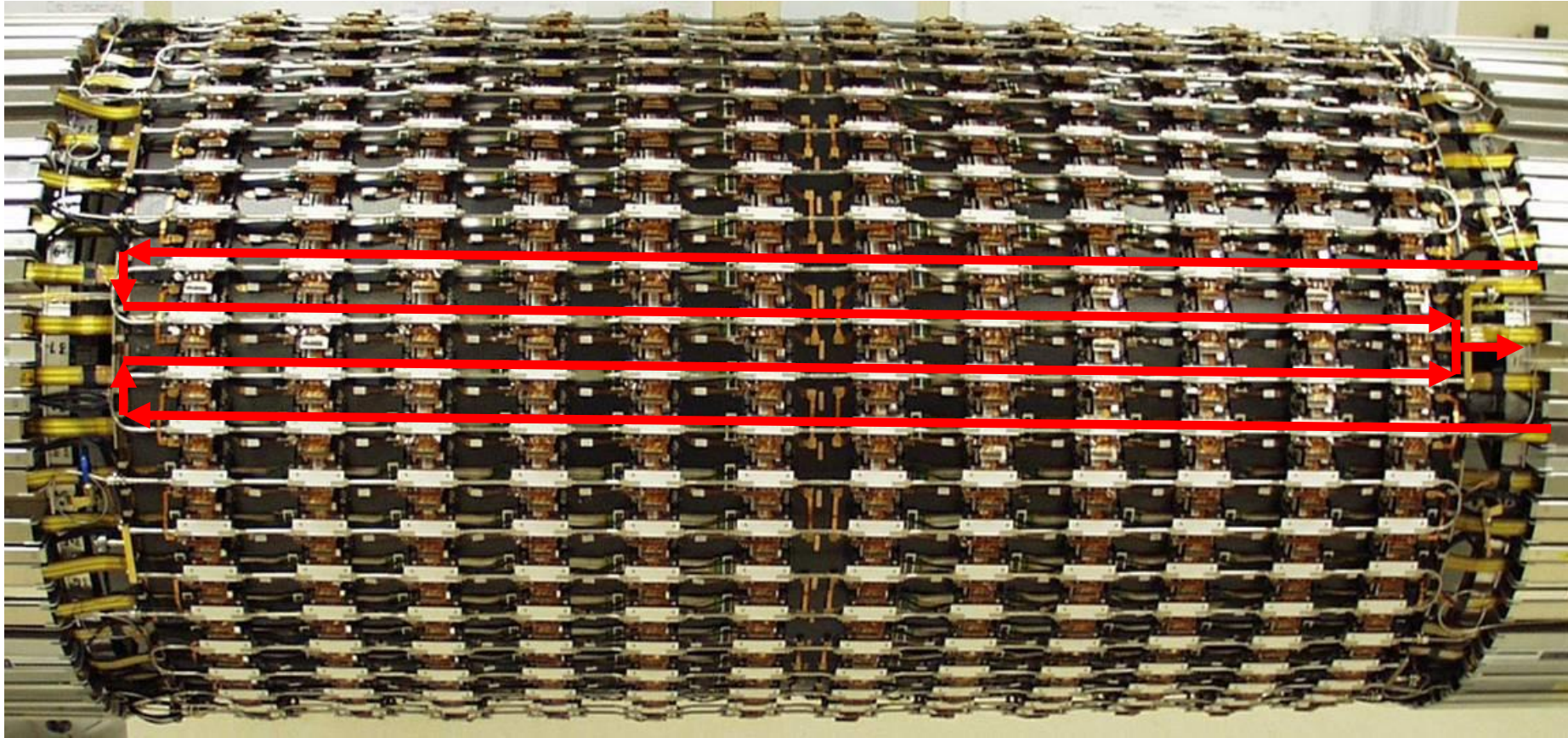.ch/atlas/atlas.jpg
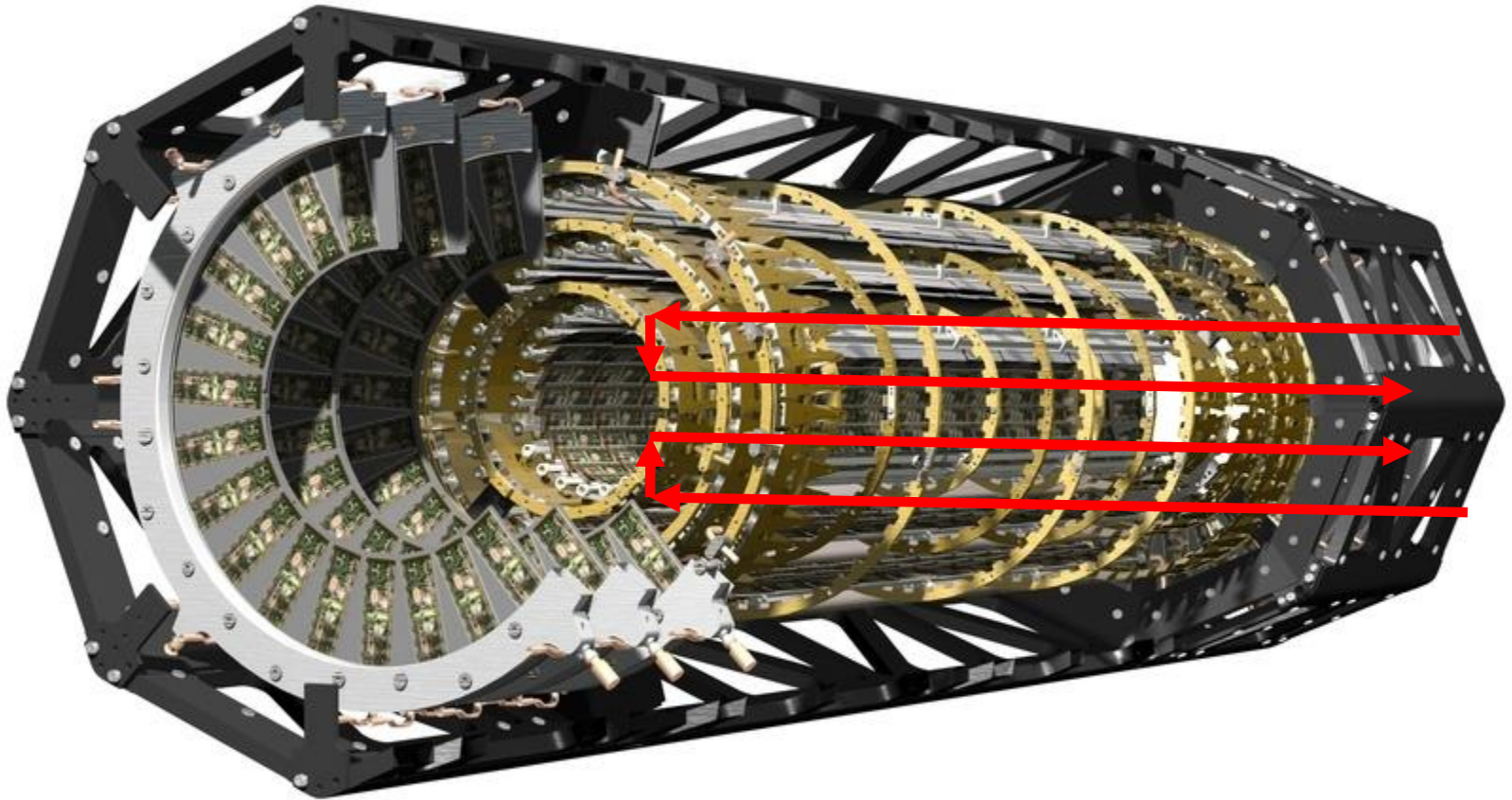
Unpeeling the ATLAS Onion
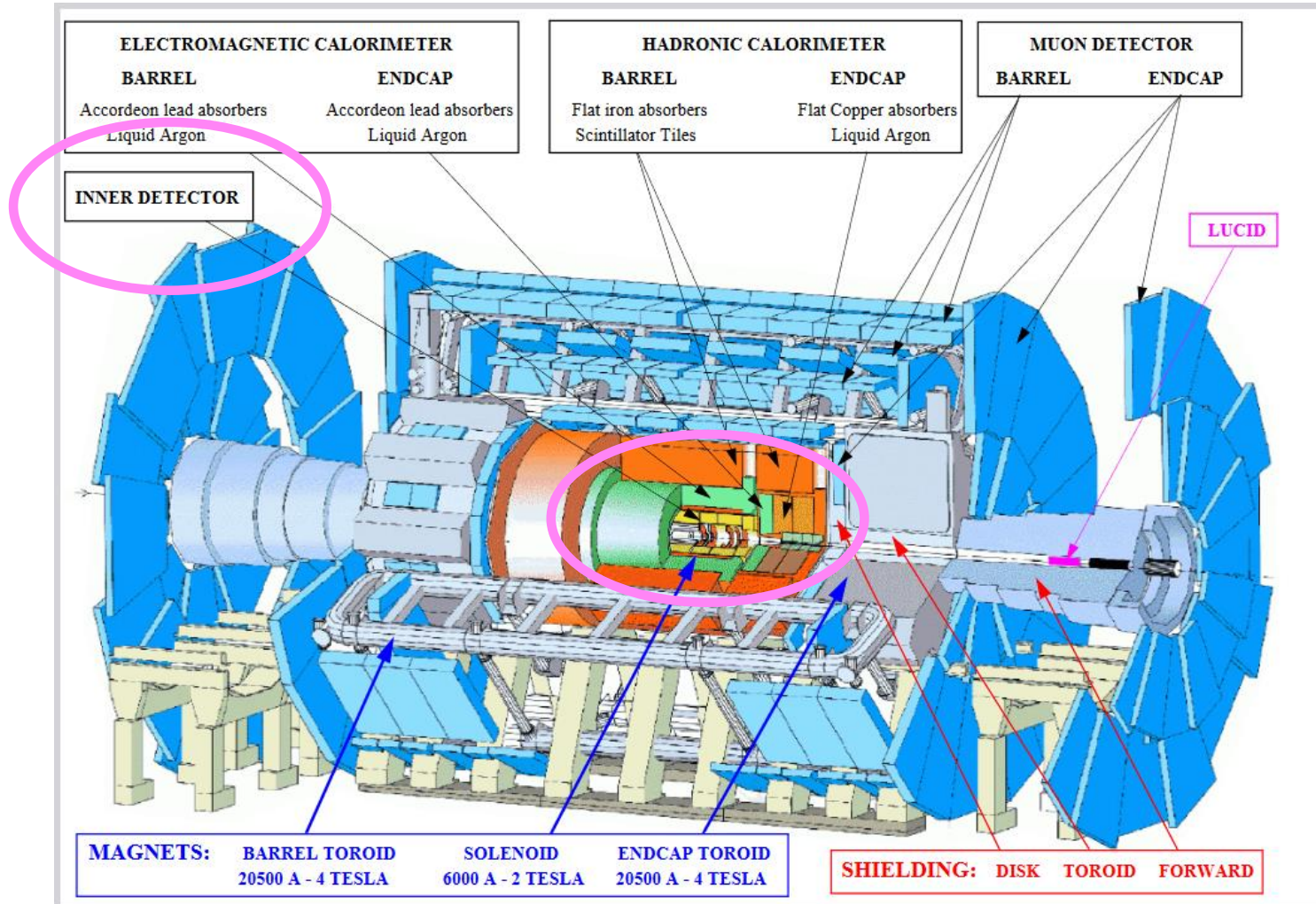
Unpeeling the ATLAS Onion: the evaporators
'Semi-Conductor Tracker' (SCT)
silicon microstrip tracker surrounding pixel detector

SCT + pixels: 204 C_3F_8 evaporative cooling circuits
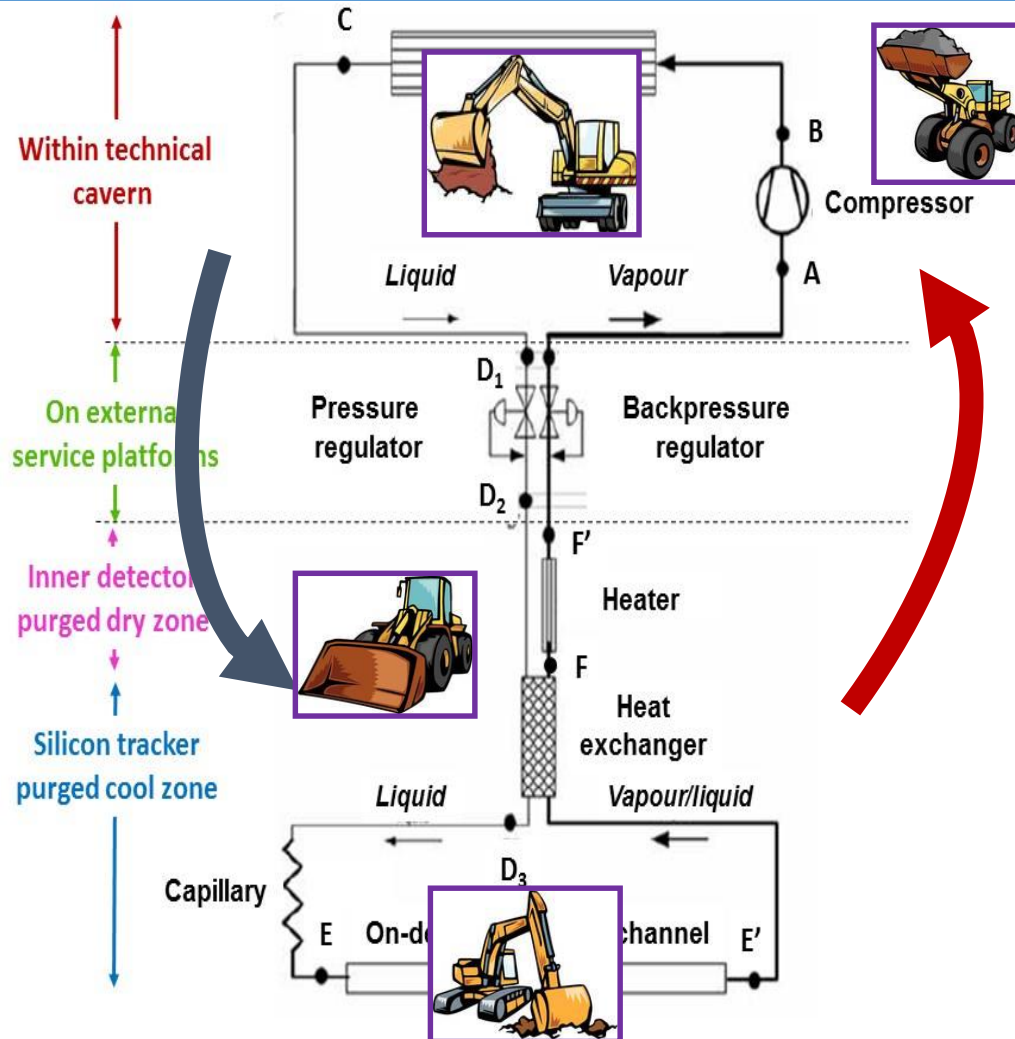60kW total power to evacuate (1.2 kgs^{-1} C_3F_8)

Unpeeling the ATLAS Onion: the evaporators
ATLAS – Silicon Pixel Detector Structure

~50 Horizontal stave cooling channels (l ~ 1,60m)
18 "radial" channels: disk sectors

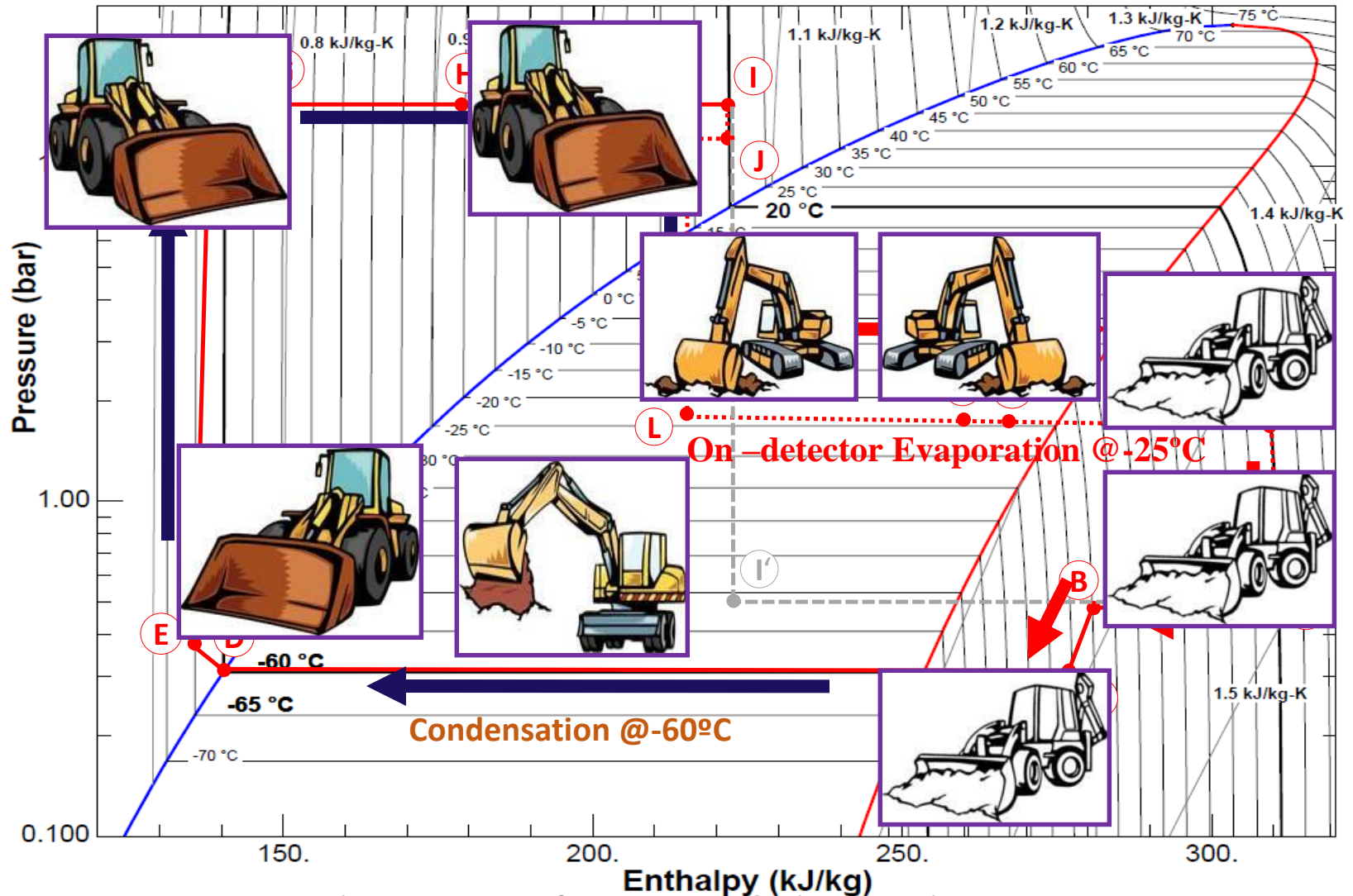# 5.3 Phase Change Cooling (8):
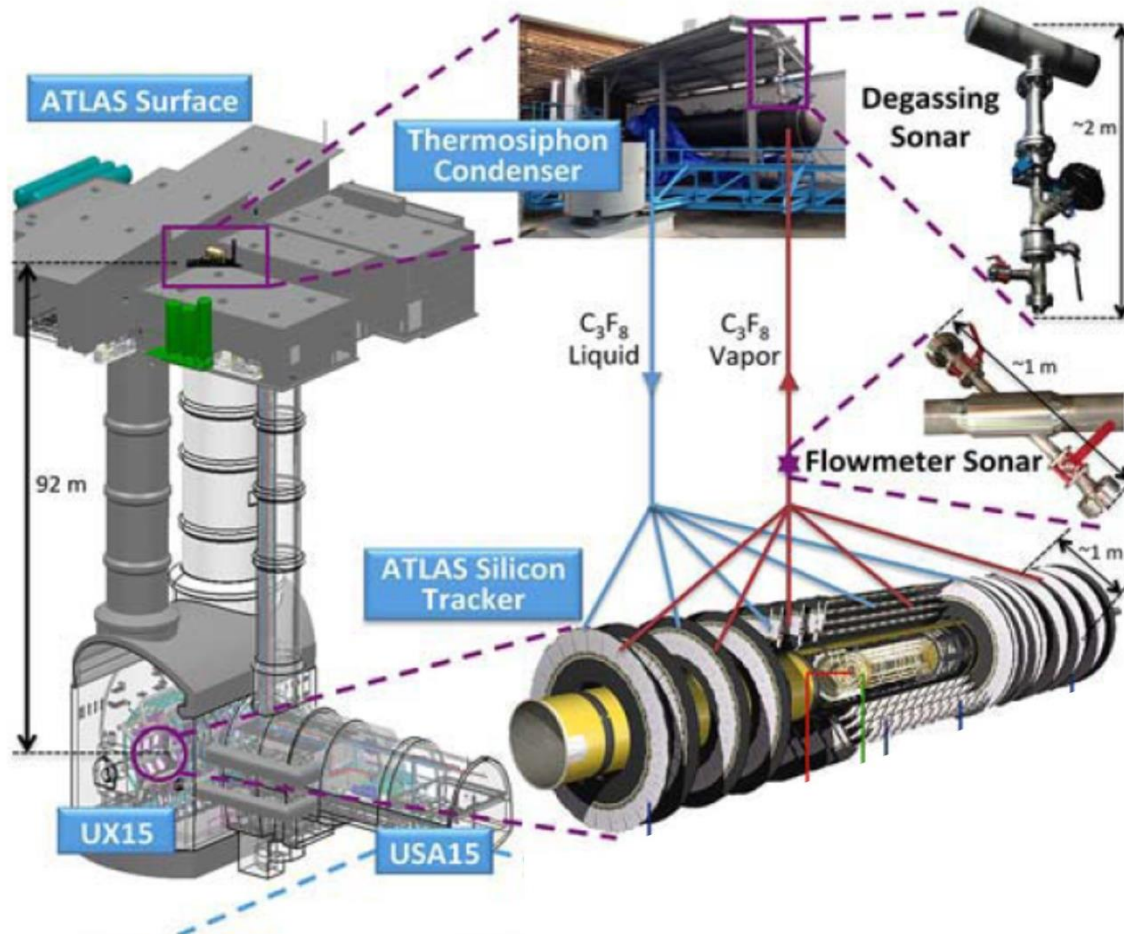## Let's get rid of the compresssors and do it in reverse with no moving parts!

Animation: Digger = fluid; heat in vapour form = sand…

On –detector Evaporation @–25°C

Condensation @–60ºC

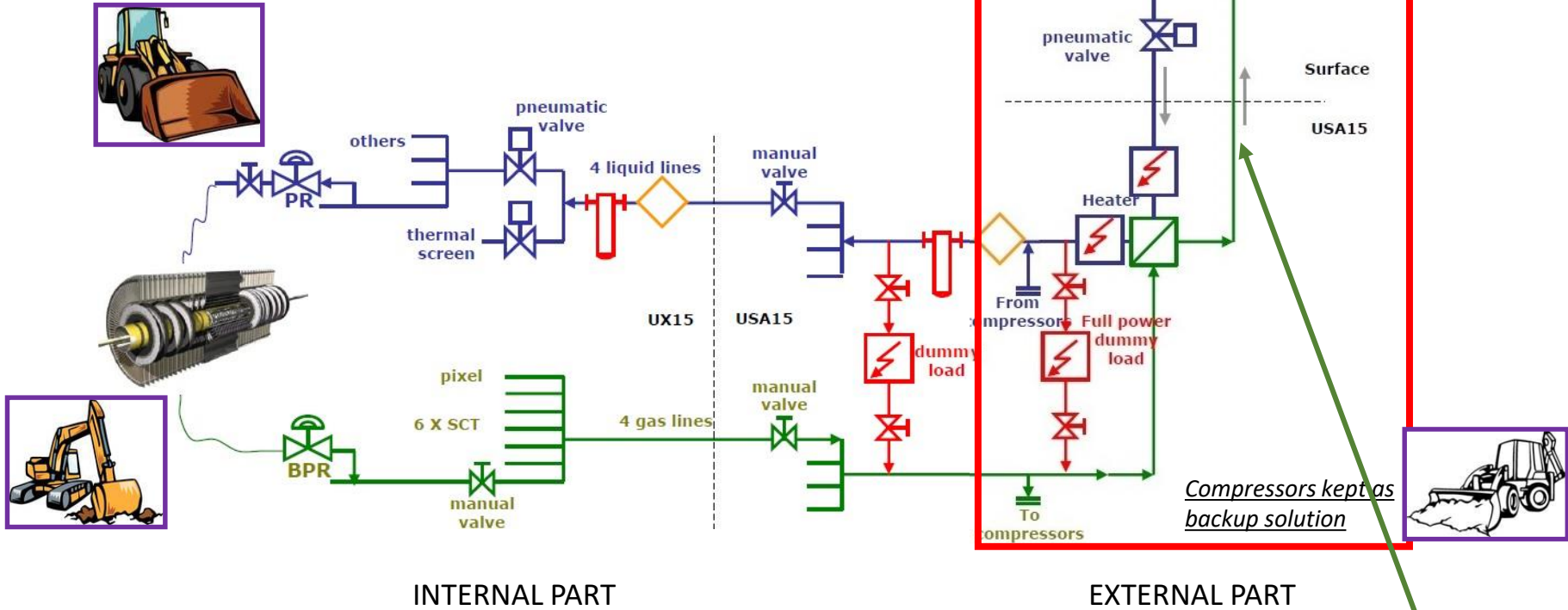Pressure (bar)

Enthalpy (kJ/kg)

5.3 Phase Change Cooling (9):

The ATLAS Si tracker C_3F_8 92 m (300') thermosiphon cooling system: no moving parts (except valves) in C_3F_8 circuit.

**❖92m pit depth at ATLAS ➜ > 13 bar (ρgh)
hydrostatic pressure liquid C_3F_8 or C_3F_8/C_2F_6**

*Gravity-driven thermosiphon
evaporative cooling system*

condenser

liquid tank

Low temperature Chiller

pneumatic valve

Surface

USA15

Heater

From compressors

Full power dummy load

dummy load

To compressors

Compressors kept as backup solution

pneumatic valve

others

thermal screen

4 liquid lines

manual valve

UX15

USA15

PR

pixel

6 X SCT

BPR

4 gas lines

manual valve

manual valve

INTERNAL PART

EXTERNAL PART

ρgh from 92m of C_3F_8 vapour is only ~70mbar …
*not difficult to return vapour to a cold condenser on the surface, but condenser
must be highest geographic - but lowest temperature & pressure - component*

Thermosiphon: Reversal on Pressure-Enthaply Diagram
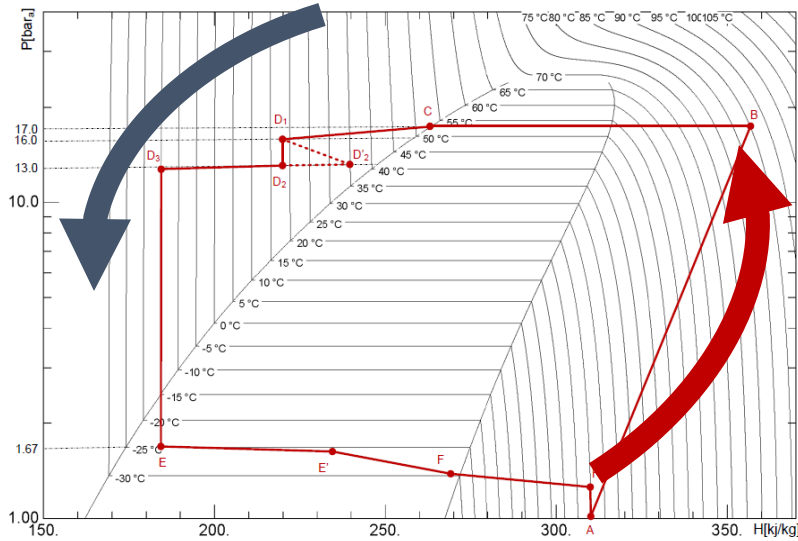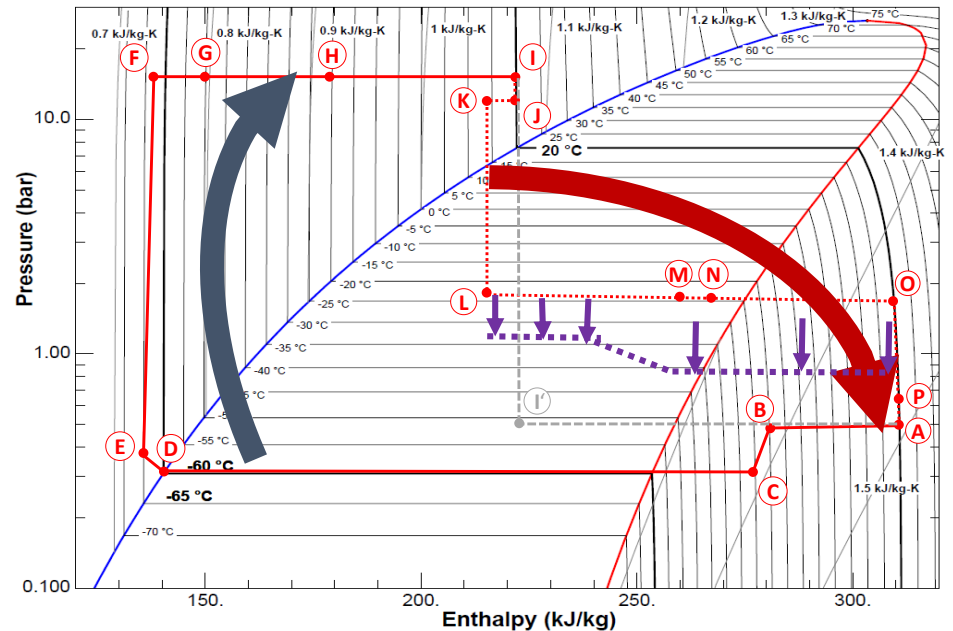

Compressor driven

Gravity thermosiphon driven

5.3 Phase Change Cooling (10):

ATLAS-LHC: Si tracker C_3F_8 thermosiphon Point 1 installation (roof, ground & pit)

TS Condenser: 15m above ground level
(92m above ATLAS): Condenses 1.2 kg/s C_3F_8
using cold liquid C_6F_{14} Pumped up at -65 °C

C_6F_{14} "Brine" Chiller circuit: Ground level

Connection to existing system: 90m underground:
Changeover valves compressors➔ thermosiphon

Water circuit: 90m underground

ATLAS Si tracker thermosiphon C_3F_8 condenser

Module	# Pipe runs
1	104
2	103
3	103
4	28
5	32

Elevation (End cap removed)

U-tube heat exchanger (Plan View)

Function	# Pipe runs
Condensation	310
Liquid Sub-cooling	32
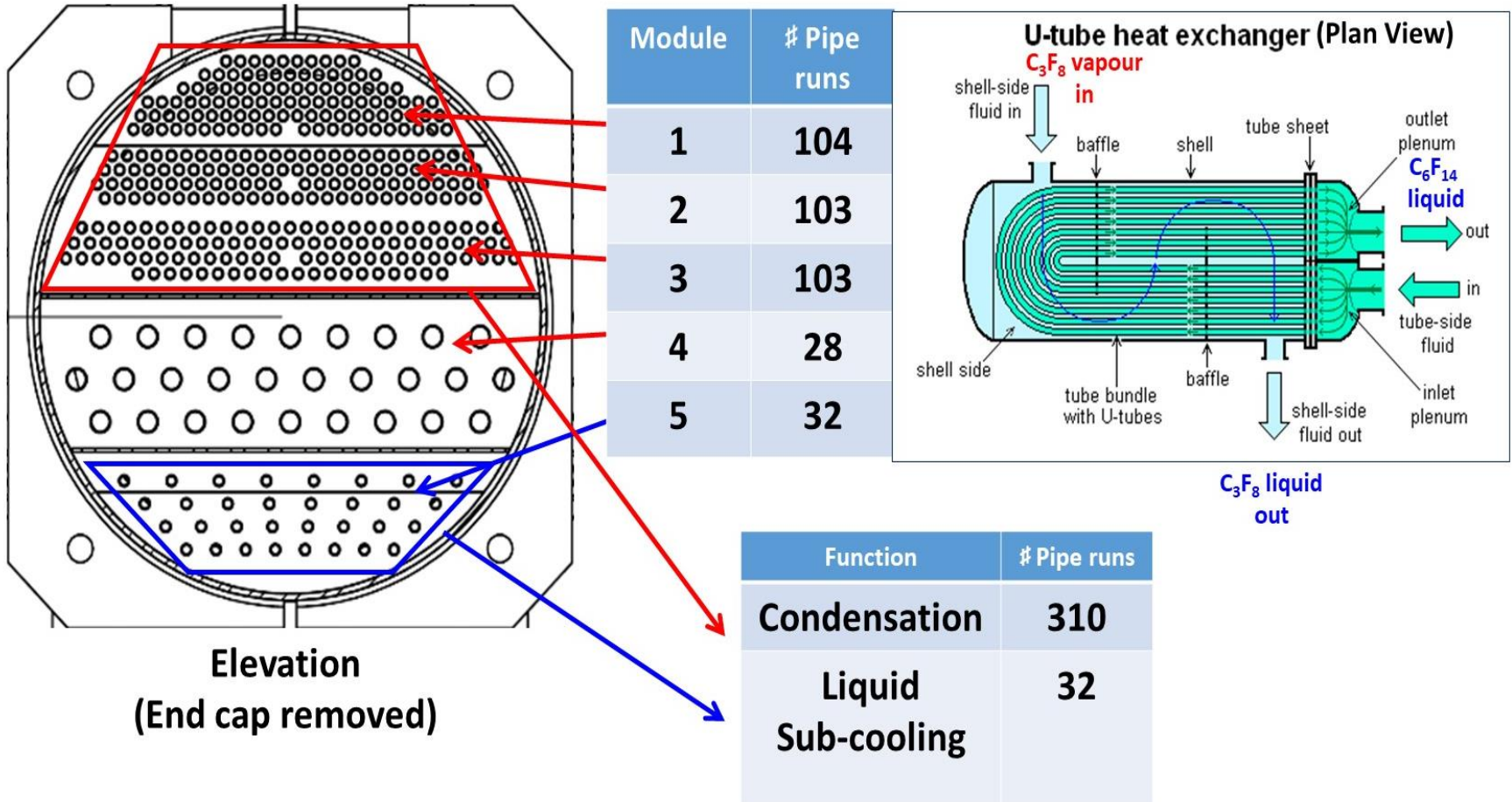
* Liquid C_6F_{14} is used to condense C_3F_8 vapor at around -60 °C

5.3 Phase Change Cooling:

Problem (3) on the ATLAS thermosiphon see also separate sheet:
From the previous slide it is clear that a large number of tubes are needed to condense
Approximately 1.2 kgs^{-1} of C_3F_8 to cool the ATLAS silicon tracker. This implies that a
high mass flow of C_6F_{14} liquid is needed, but what this mass flow (kg.s^{-1})?

Hints to solve this problem:

• Looking at figure 3.10 we see that considerable thermal energy has to be extracted from
the C_3F_8 vapor to reduce its temperature from around 20 ˚C (the temperature acquired
in traveling through more than 92 meters of pipes to the condenser) to -60 ˚C,
where phase change can occur under the "dome";

• Some of this heat is extracted from the vapour at a C_3F_8 pressure of 320 mbar within
the condenser itself (using a counter-flow of cold C_6F_{14}), cooling the vapor from -25 ˚C
(point **C**) to -60 ˚C before the vapour begins to condense at the saturated vapour
boundary of the dome.

• Moving left from the saturated vapour boundary of the dome all energy goes into
condensing the C_3F_8. You should therefore use the entire **CD** enthalpy difference in your
calculation, and only this;

• The specific heat capacity of C_6F_{14} in the range -60 ➔ -65 ˚C is around 925 J.kg^{-1}.
C_6F_{14} remains a liquid and does not change phase during this process, but heats up by 5 ˚C.

5.3 Phase Change Cooling (12.2):
Problem on the ATLAS thermosiphon see also separate sheet
*(Diggers removed to make the cycle on the C_3F_8 **ph** diagram easier to read)*