Physics 524

Survey of Instrumentation & Laboratory Techniques:
Unit 5: Cooling & Thermal management

Lecture 2 of 4
(24:1)

5.3 Phase Change Cooling (here seawater)

*Solid fresh water melts, cooling sea water (water with around 35 kg/tonne of salt)*

(Picture credit: 𝔗𝔥𝔢ℜ𝔦𝔡𝔢𝔯𝔓𝔬𝔰𝔱.𝔠𝔬𝔪:
https://www.theriderpost.com/lifestyle/environnement/iceberg-titanic-sechoue-cote-canada/)

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
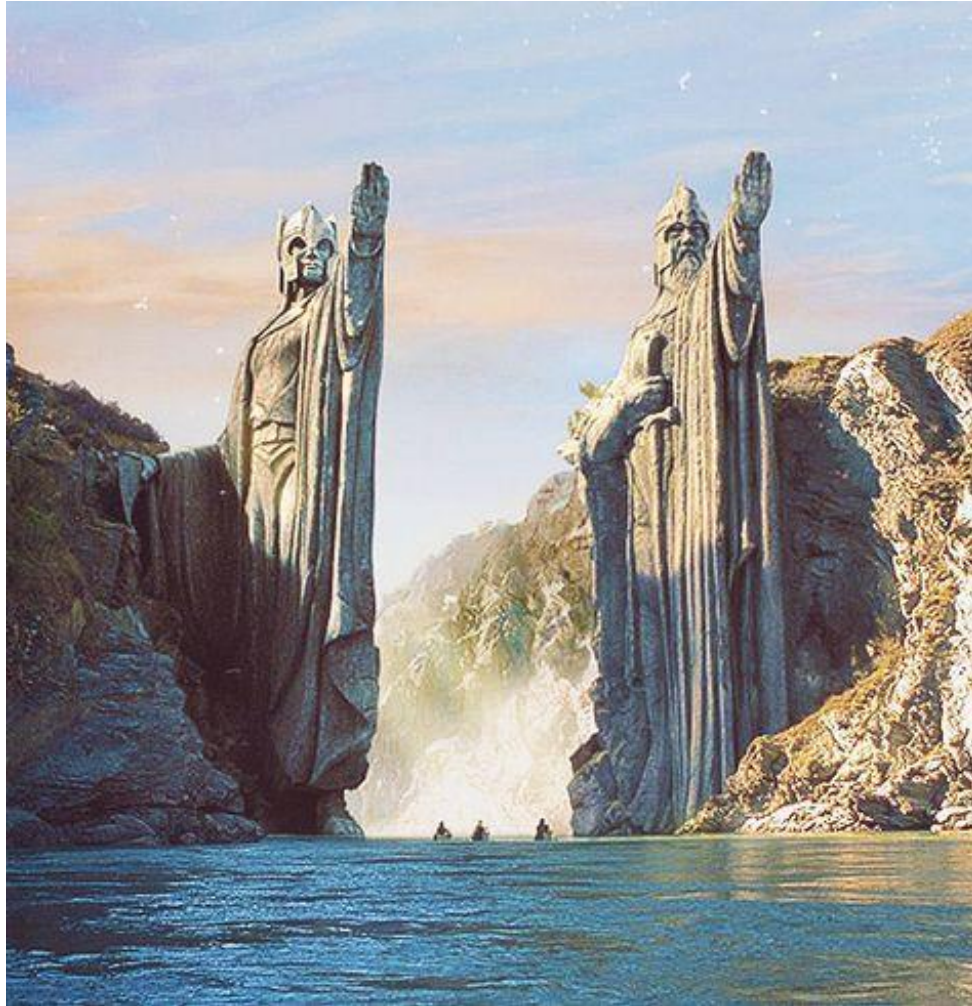
5.3 Phase Change Cooling (2)

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)
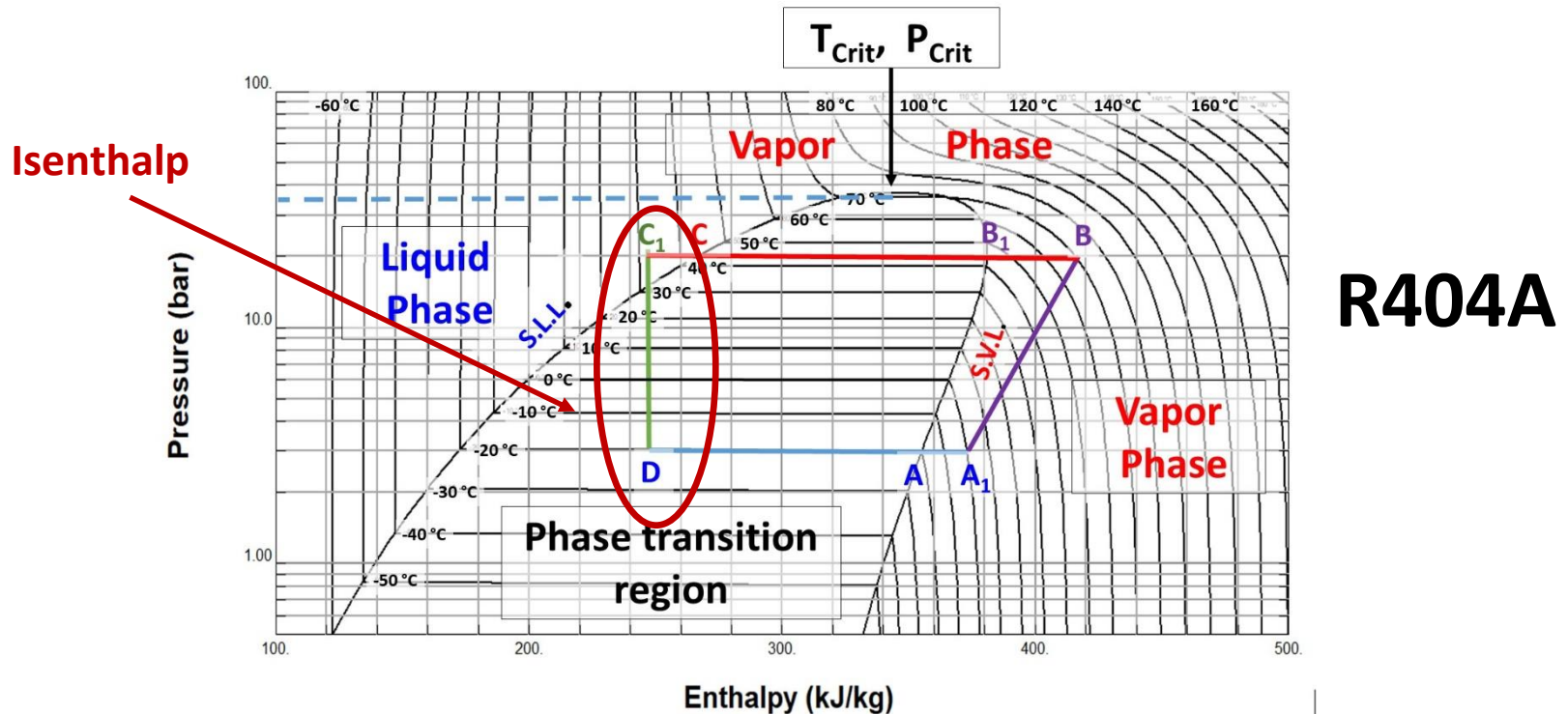
Pressure-enthalpy diagram: example: *for a domestic refrigerator closed-loop cycle (R404A):*

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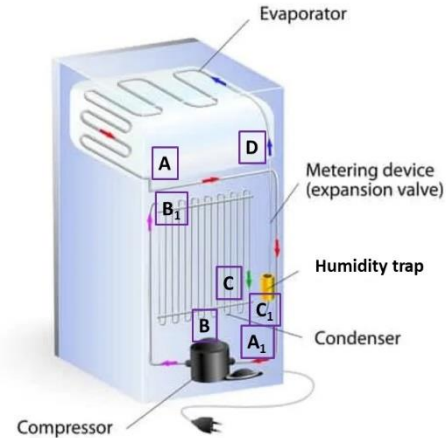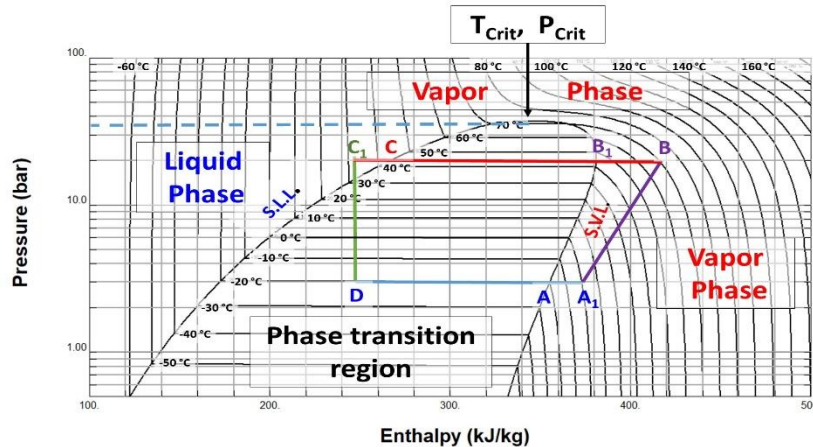
Path (D➔A): shows the that *difference in enthalpy* necessary to evaporate 1 kg of R404A between points D (360 kJ.kg^{-1}) & A (245 kJ.kg^{-1}) is 115 kJ.kg^{-1} on the enthalpy axis.

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:

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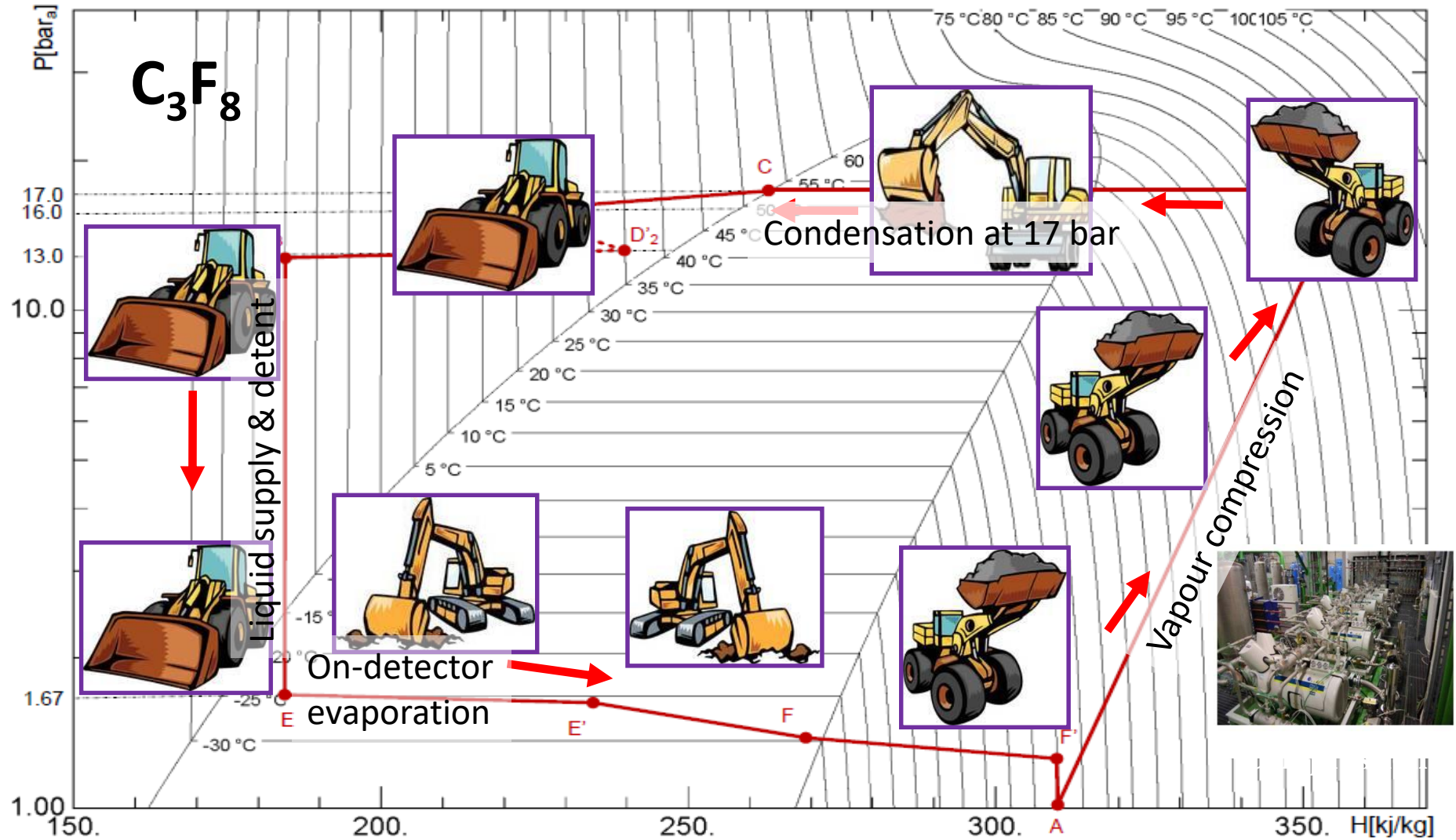
where $\dot{m}$ is the mass flow in kg.s^{-1}

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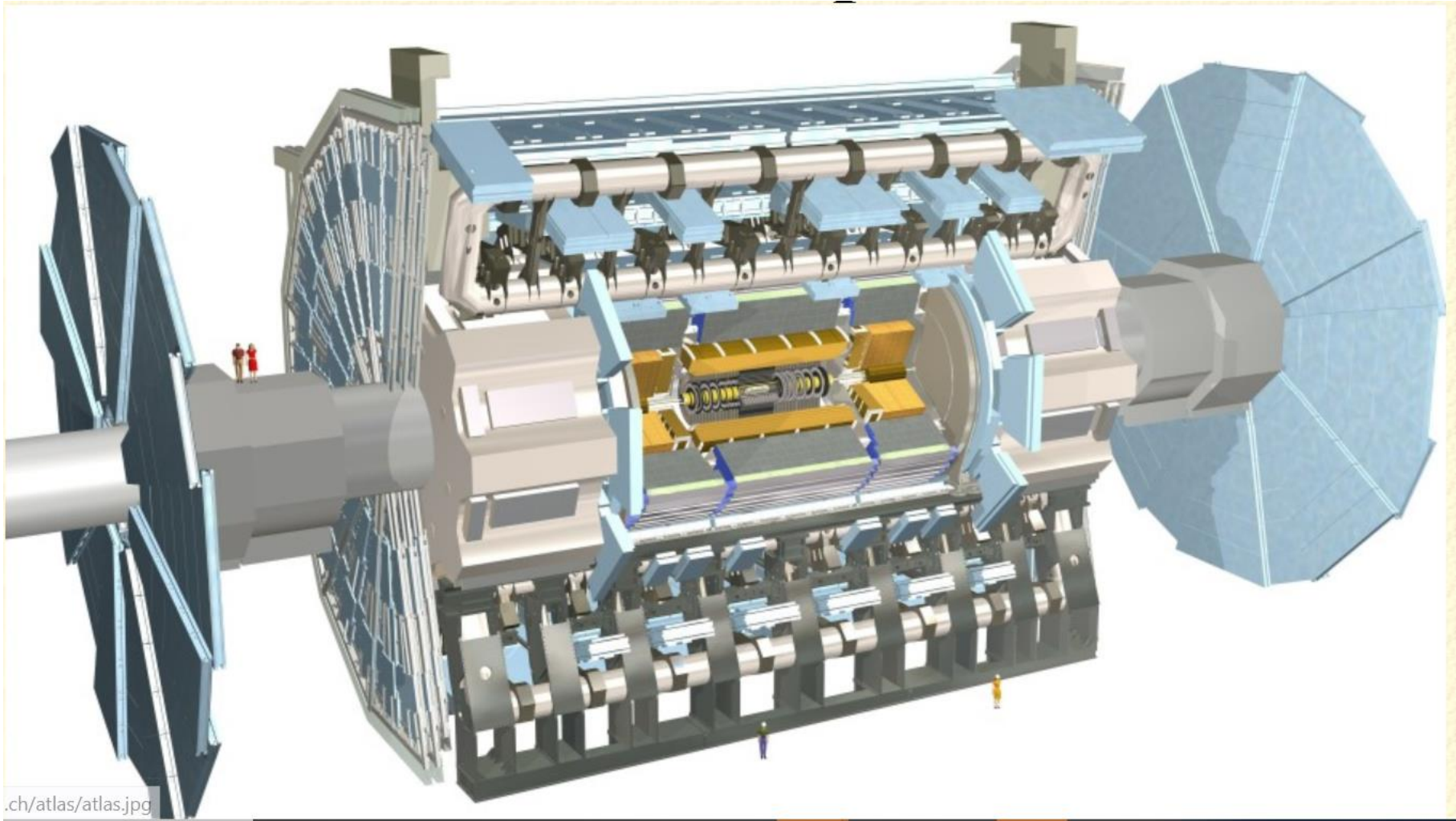
$$\dot{m} = ERP/\delta H_{P,T}$$

For example, a 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

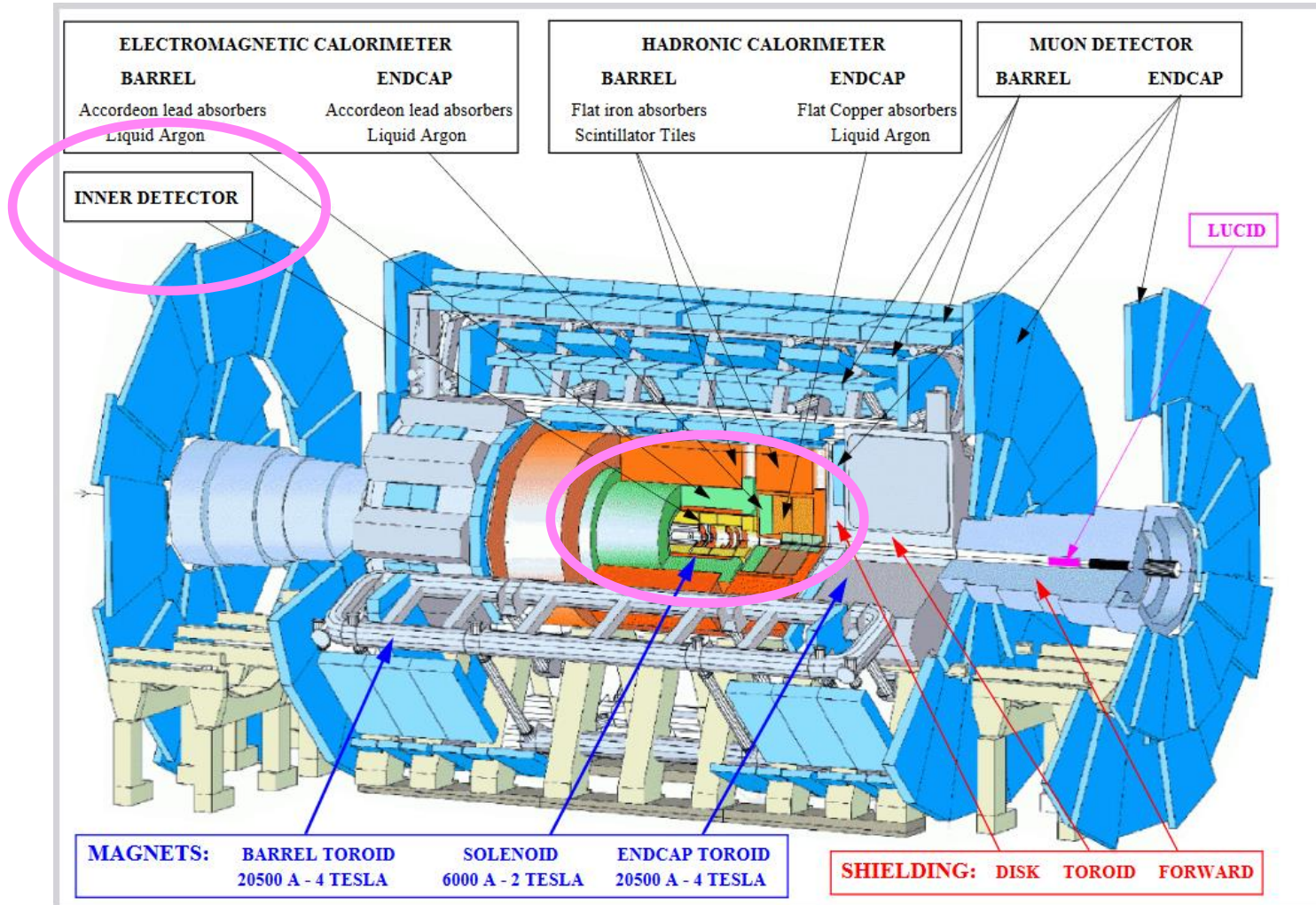Liquid supply & detent

On-detector evaporation
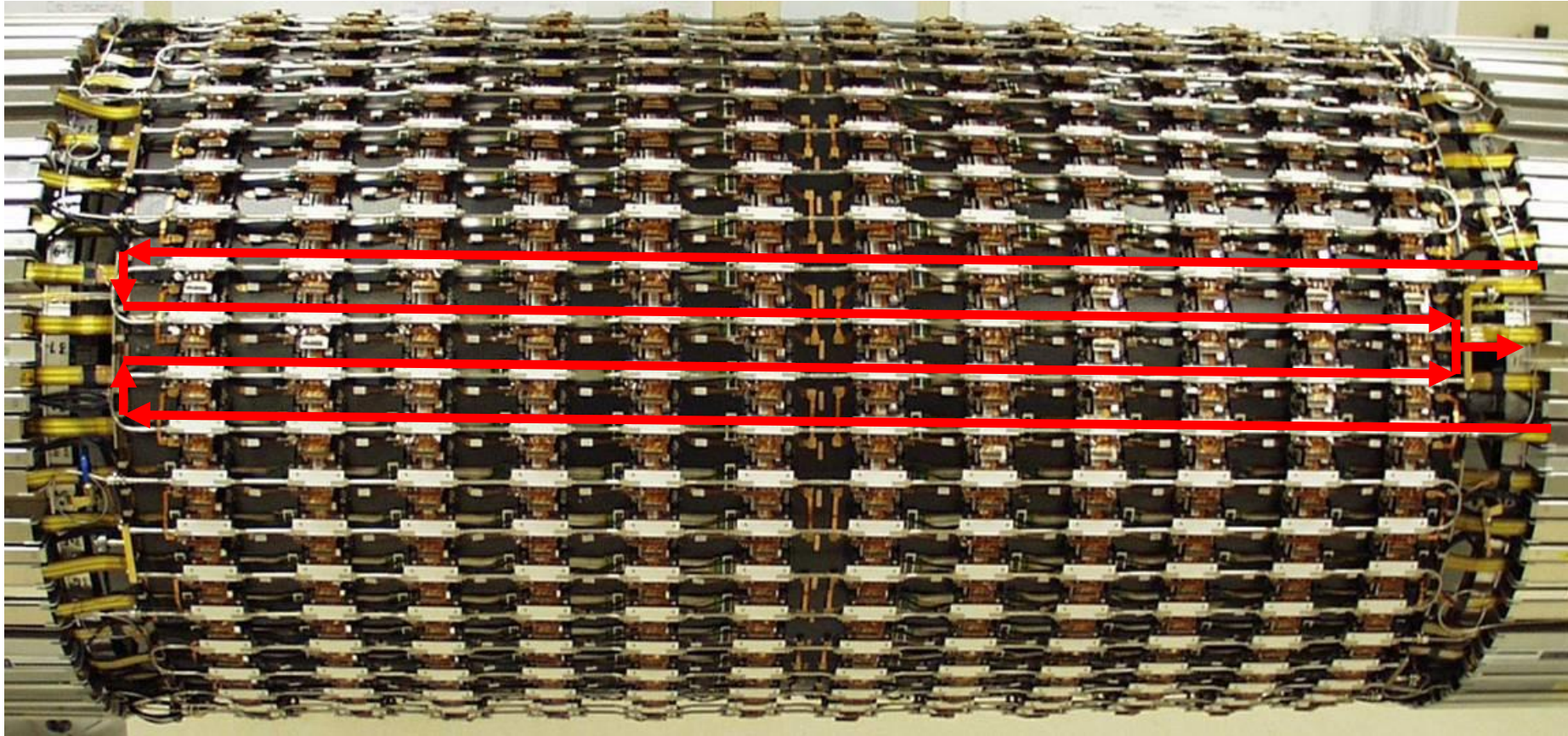
Vapour compression

Let's digress!   Here is ATLAS at LHC
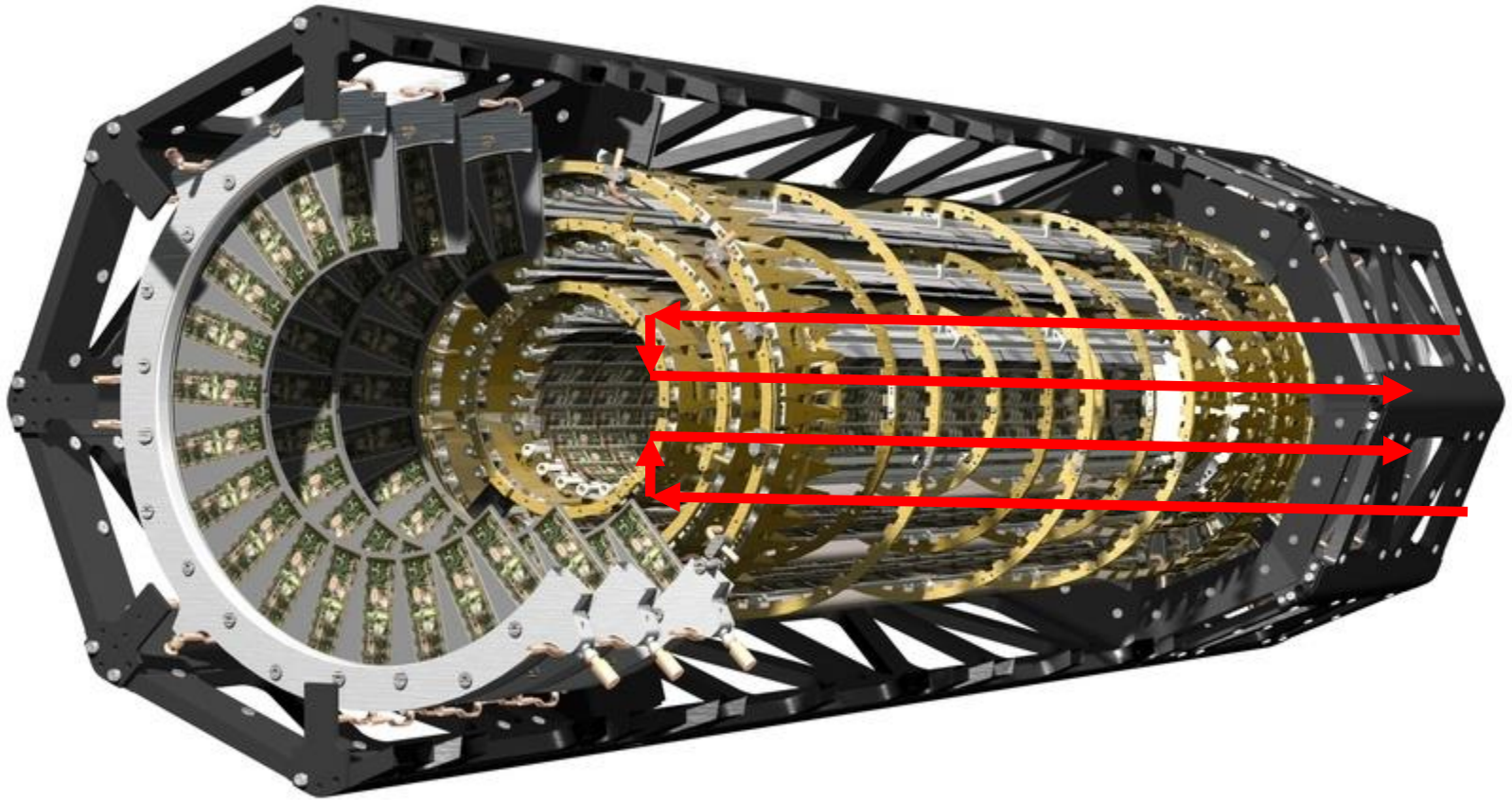
Unpeeling the ATLAS Onion

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
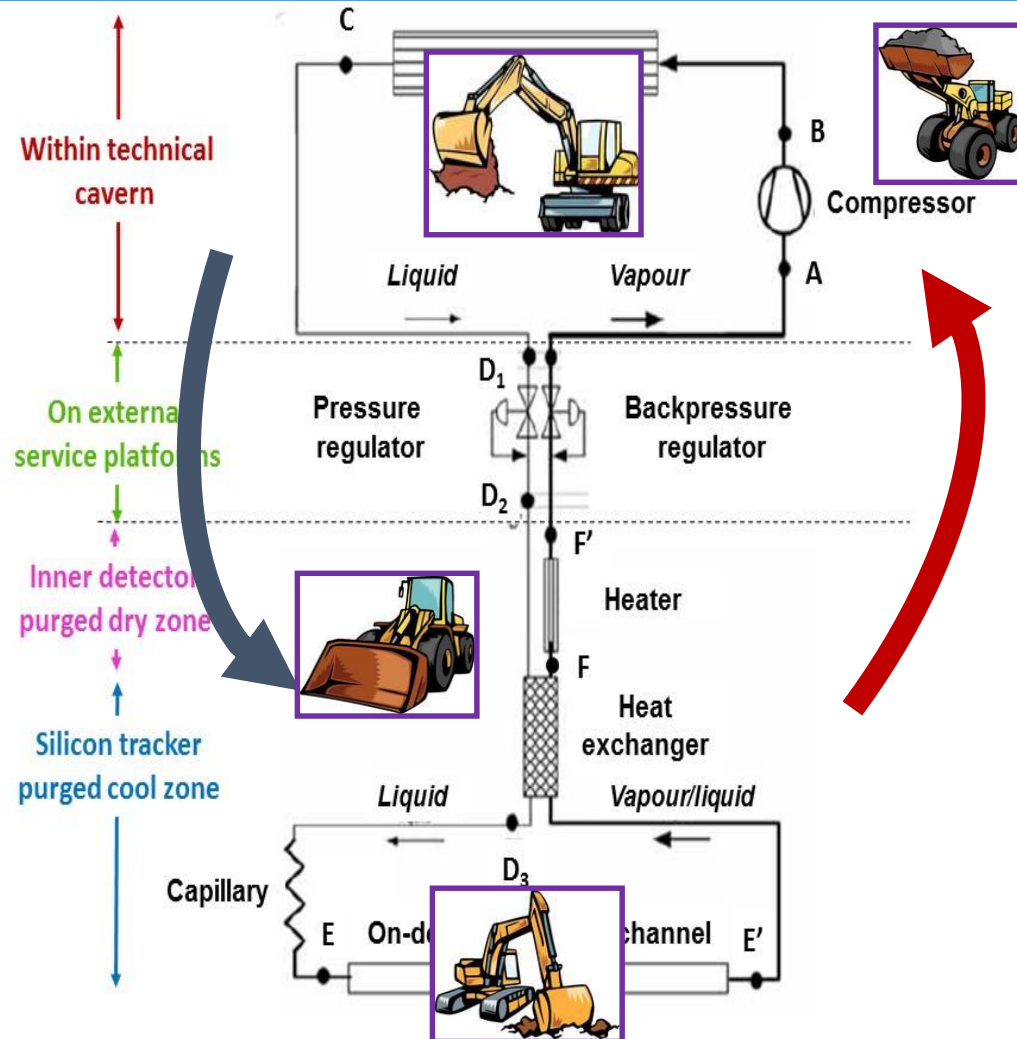60kW total power to evacuate (1.2 kgs^{-1} C_3F_8)

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

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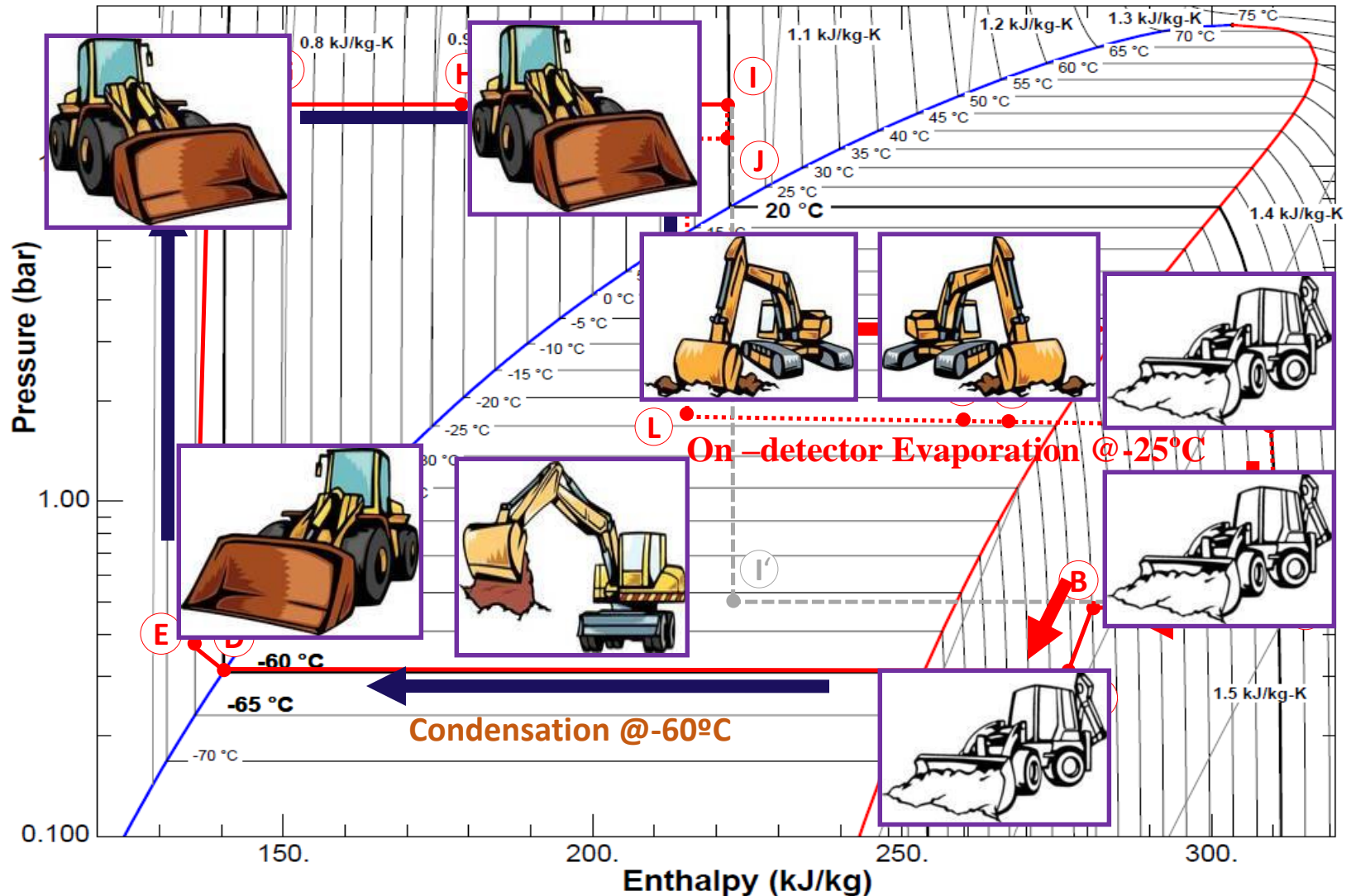18 "radial" channels: disk sectors

5.3 Phase Change Cooling (7): LHC ATLAS Pixel & SCT detector cooling with evaporating C_3F_8 : you've just seen the evaporators; now the other parts of the system (including the problematic compressors)

Within technical cavern

On external service platforms

Inner detector purged dry zone

Silicon tracker purged cool zone

C

B Compressor

A

Liquid

Vapour

D_1

Pressure regulator

Backpressure regulator

D_2

F'

Heater

F

Heat exchanger

Liquid

Vapour/liquid

D_3

Capillary

E On-detector channel E'

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

Pressure (bar) vs Enthalpy (kJ/kg) diagram with labelled points E, D, H, I, J, L, I', B.

On –detector Evaporation @ –25°C
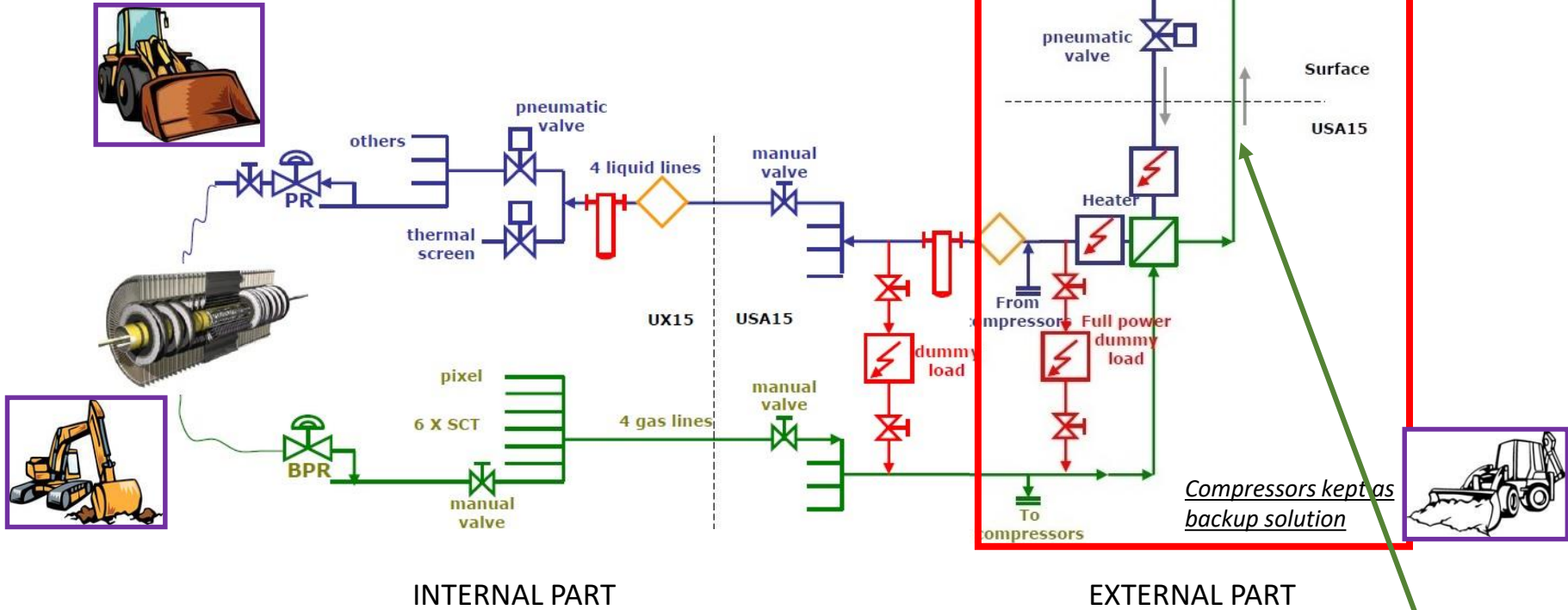
Condensation @ –60°C

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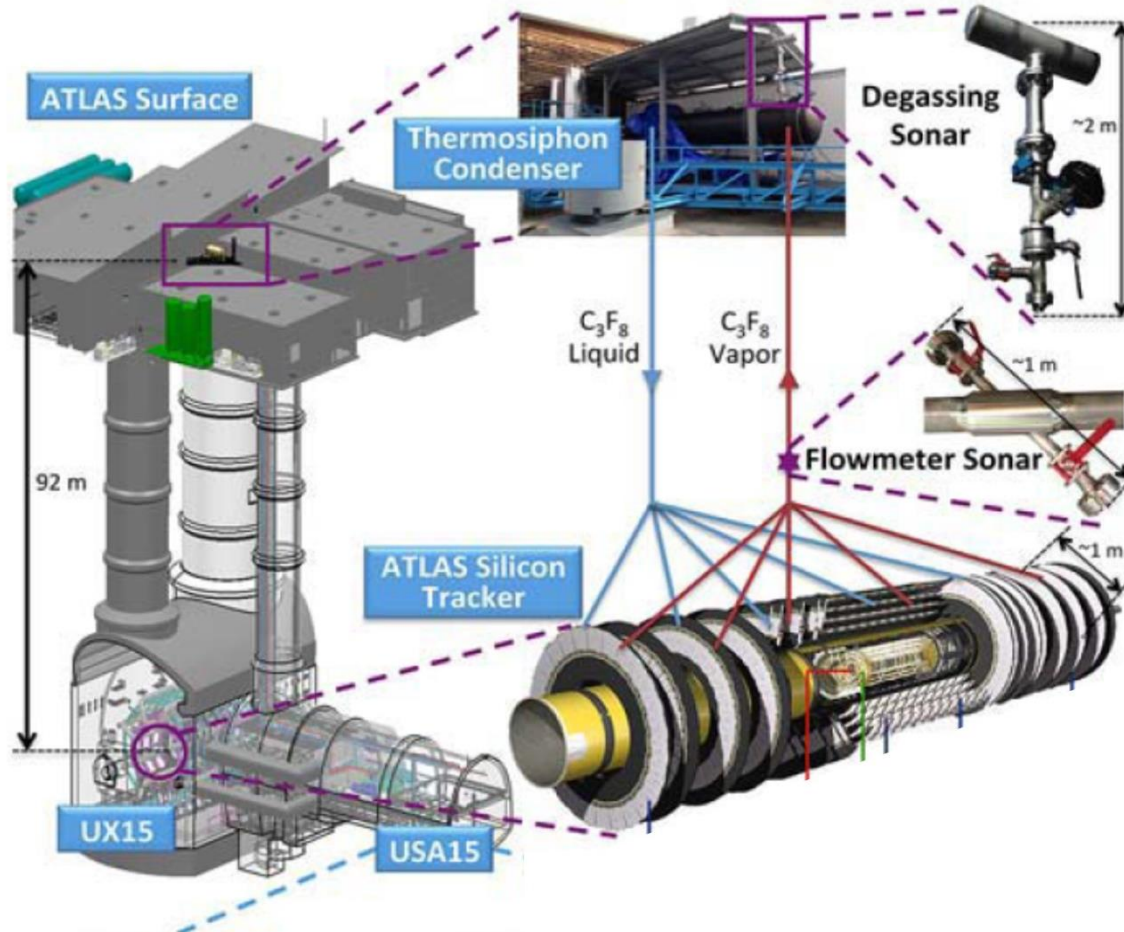
❖92m pit depth at ATLAS ➜ > 13 bar (ρgh) hydrostatic pressure liquid C_3F_8 or C_3F_8/C_2F_6

Gravity-driven thermosiphon evaporative cooling system

INTERNAL PART   EXTERNAL PART

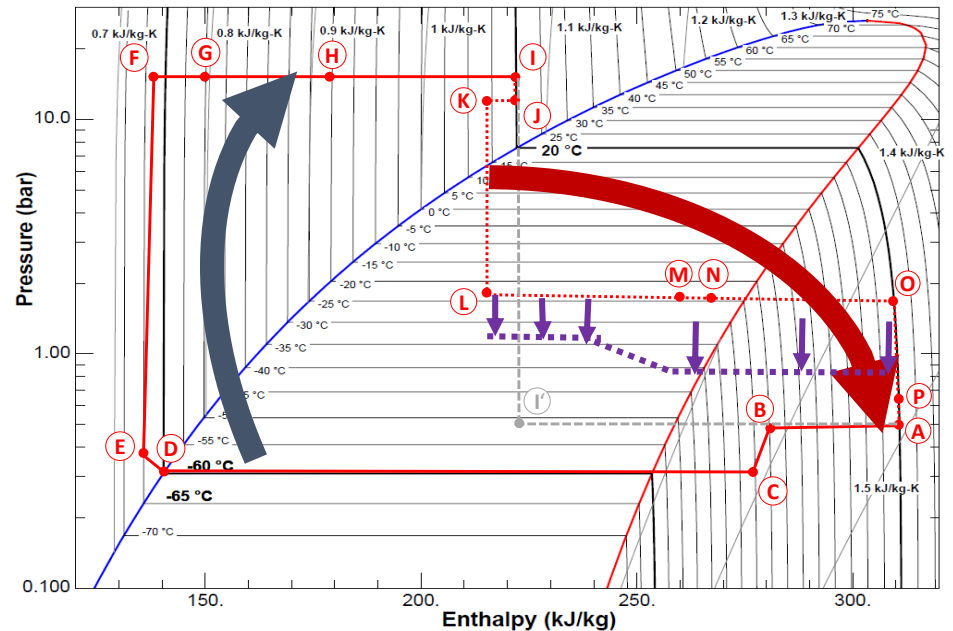*Compressors kept as backup solution*

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
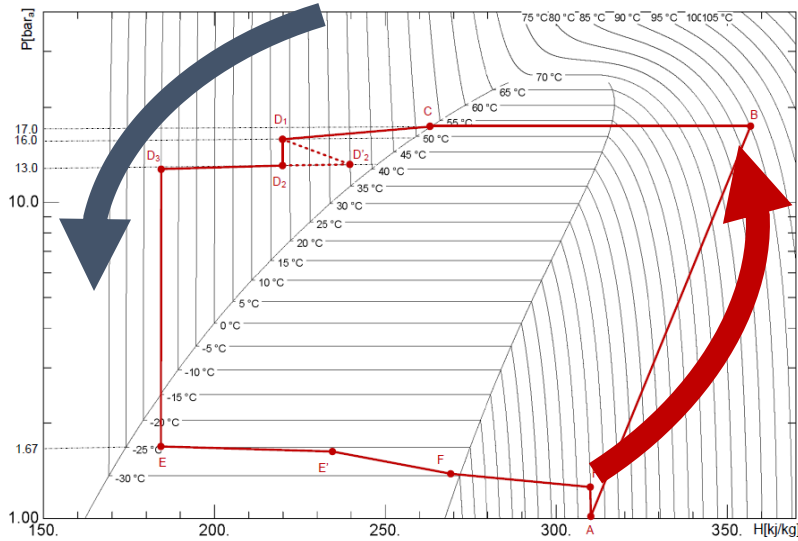
Compressor driven

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 liquidC_6F_{14} Pumped up at -65 °C

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

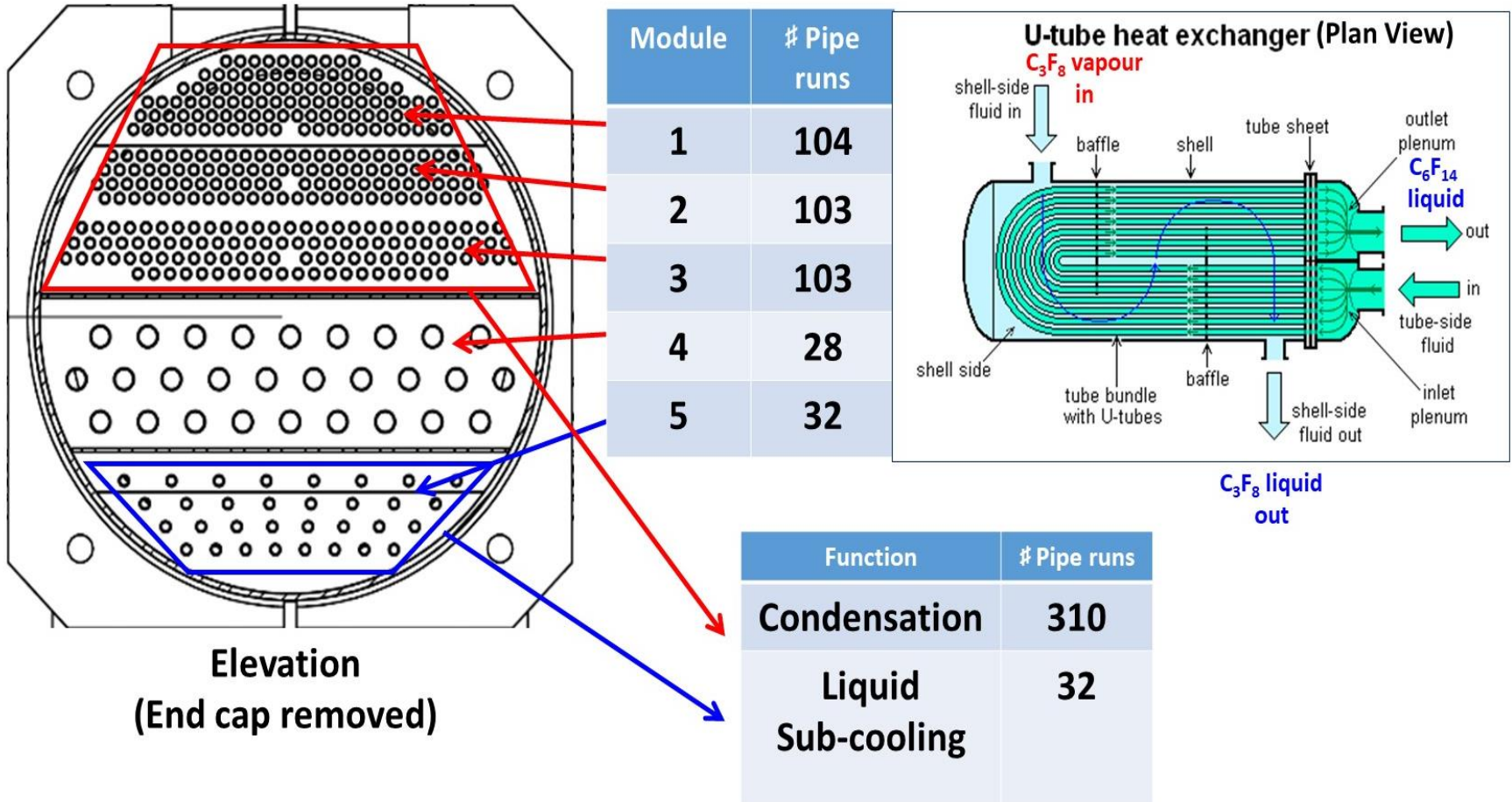

Connection to existing system: 90m underground:
Changeover valves compressors➔ thermosiphon

Water circuit: 90m underground

ATLAS Si tracker thermosiphon C_3F_8 condenser

Elevation
(End cap removed)

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

U-tube heat exchanger (Plan View)

C_3F_8 vapour in — shell-side fluid in — baffle — shell — tube sheet — outlet plenum — C_6F_{14} liquid out — in — tube-side fluid — inlet plenum — shell-side fluid out — baffle — tube bundle with U-tubes — shell side

C_3F_8 liquid out

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 the thermosiphon cycle diagram superimposed on the C_3F_8 ***p-H*** diagram, and particularly at path C➜D we see that considerable thermal energy has to be extracted from the C_3F_8 vapor (in the condenser) to reduce its temperature from around 20 ˚C (the temperature acquired in ascending through more than 92 meters of pipe to the condenser) to -60 ˚C, where phase change can occur under 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;

- 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)

C_3F_8

On –detector Evaporation @ -25°C

Condensation @ -60°C
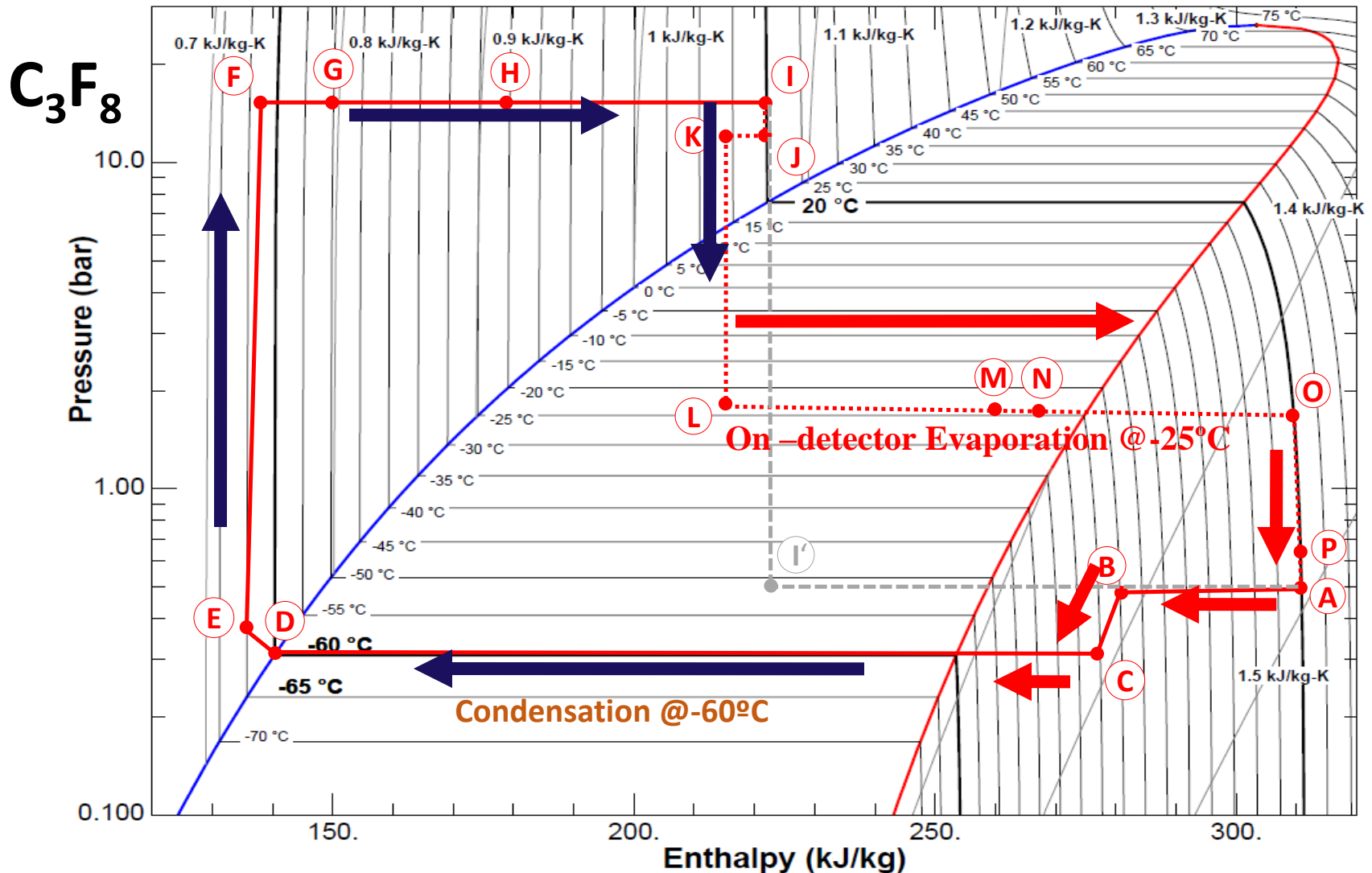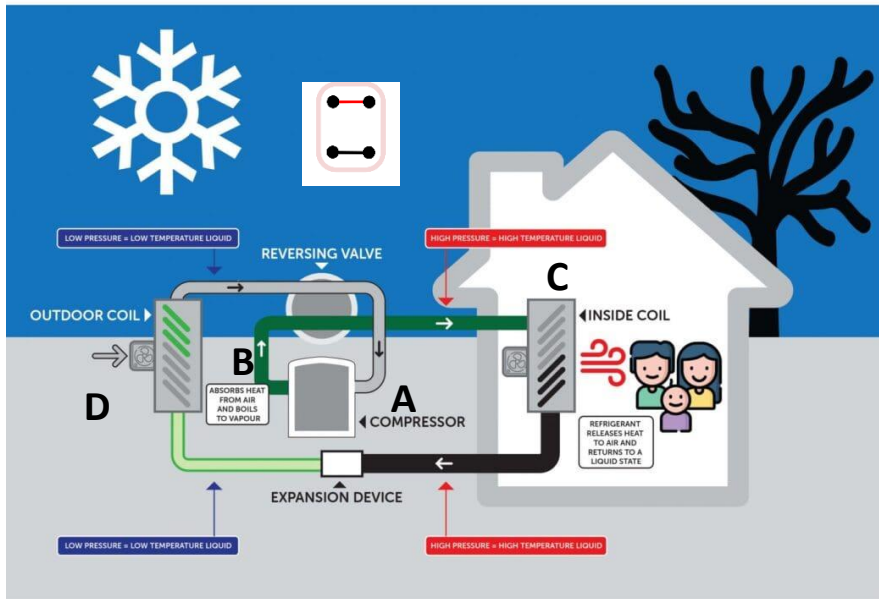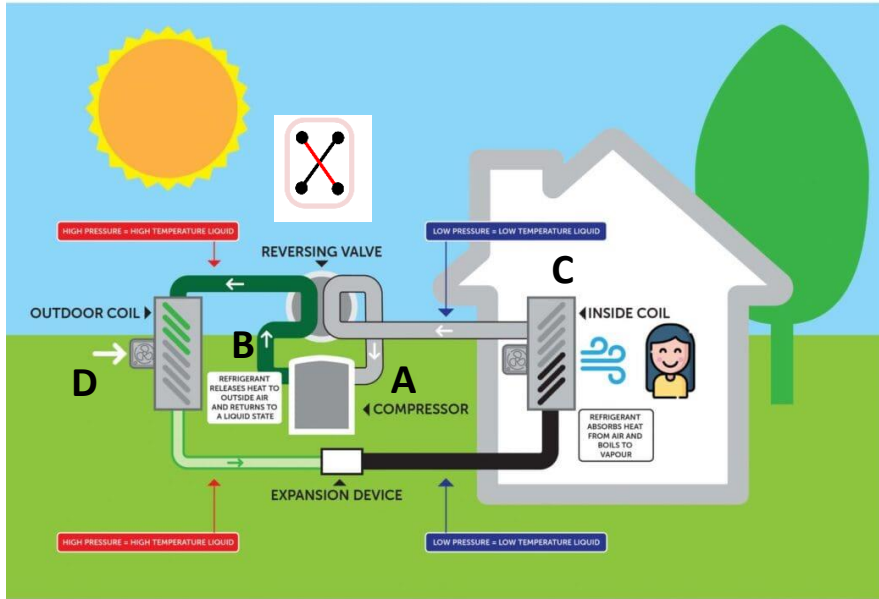
The special component: a (usually electric – driven) fluid "4-way switch"