# Dynamic simulations of Phase-2 detector cooling systems

2022-06-09

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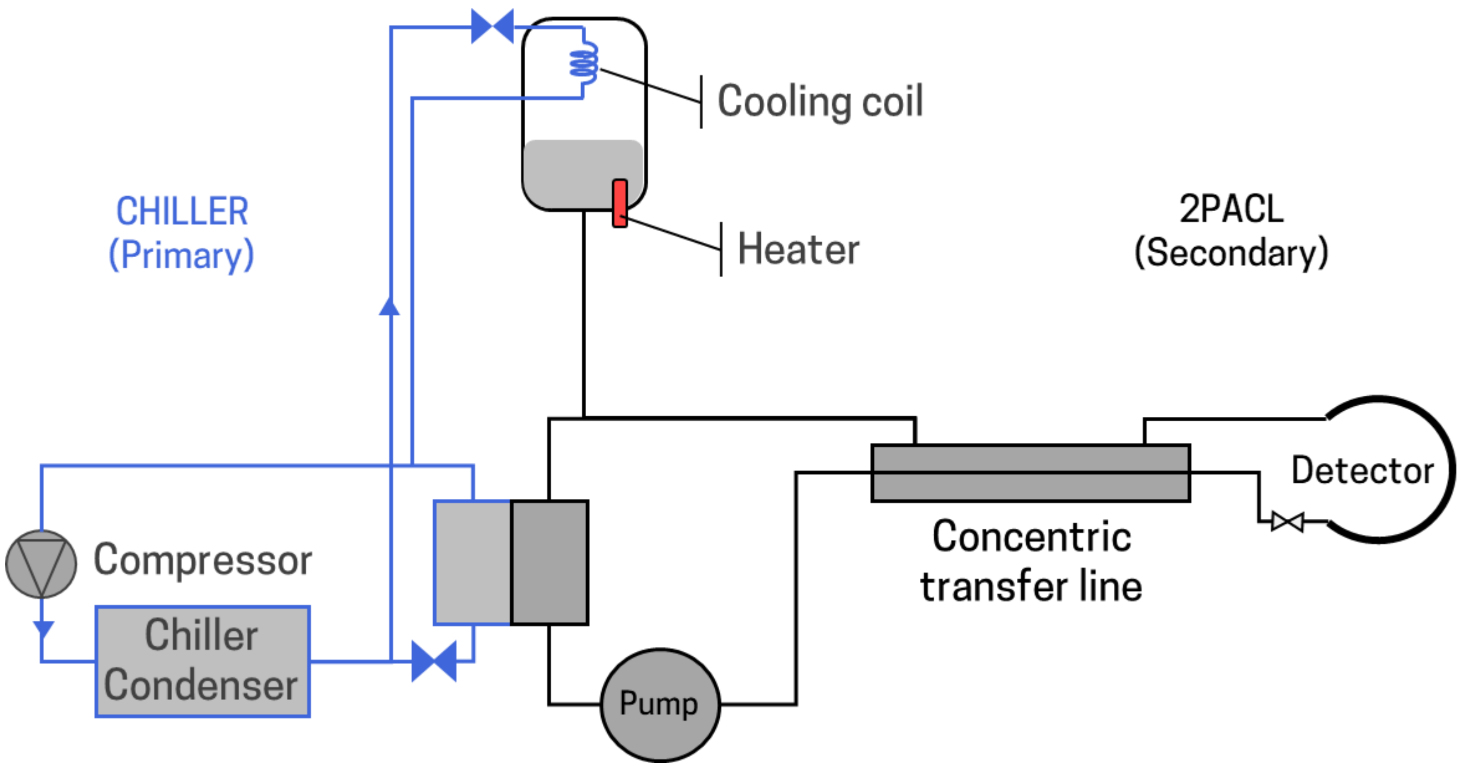
# Context

Past, present and future of Silicon detector cooling

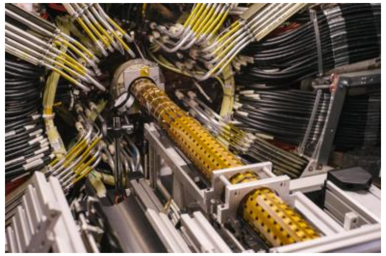
- Silicon detector cooling is hard
  - Low material budget
  - Low temperatures
  - Low thermal gradients
  - Many parallel lines
- CO2 as a working fluid
  - Large latent heat
  - Low pressure drop
  - (and more resistant to it)
  - Small tubes



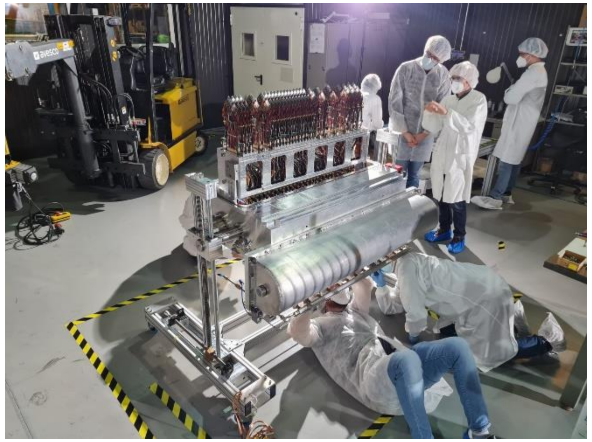

Two-Phase Accumulator Controlled Loops (2PACL)

# The CO2 story

LHCb VTCS



ATLAS IBL



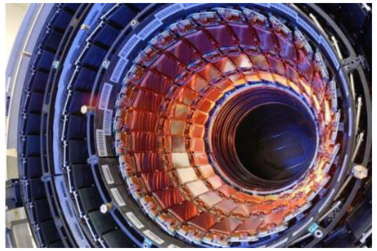
LHCb Velo + UT

Ever bigger and ever colder…

2009 2010 2011 2012 2018 2019 2020 2021+

AMS TTCS

CMS Pixel



# Present

- CMS and ATLAS working towards Phase-2 upgrades

- Phase 2 detector cooling:
  - More (**8x** plants for CMS, **6x** for ATLAS)
  - Larger (up to **70 kW** per plant)
  - Colder (**-45°C** on the Accumulator)
  - Longer (**15-**year lifetime)

- Design changes to 2PACL needed

## Future (aka design changes)

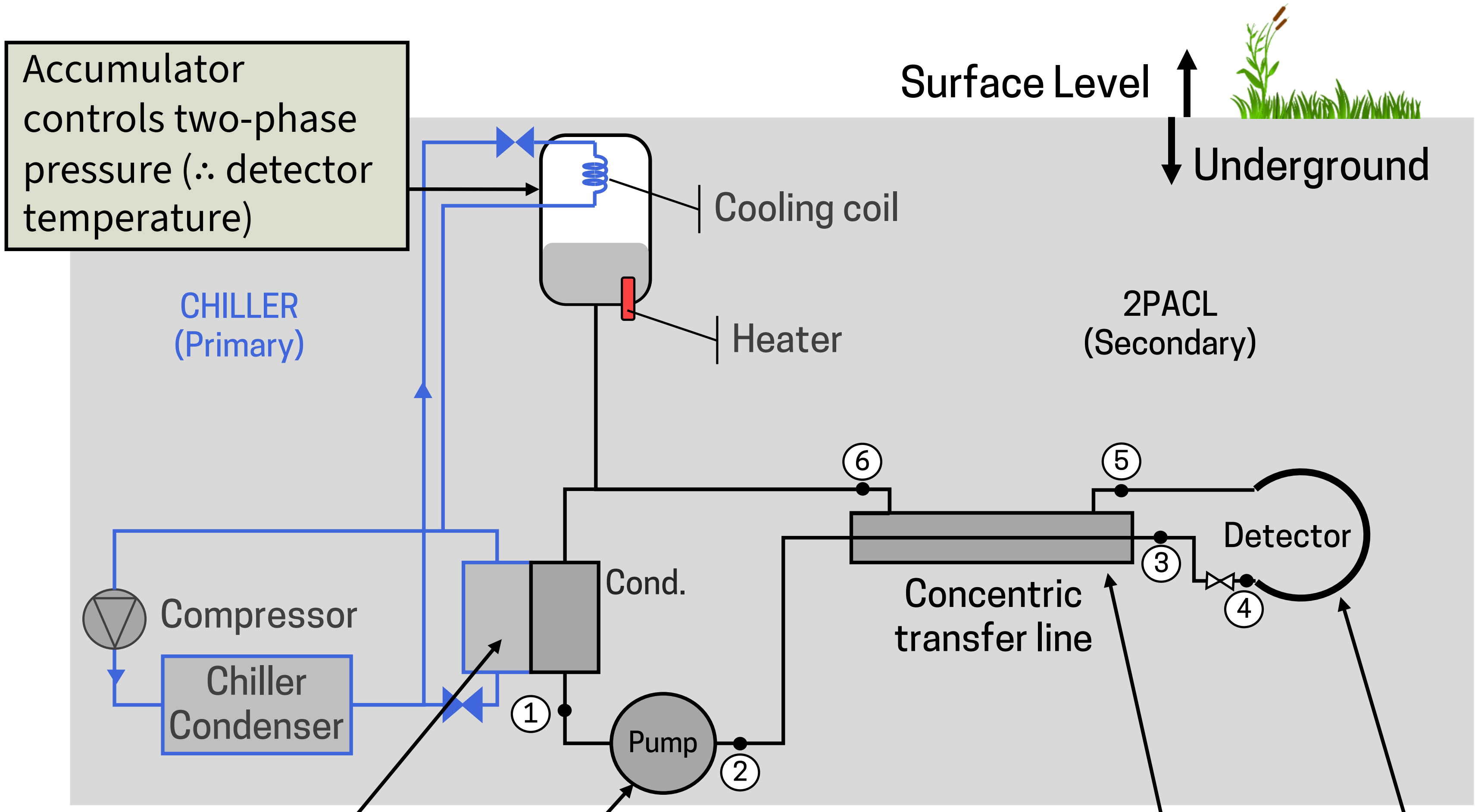
- Impossible to keep all the refrigerant needed underground
  - Large amount of $CO_2$ for detector heat loads (up to 1000 kg per system)
  - Stored Energy = Pressure × **Volume** → Large volumes = safety concern
  - Integration constraints
- Smaller accumulators → change in system startup
- Store excess $CO_2$ on surface → Surface storage
- Surface storage pressure limit → Back pressure regulator
- Many parallel plants → Spare plant (always running)

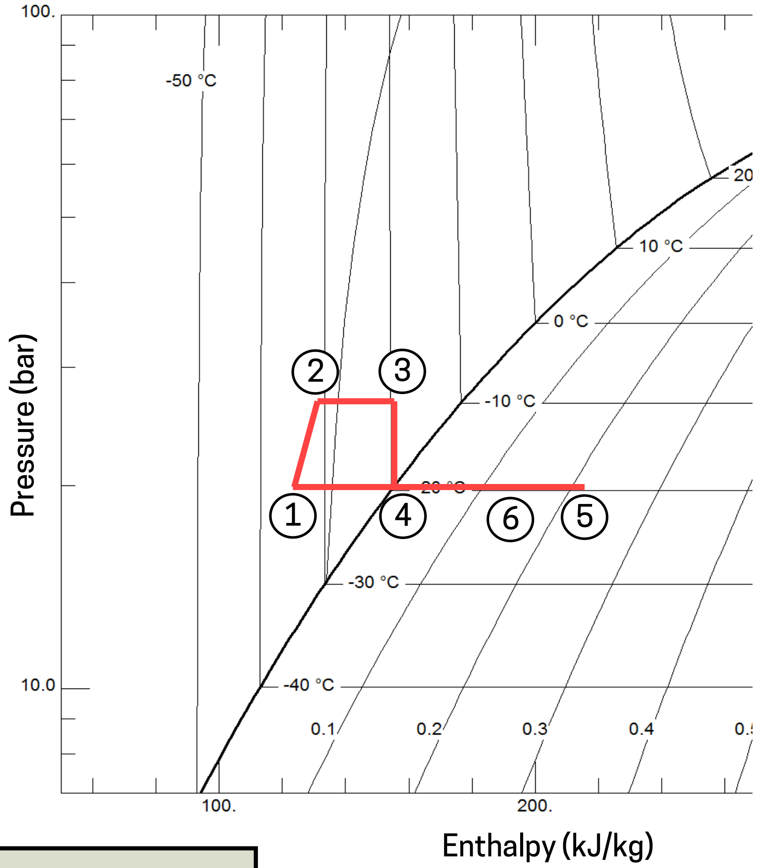
Simulations: help understand new systems

# 2PACL system design

How 2PACL systems used to work, and how they will in the future

# Existing-2PACL systems



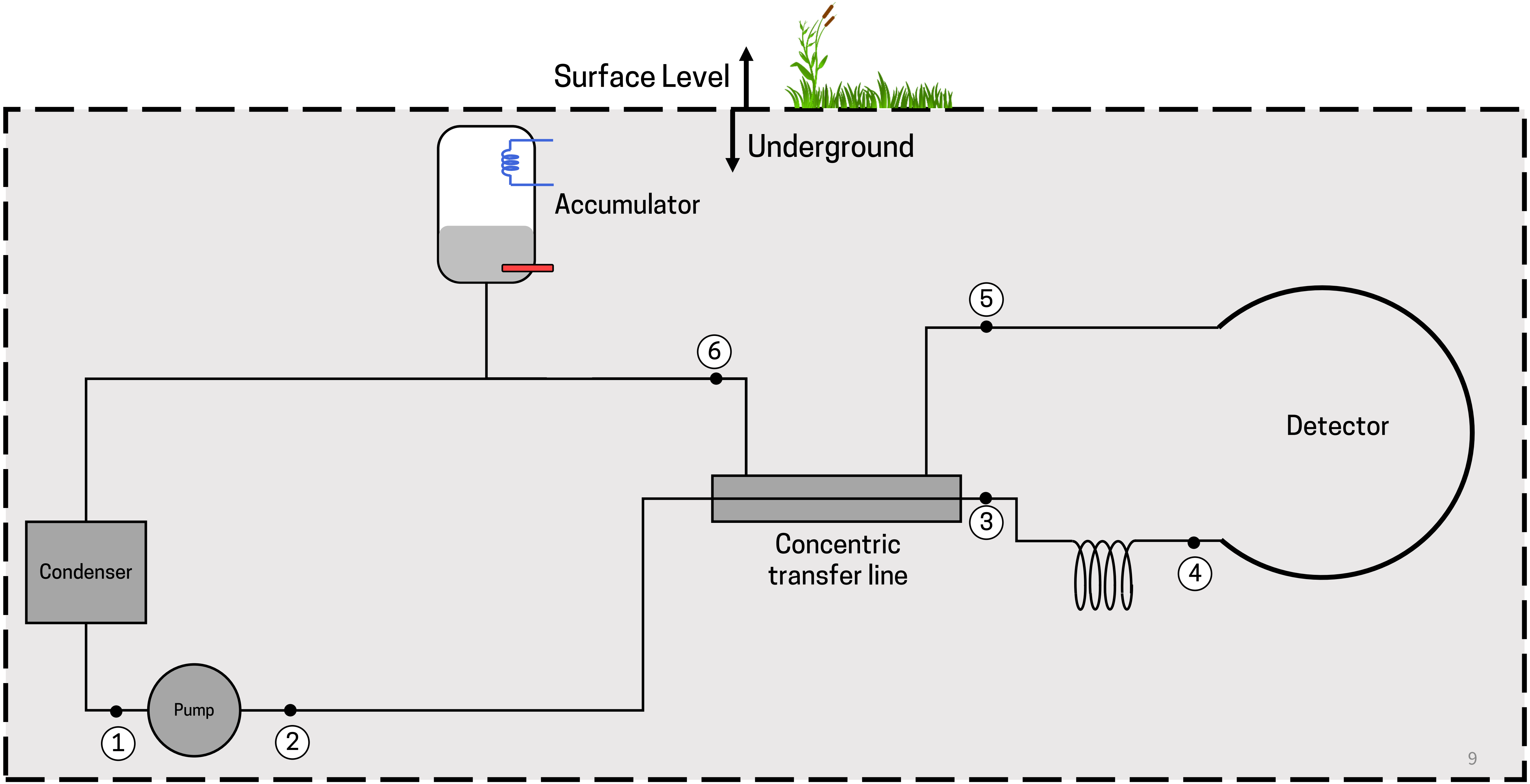

Chiller can cool CO2 as much as it can, Detector will still be at user set-point temperature

Liquid pumped loop

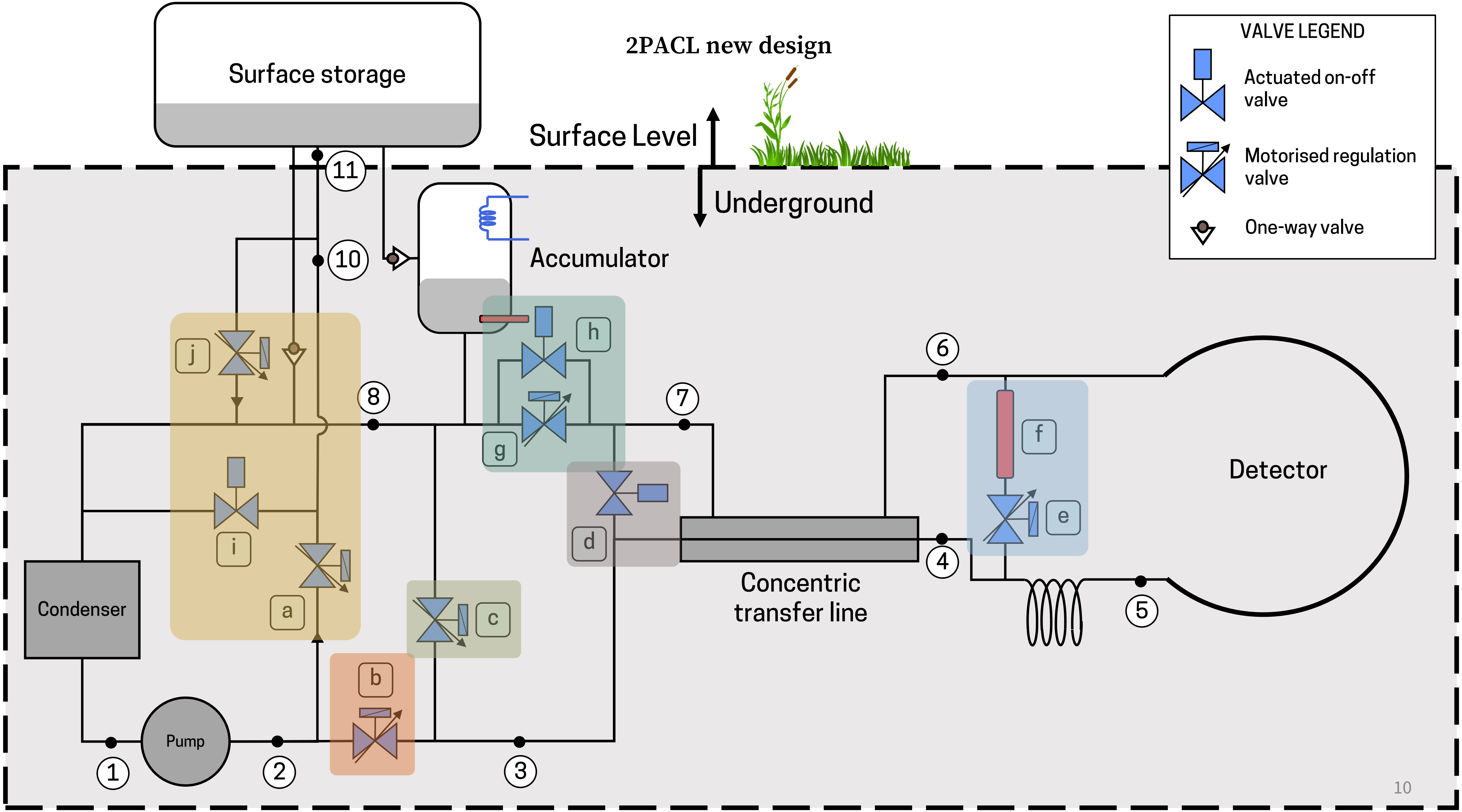
Transfer line heat exchange brings cold refrigerant to saturation temperature

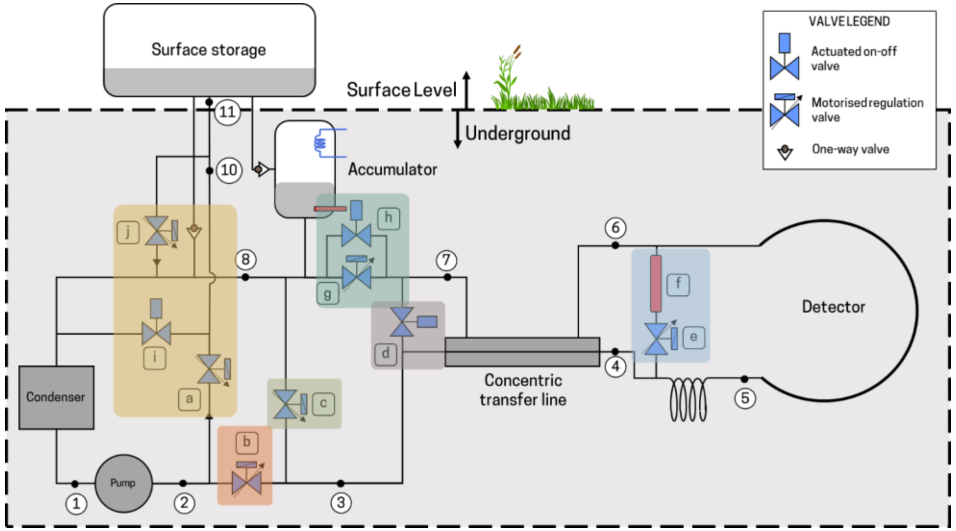
Highly efficient two-phase convective heat transfer in the Detector tubes

# 2PACL existing design



## 2PACL new design






## New design aspects

- Surface storage valves
- Excess refrigerant stored on surface level
- Transport as necessary

- Pump discharge pressure must be higher than surface storage
- Otherwise, cannot pump up to surface

- Controlling detector dP controls detector flow
- Detectors designed for a particular dP.

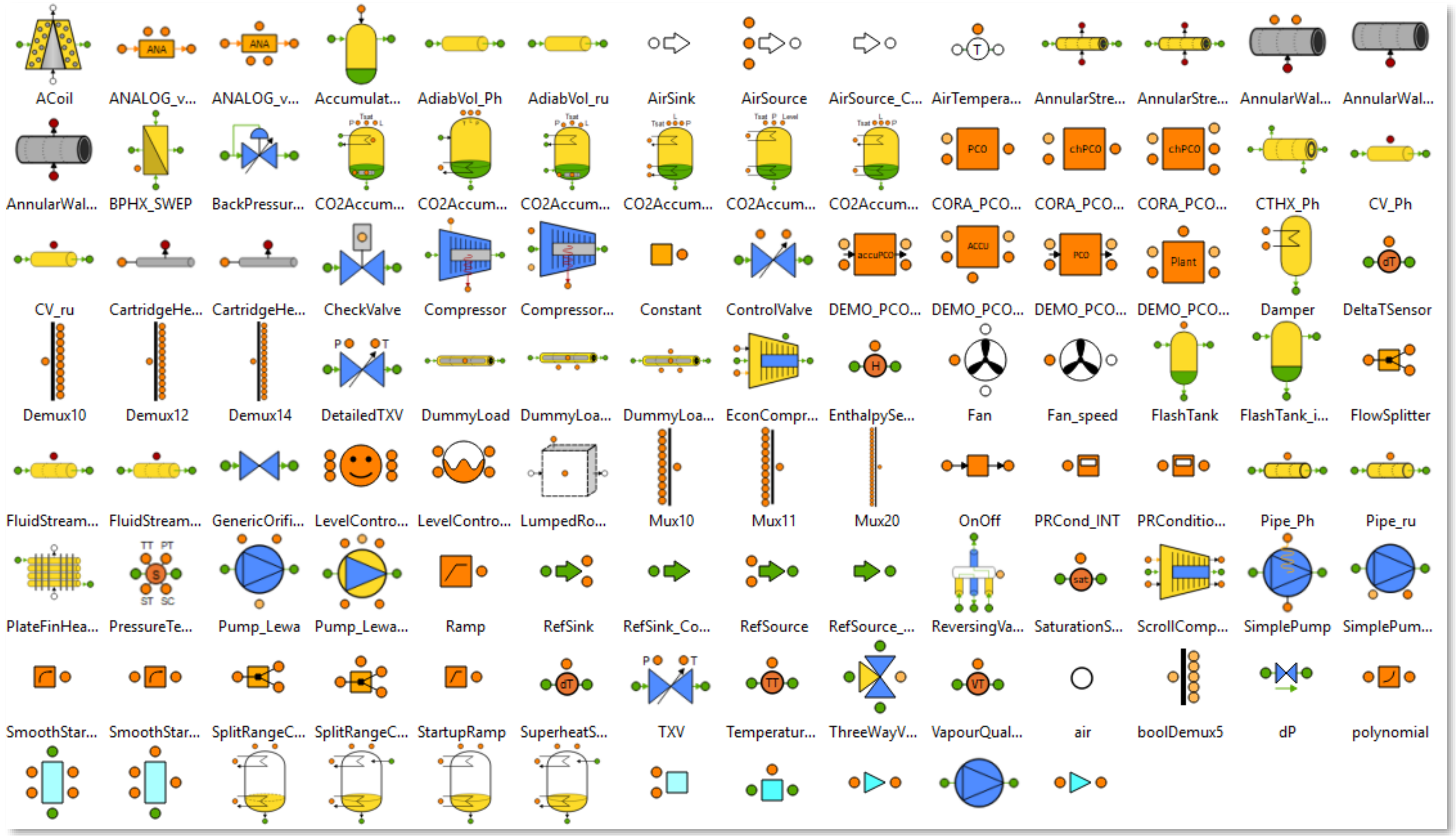
- Provide a pathway for pump flow while we pressurise using back pressure regulator
- Thermal shocks to detector are a bad idea

- Pre-vapourisation allows the Accumulator filling up to be split into 2 parts
- Easier for level controller
- Smaller Accumulator

- Back pressure regulator to raise detector pressure above Accumulator
- Accu pressure < Surface storage pressure

# Simulation tool

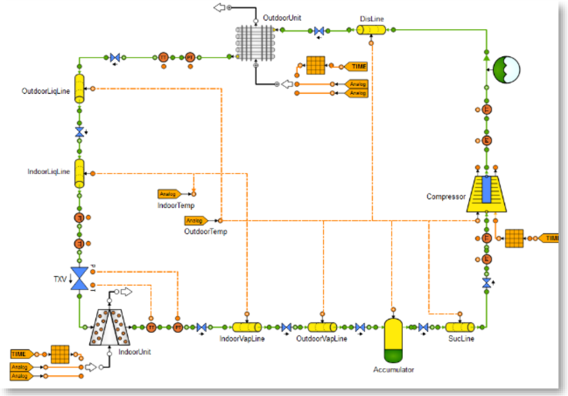
- Component library in EcosimPro for modelling/simulating detector cooling systems
- Expands on Cryolib (by CERN Cryo)
- Validated against 3 sets of measured data (3 different systems)
- Startup, shutdown, step changes…

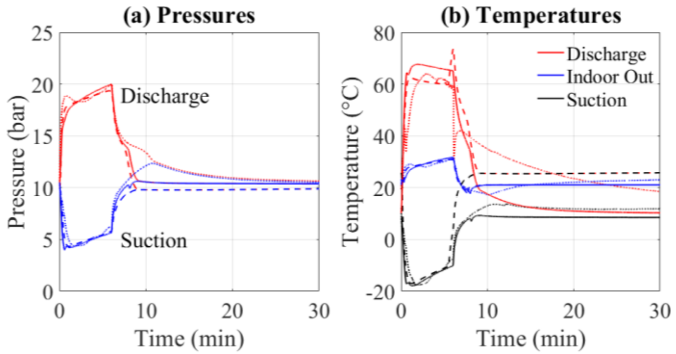


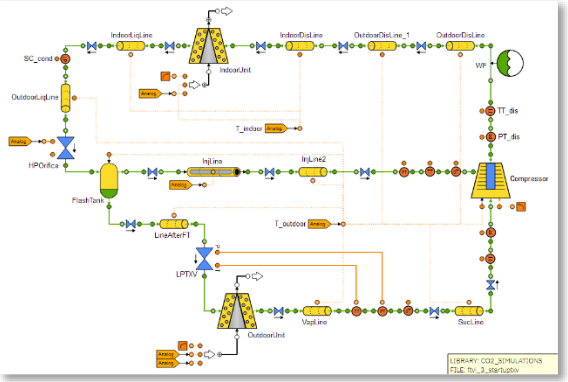
## Heat Pump Cycles

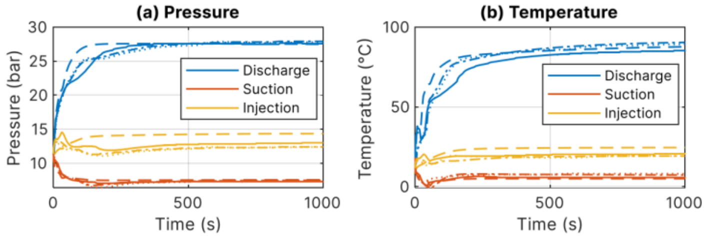
# The validations

## 2PACL Cycles



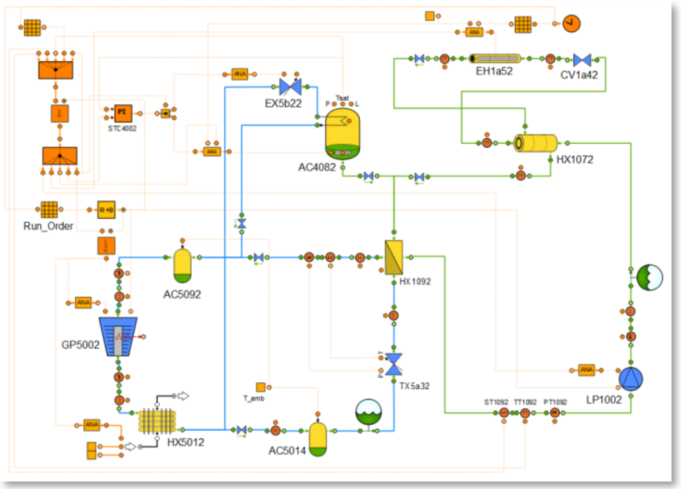



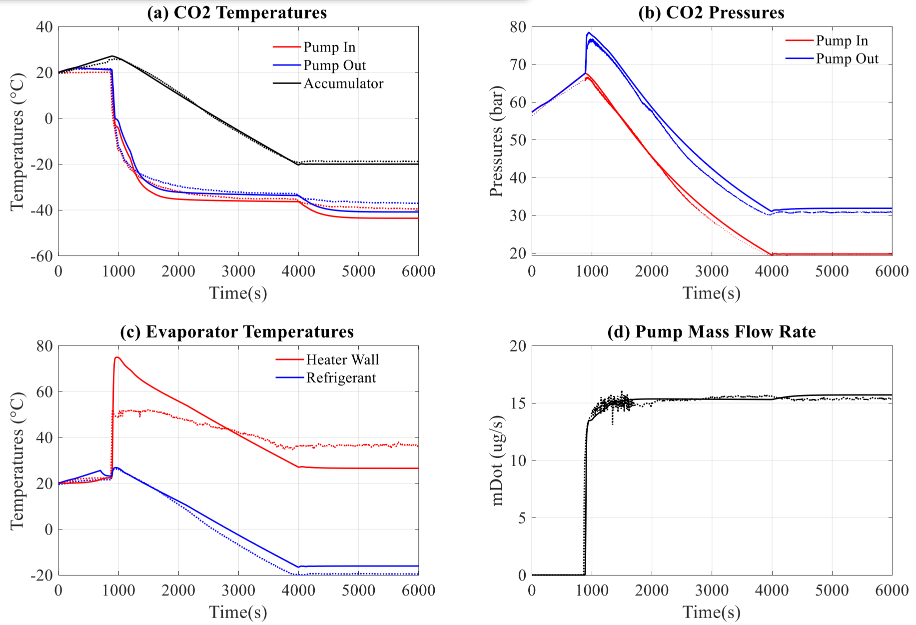




V. Bhanot, R. Dhumane, P. Petagna, A. Cioncolini, H. Iacovides, J. Ling, V. Aute, **Development of a Numerical Tool for Dynamic Simulations of Two-Phase Cooling Systems**, Int. j. Simul. Model. 18 (2019) 302–313. https://doi.org/10.2507/IJSIMM18(2)476.

Bhanot, Viren; Petagna, Paolo; Cioncolini, Andrea; Ling, Jiazhen; and Aute, Vikrant, "**Modelling and Simulation of a Flash Tank Vapour Injection Heat Pump in Several Platforms**" (2021). International Refrigeration and Air Conditioning Conference, Purdue, Paper 2170



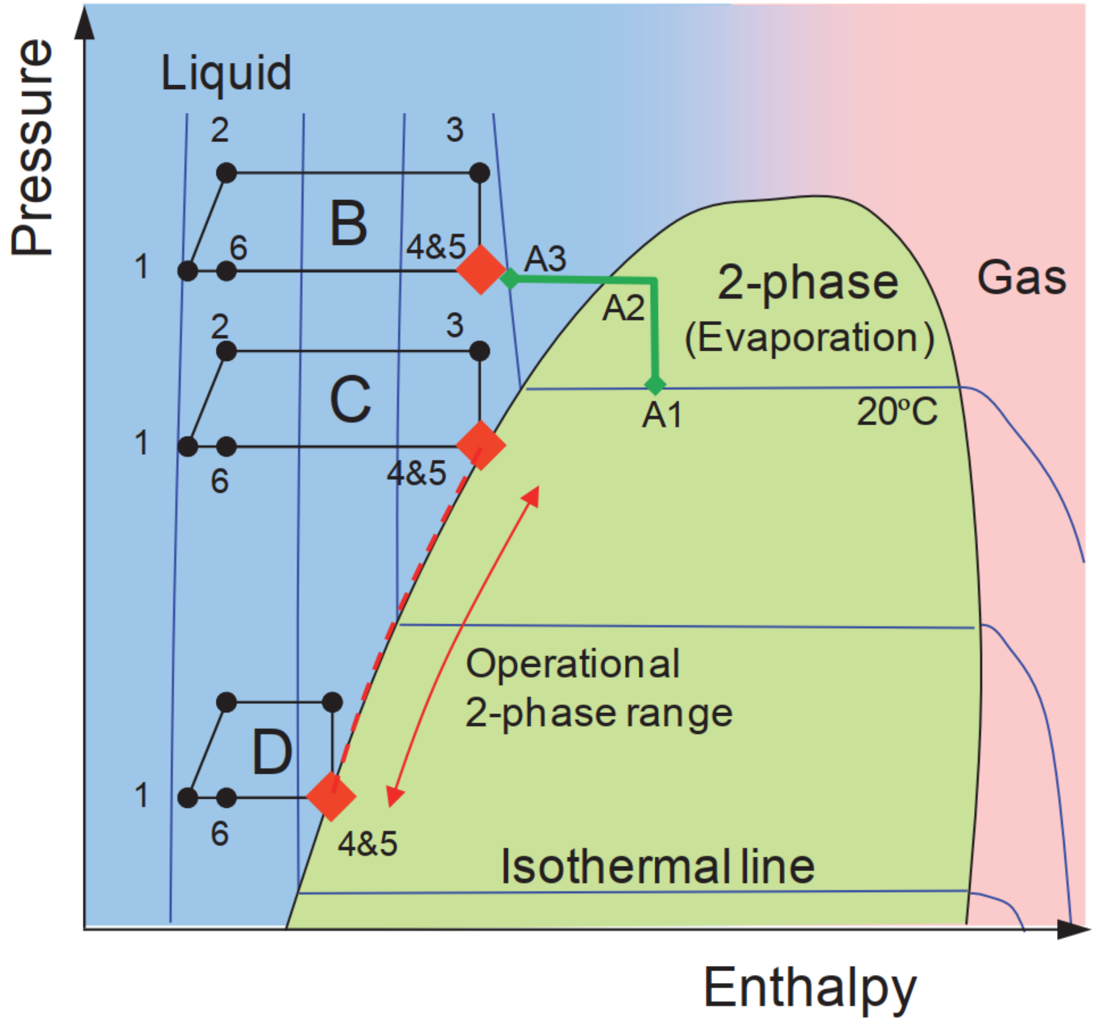




Bhanot, P. Petagna, A. Cioncolini, H. Iacovides, **Development and validation of a simulation tool for next generation detector cooling systems**, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment. 955 (2020) 163264. https://doi.org/10.1016/j.nima.2019.163264.

# New 2PACL simulations

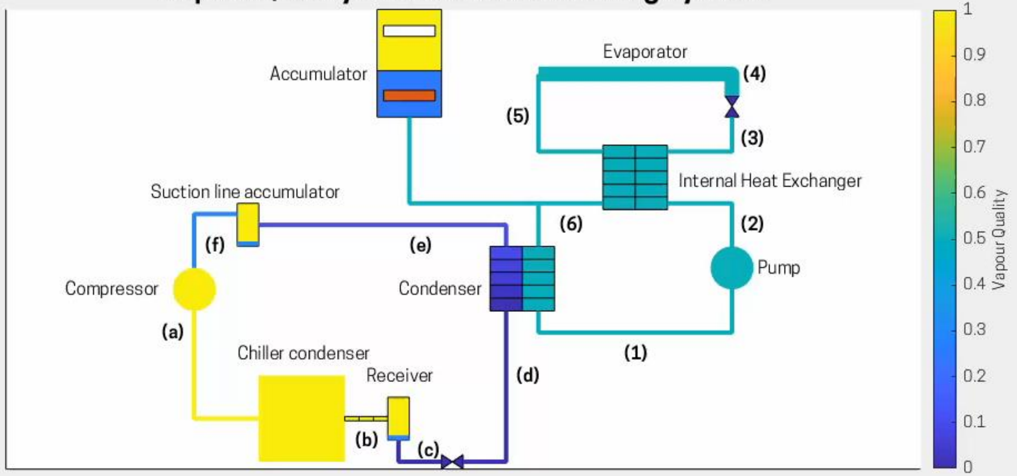
Startup, set-point change, power-cycle

- The problem of startup:
  - Diaphragm pumps cannot pump vapour → liquefy refrigerant at pump inlet
  - Detectors hate thermal shocks → change temperature gradually
- CO2 during off-period:
  - Two-phase state (undefined exactly)
  - Fluid pressure corresponds to ambient temperature
- Existing system startup:
  - Pressurise whole system by Accumulator
  - Liquefy detector and pump inlet together

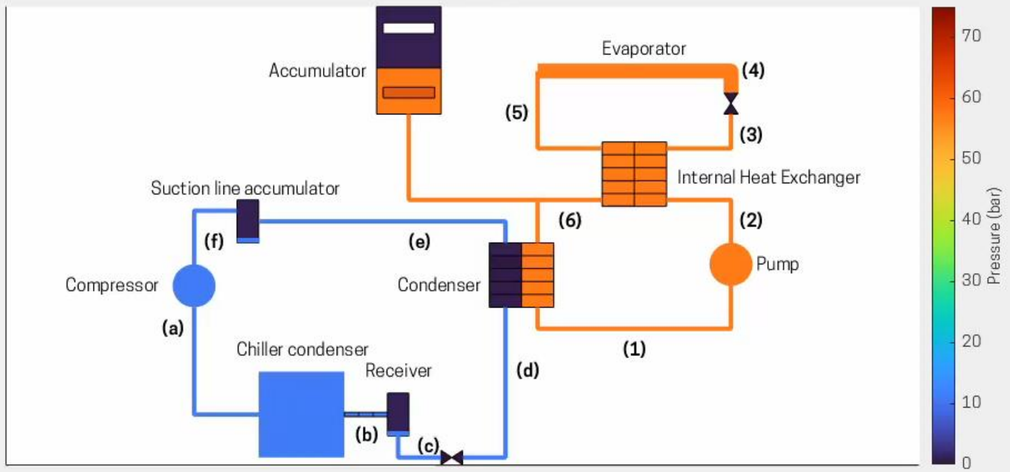



Thome, John R., ed. *Encyclopedia Of Two-phase Heat Transfer And Flow Iv: Modeling Methodologies, Boiling Of Co2, And Micro-two-phase Cooling (A 4-volume Set)*. World Scientific Publishing, 2018.

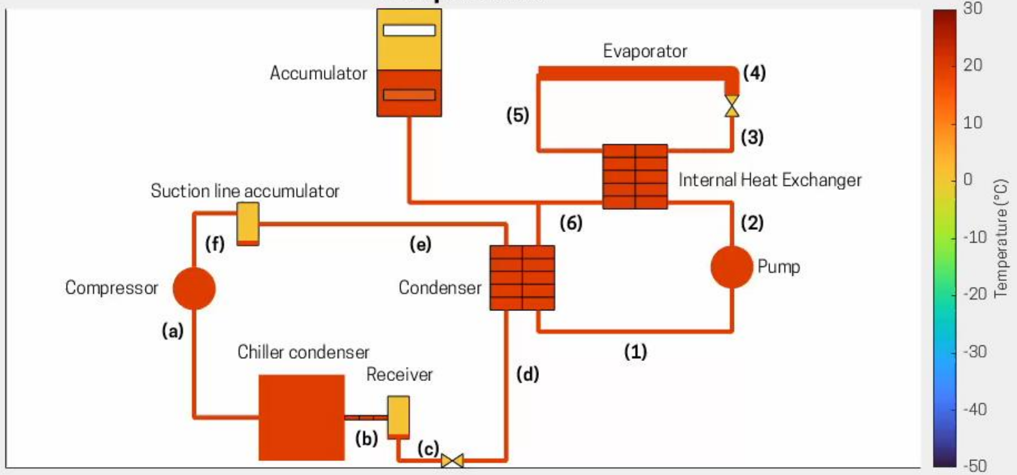
Vapour Quality. Time: 0 s Pressurising system



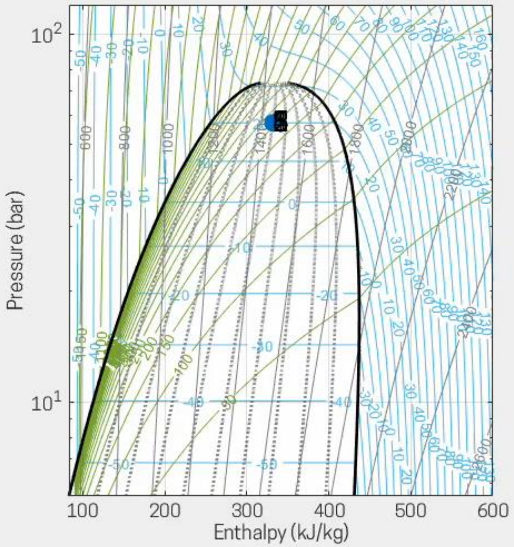

Pressure



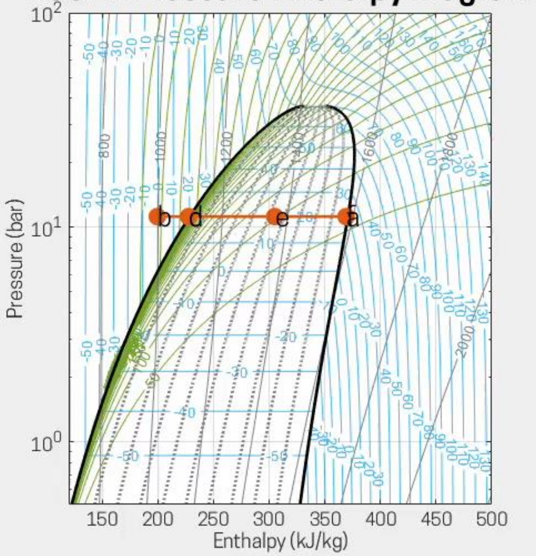

Temperature




CO2 Pressure-Enthalpy Diagram



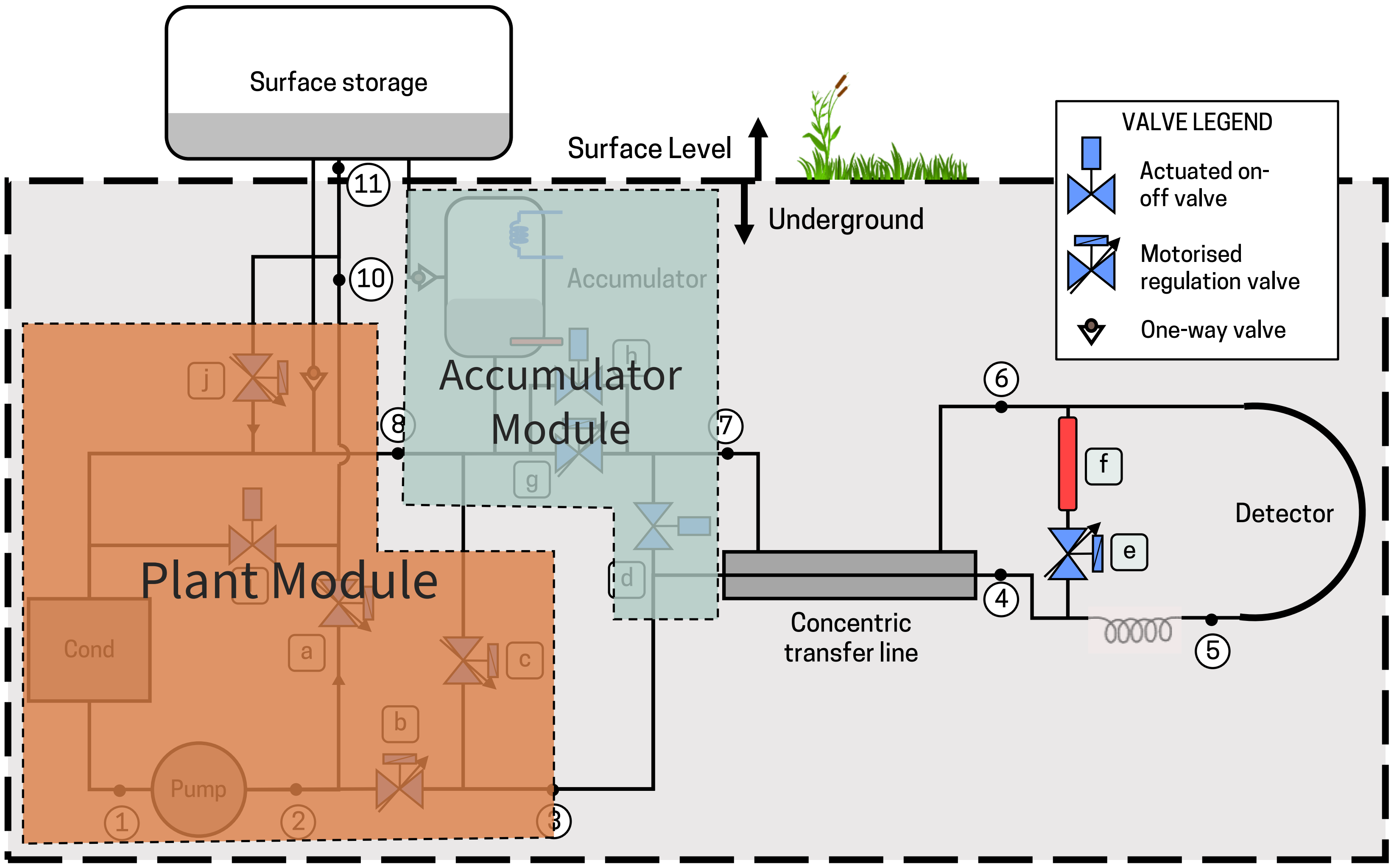

R507A Pressure-Enthalpy Diagram



**Accumulators are now not big enough to pressurise the whole system**

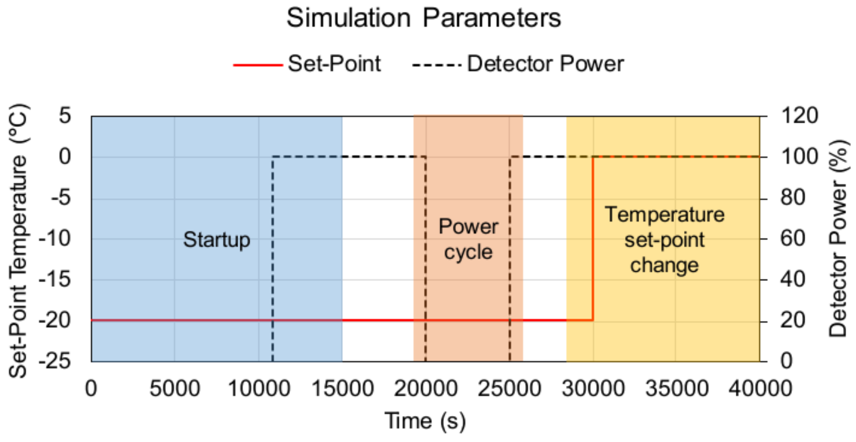
# New startup

- Stage 1: Liquefy pump inlet
  - Allow pump start
  - Plant acts as ‘actuator’ for Accumulator
- Stage 2: Liquefy detector
  - Prevent thermal shock
  - Accumulator controls pump flow to detector
  - Pressurisation via back pressure regulator
- Stage 3: Cooldown and power-on

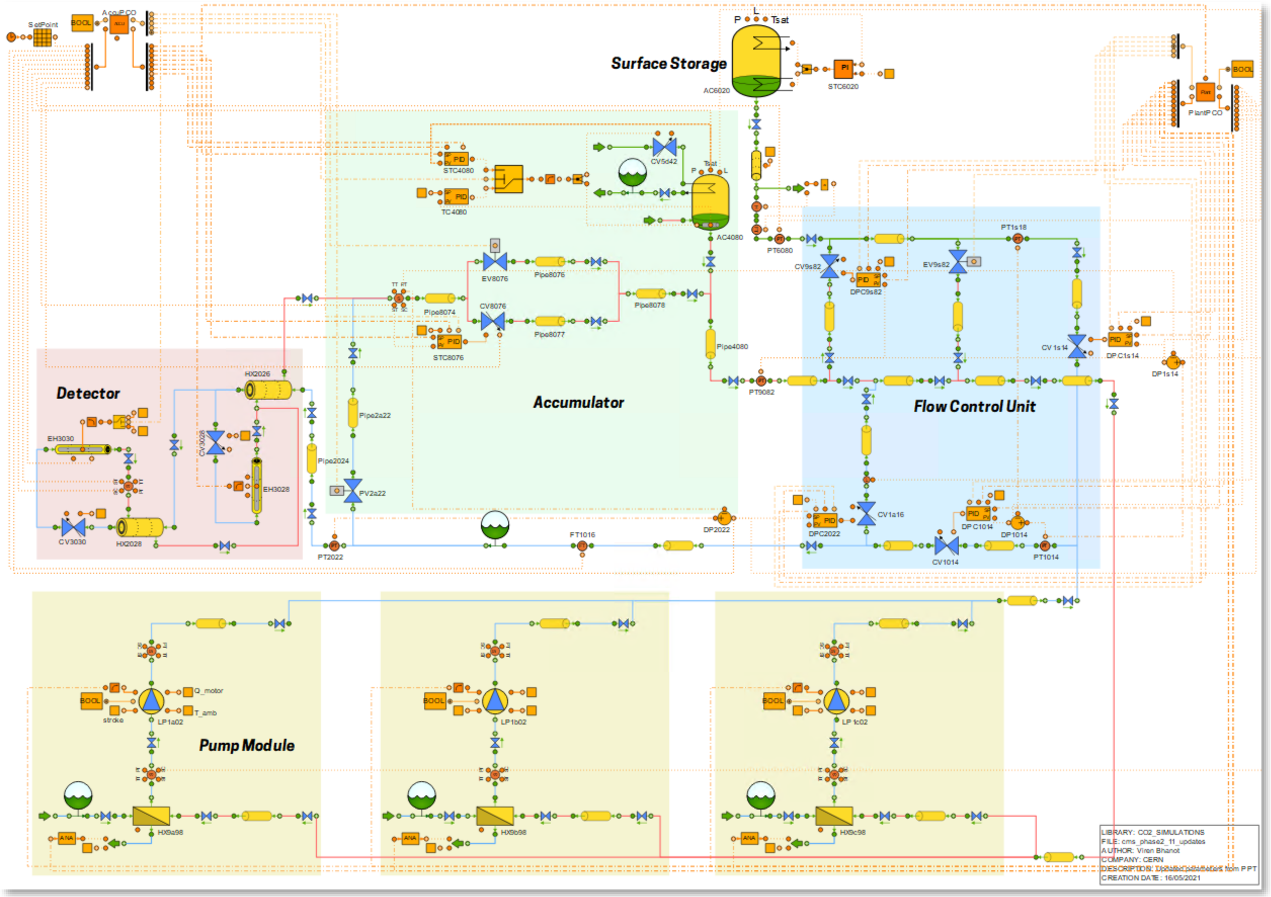


- CMS TK1 modelled *(kind of)*
- DTL and MTL models: single long line with cumulative volume
- Poor detector mechanics model
  - Parallel lines not modelled
  - Single long line
  - Goal is to study CO2 side initially,

| Parameter | Value | Units |
|---|---|---|
| Initial system pressure | 58 | bar |
| Initial system vapour quality | 0.5 | kg/kg |
| Initial surface storage pressure | 20 | bar |
| Initial surface storage level | 10 | % |
| Detector heat load | 72 | kW |
| Bypass heater power | 22 | kW |
| Surface storage volume | 10 | m3 |
| Accumulator volume | 440 | L |
| Main Transfer Line return volume | 197 | L |
| Detector transfer line return volume | 133 | L |
| Detector volume | 48 | L |




**Simulation Model**

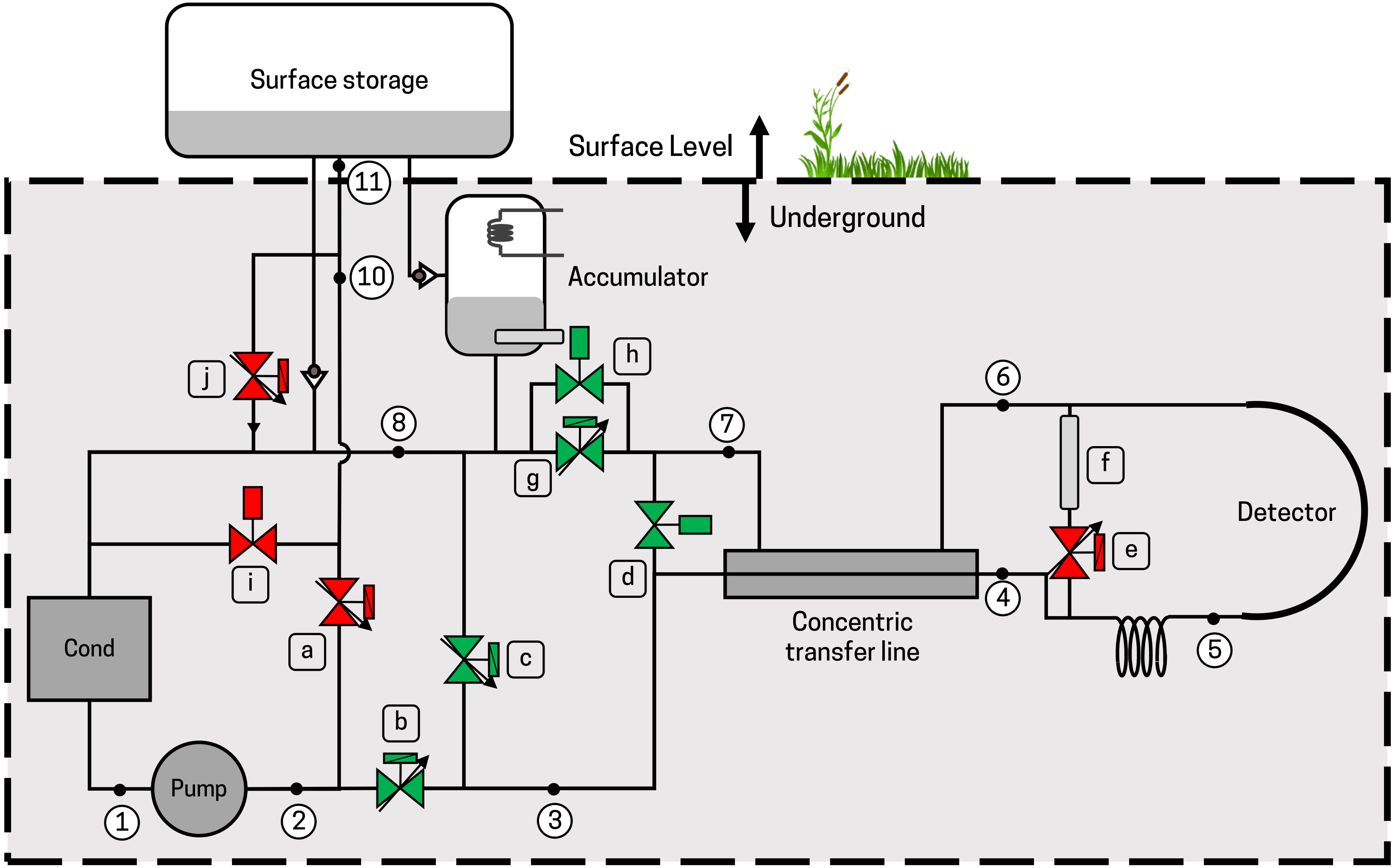


## Plant Startup

**(plant is just an ‘actuator’ for the Accumulator)**

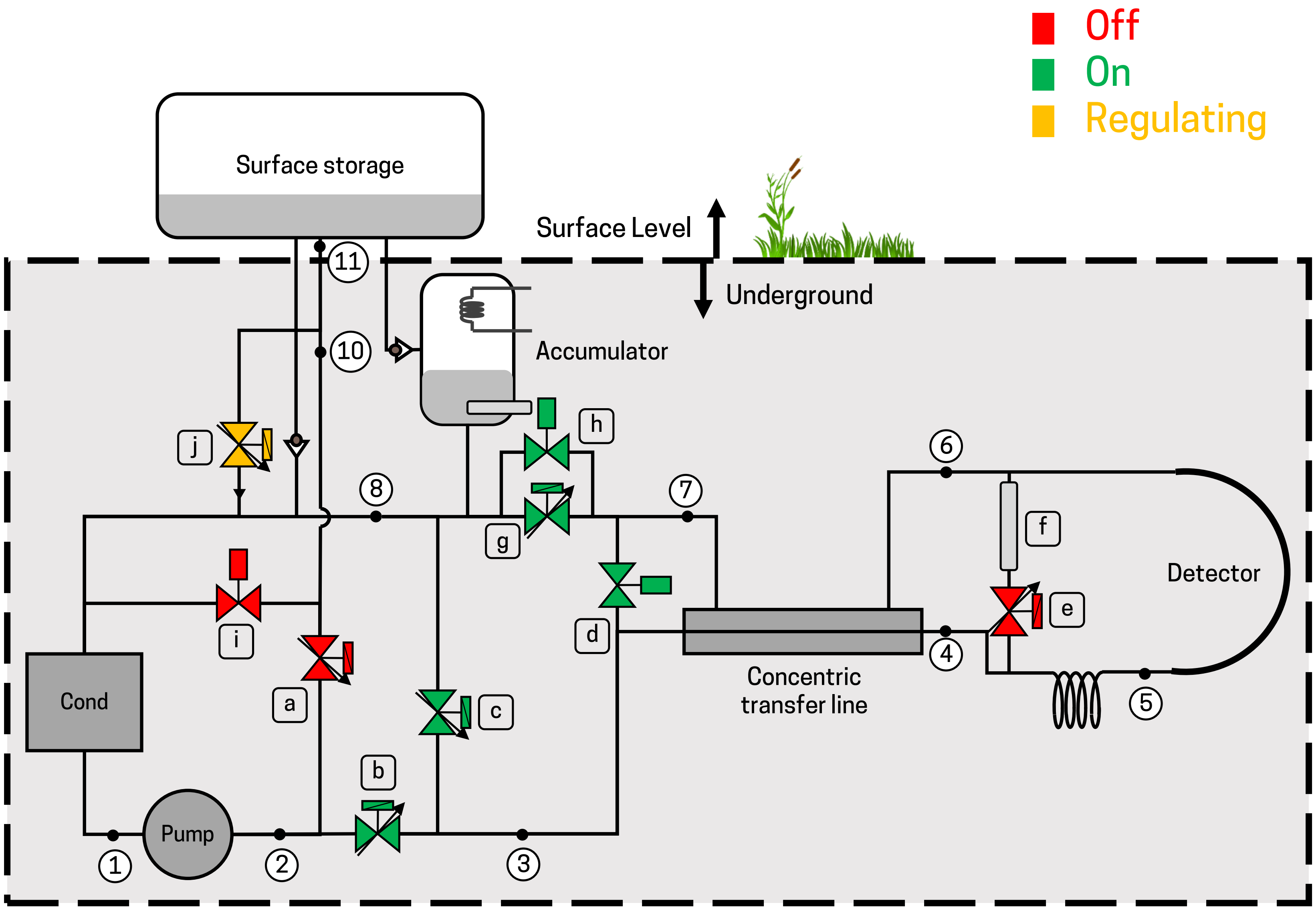
# New startup

- Step 0: Safety position
- Keep surface storage disconnected
- Keep everything else open
  - avoid liquid traps
  - everything at the same pressure

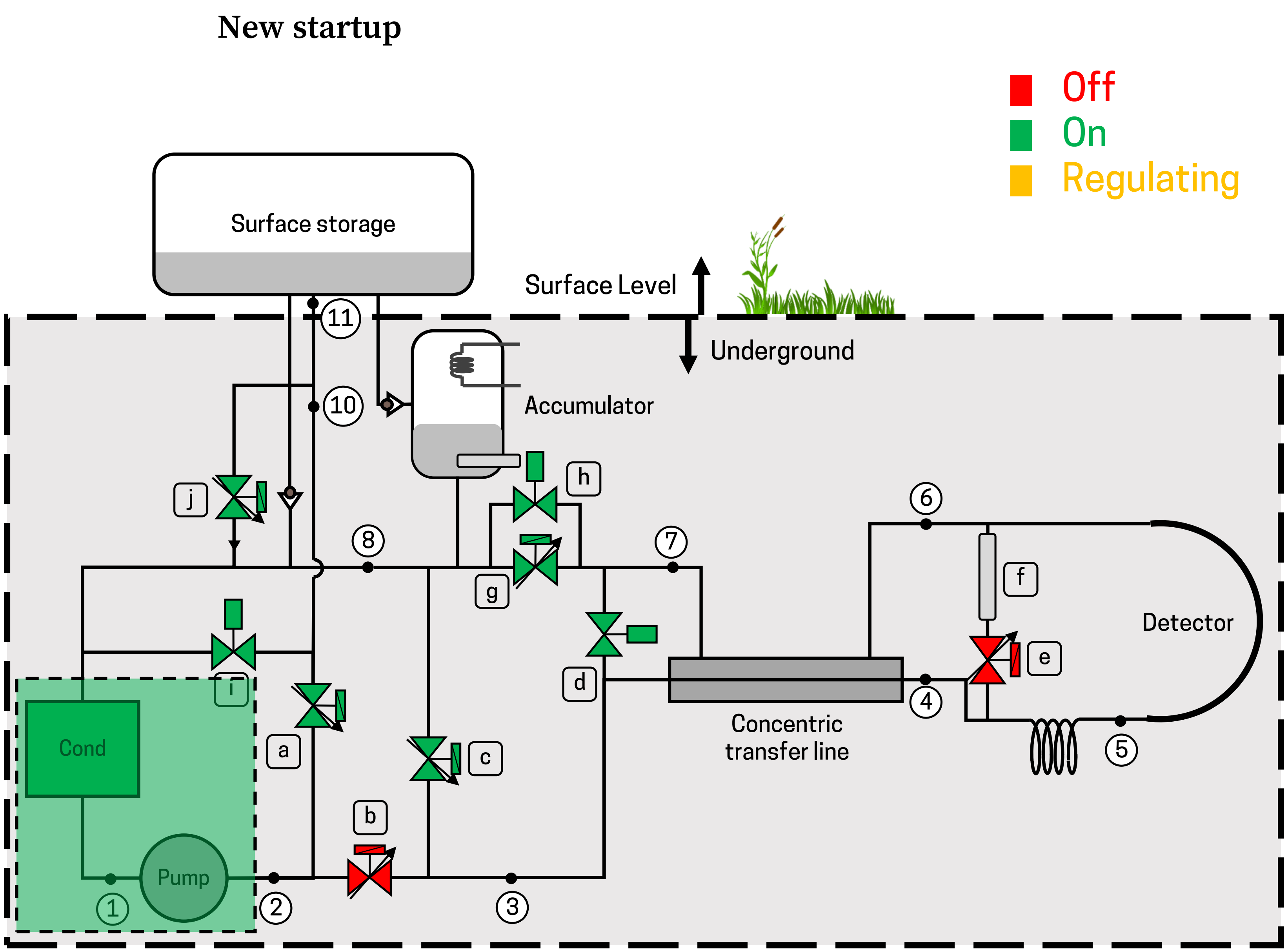


# New startup

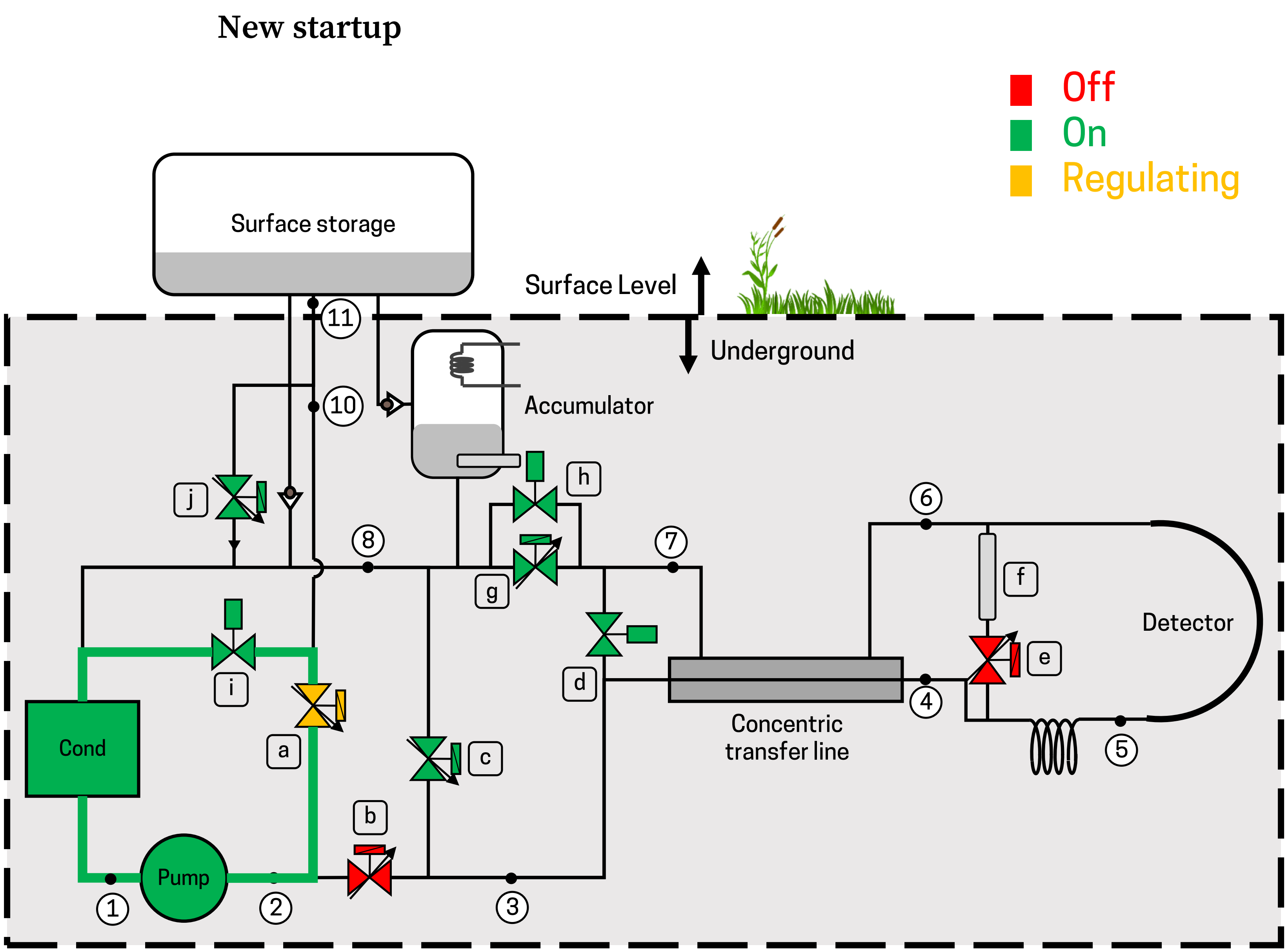
- Step 1: Equalise pressure
- Open plant to surface storage
  - Start from a defined state
- Surface storage will act as Accumulator



- Step 2: Liquefy pump inlet
- Turn on coldbox cooling
  - Condenser
  - Pump inlet
- We obtain subcooled liquid at pump inlet
- Ready to start circulation

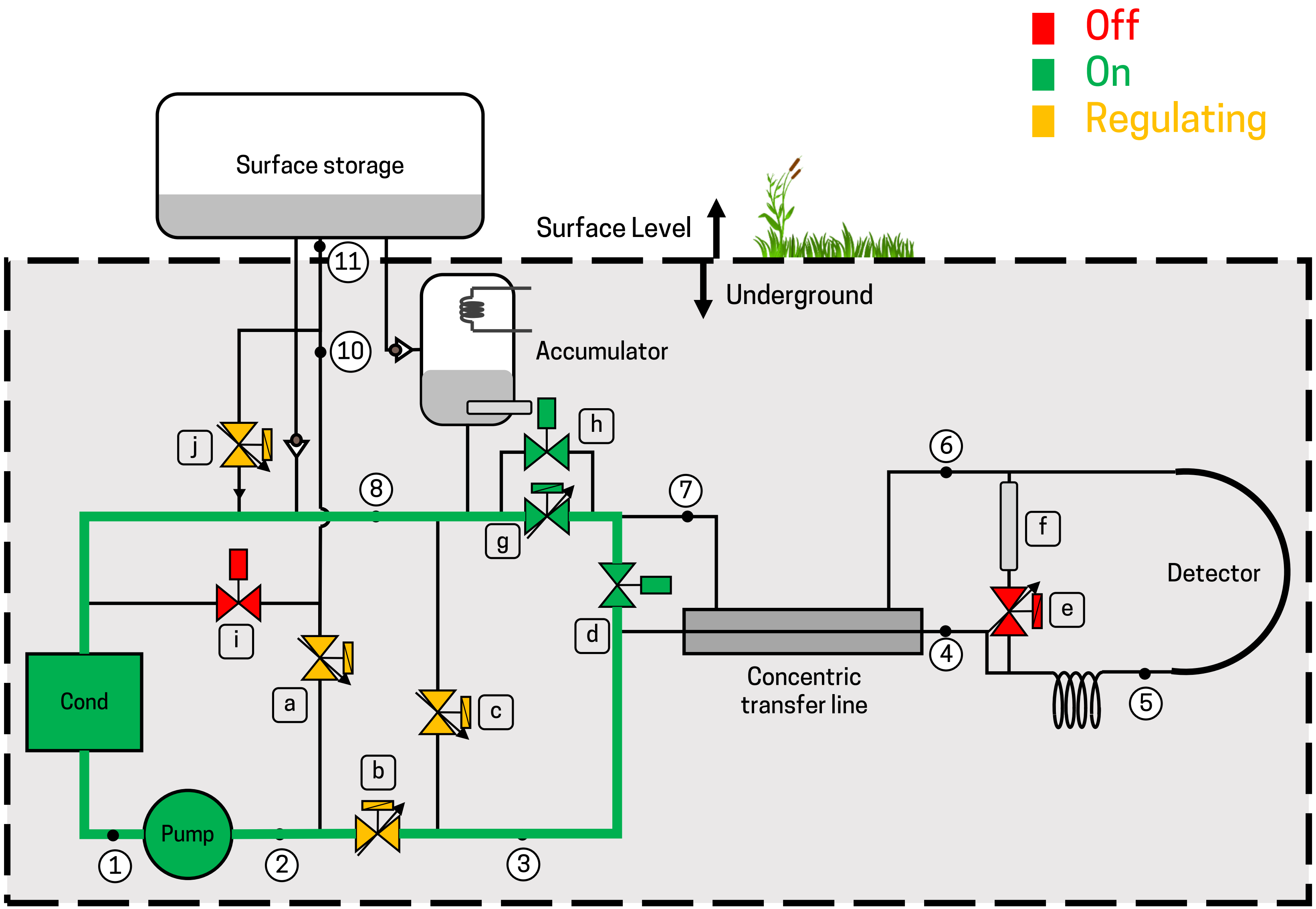


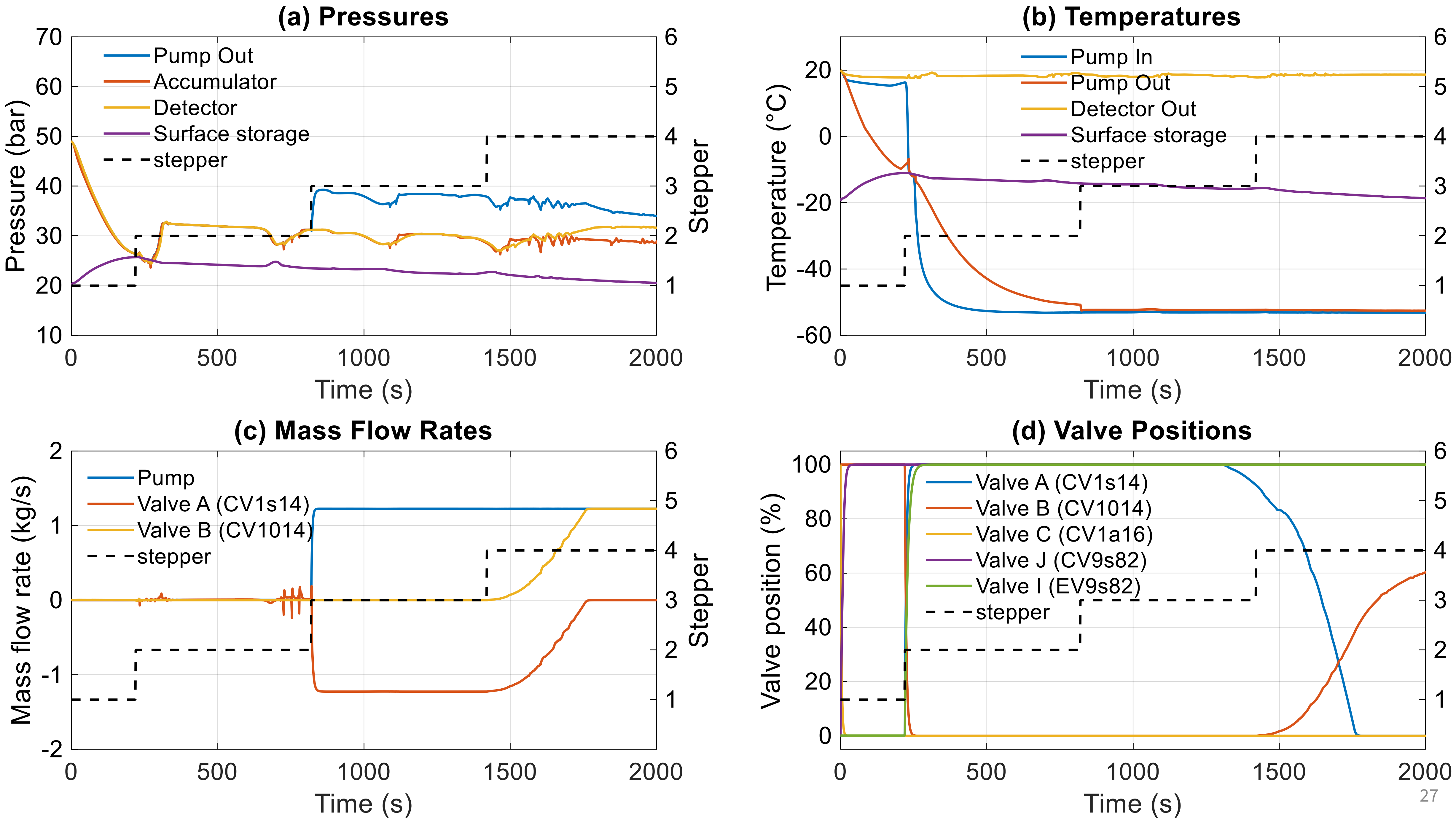
- Step 3: Turn on pump
- Not yet ready to send to detector!
- Circulate locally
- Get stable flow, subcool at pump inlet



# New startup

- Step 4: Supply liquid
- Send liquid towards Accumulator
- Slowly steal from local bypass
- Surface storage valves ready for level control
- Pump module has done its job





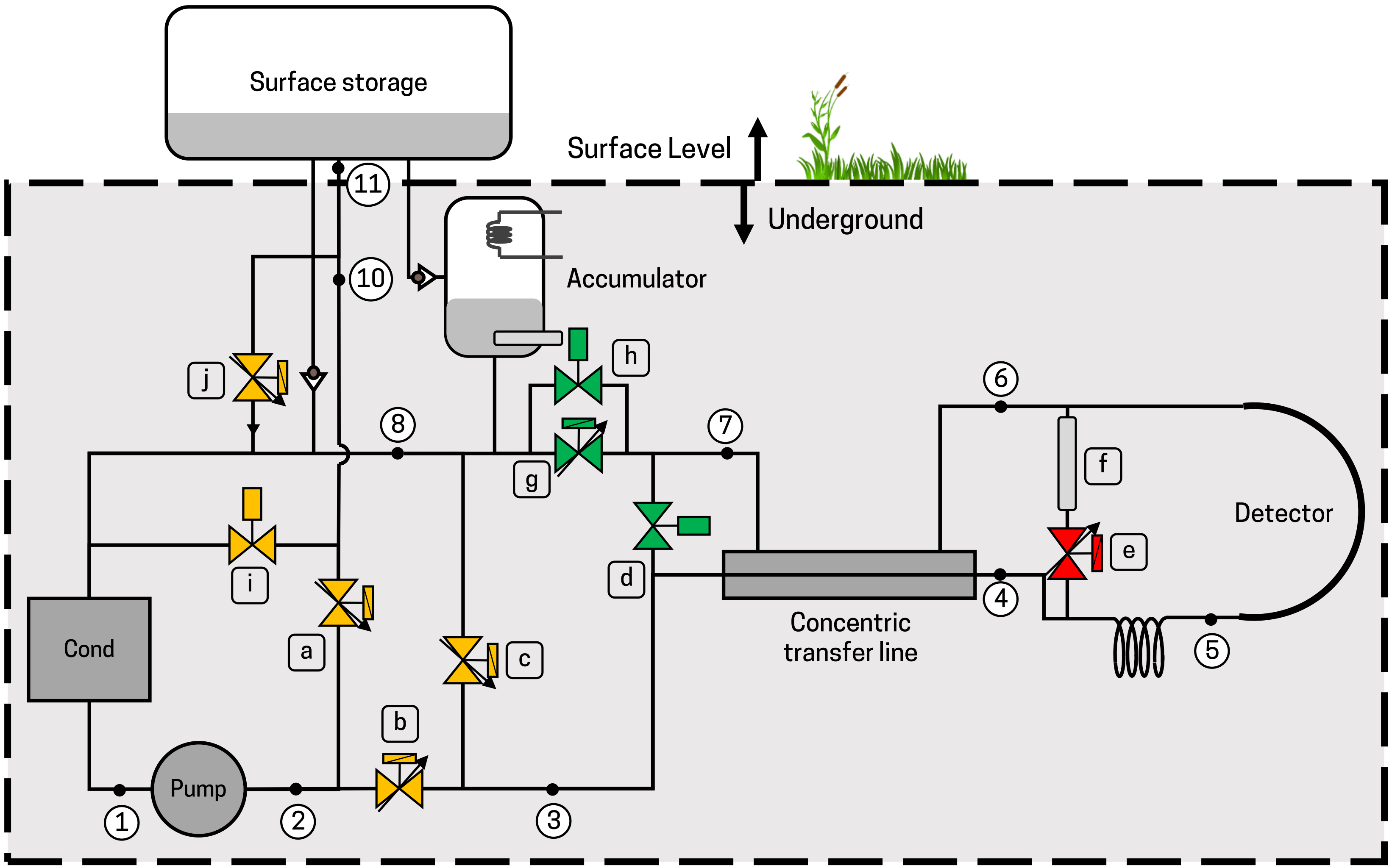
(a) Pressures
Pressure (bar)
Stepper
Time (s)
Pump Out
Accumulator
Detector
Surface storage
stepper
(b) Temperatures
Temperature (°C)
Stepper
Time (s)
Pump In
Pump Out
Detector Out
Surface storage
stepper
(c) Mass Flow Rates
Mass flow rate (kg/s)
Stepper
Time (s)
Pump
Valve A (CV1s14)
Valve B (CV1014)
stepper
(d) Valve Positions
Valve position (%)
Stepper
Time (s)
Valve A (CV1s14)
Valve B (CV1014)
Valve C (CV1a16)
Valve J (CV9s82)
Valve I (EV9s82)
stepper

**Accumulator startup**

**(Goal is to liquefy detector and then cool it down)**

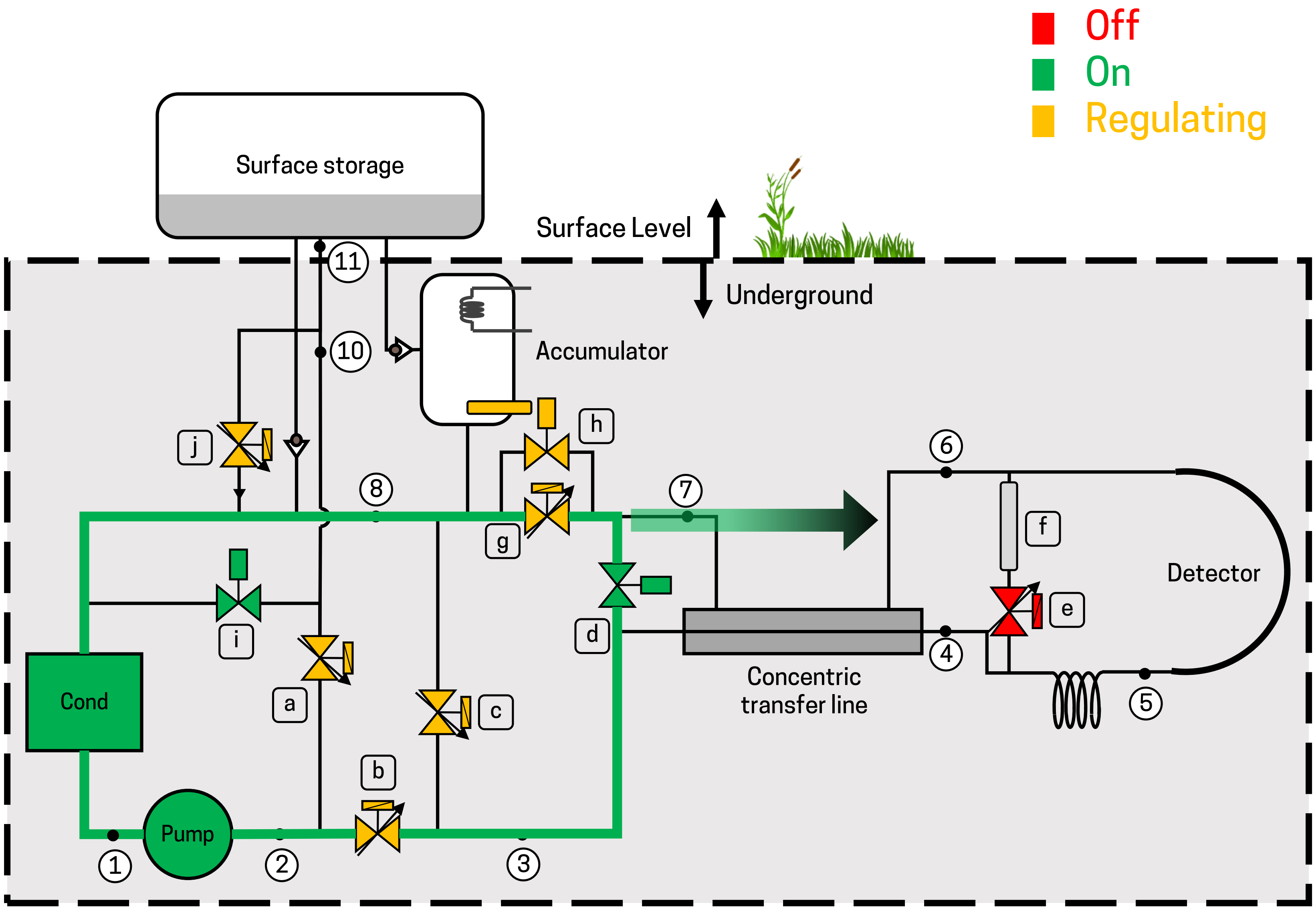
# New startup

- Step 1: Request flow
- Accumulator waits patiently for flow
- Empty the accumulator
  - Otherwise, two "accumulators" fighting for control
- Set up bypass flow



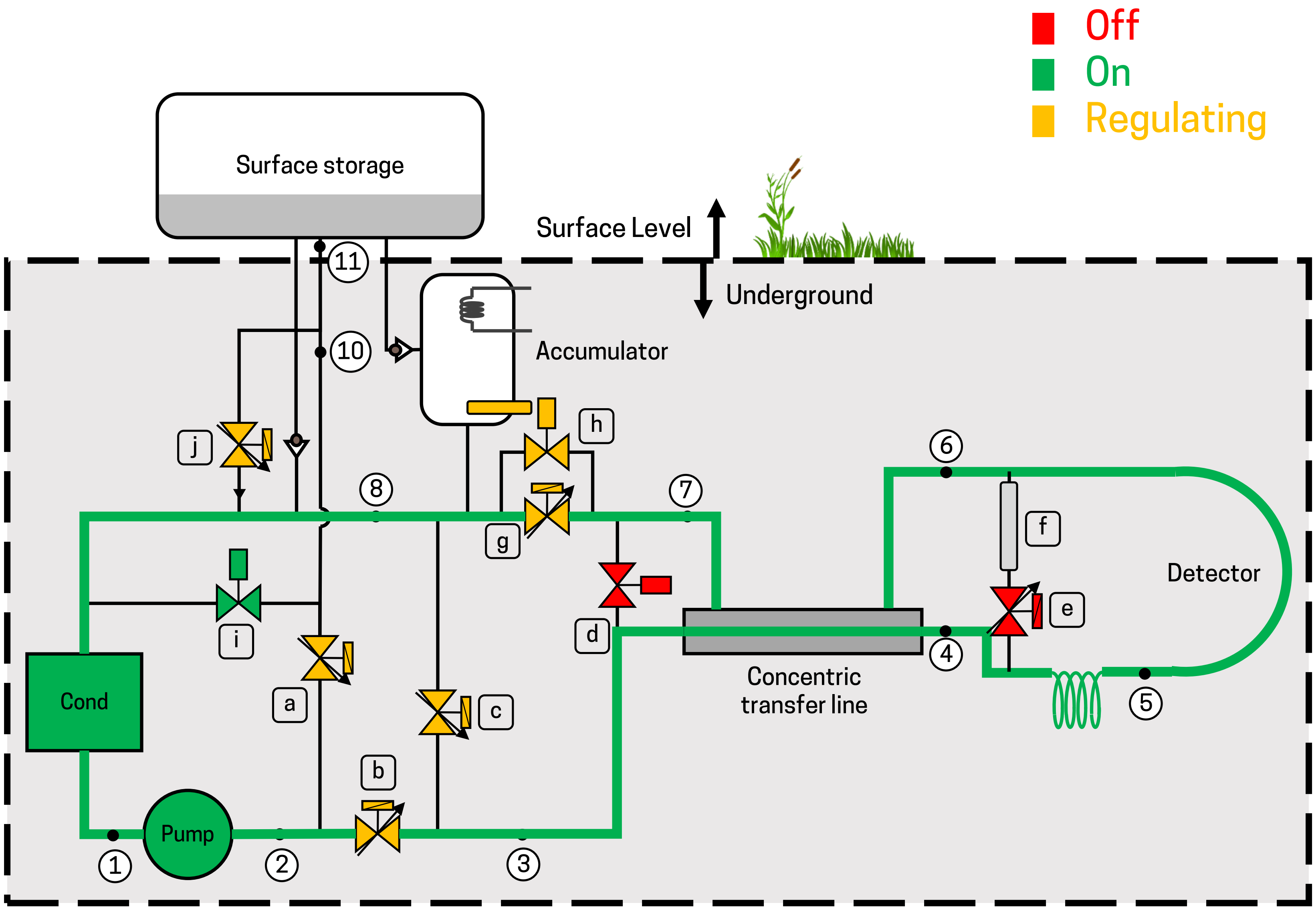
## New startup

- Step 2: Pressurise detector
- Throttle flow using back pressure regulator
- Trickle-flow liquid towards detector
- Slowly subcool detector



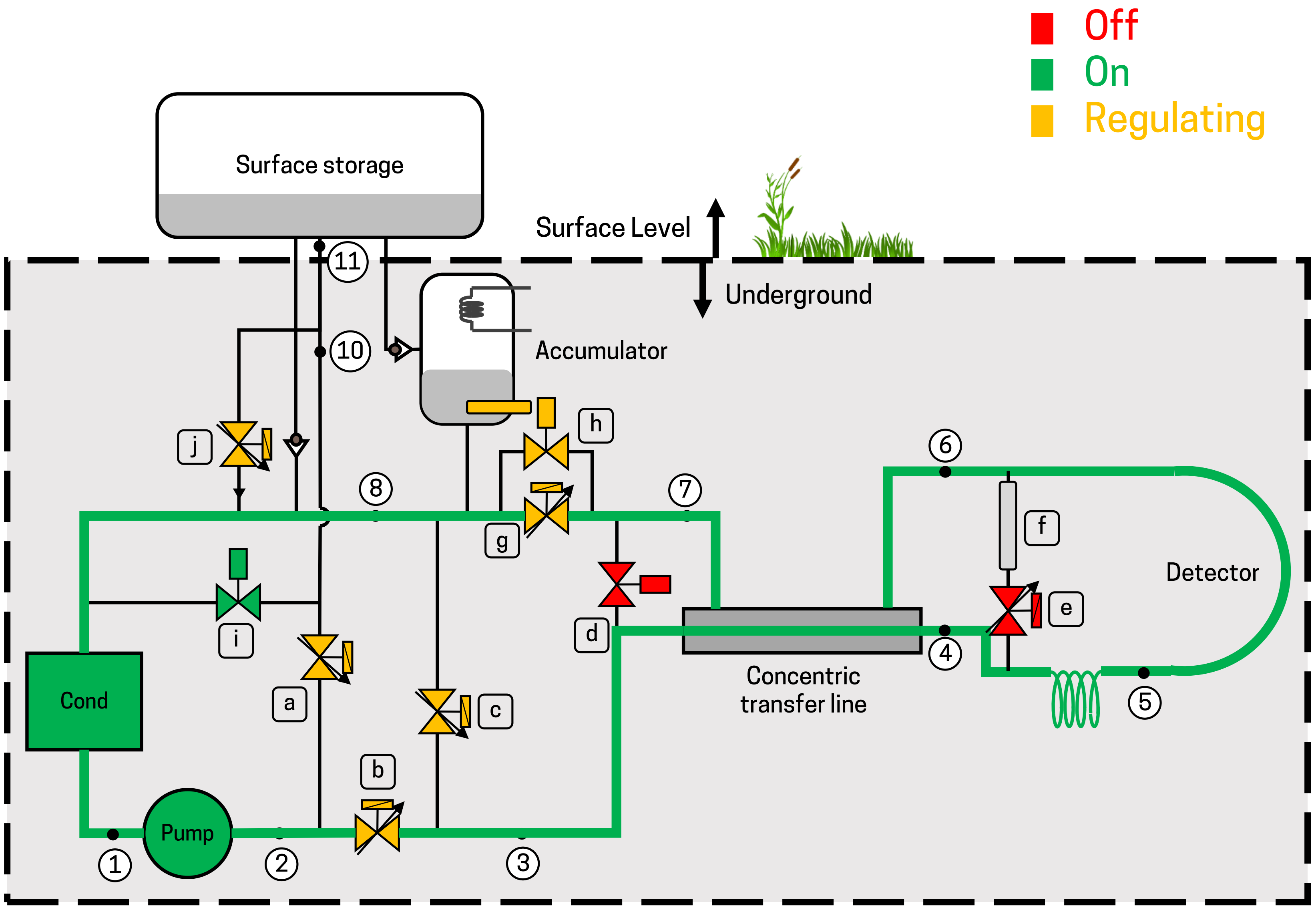
## New startup

- Step 3: Detector circulation
- Safe to start circulating through detector
- Close TL bypass valve
- Detector flow control valve now regulates (Valve c)



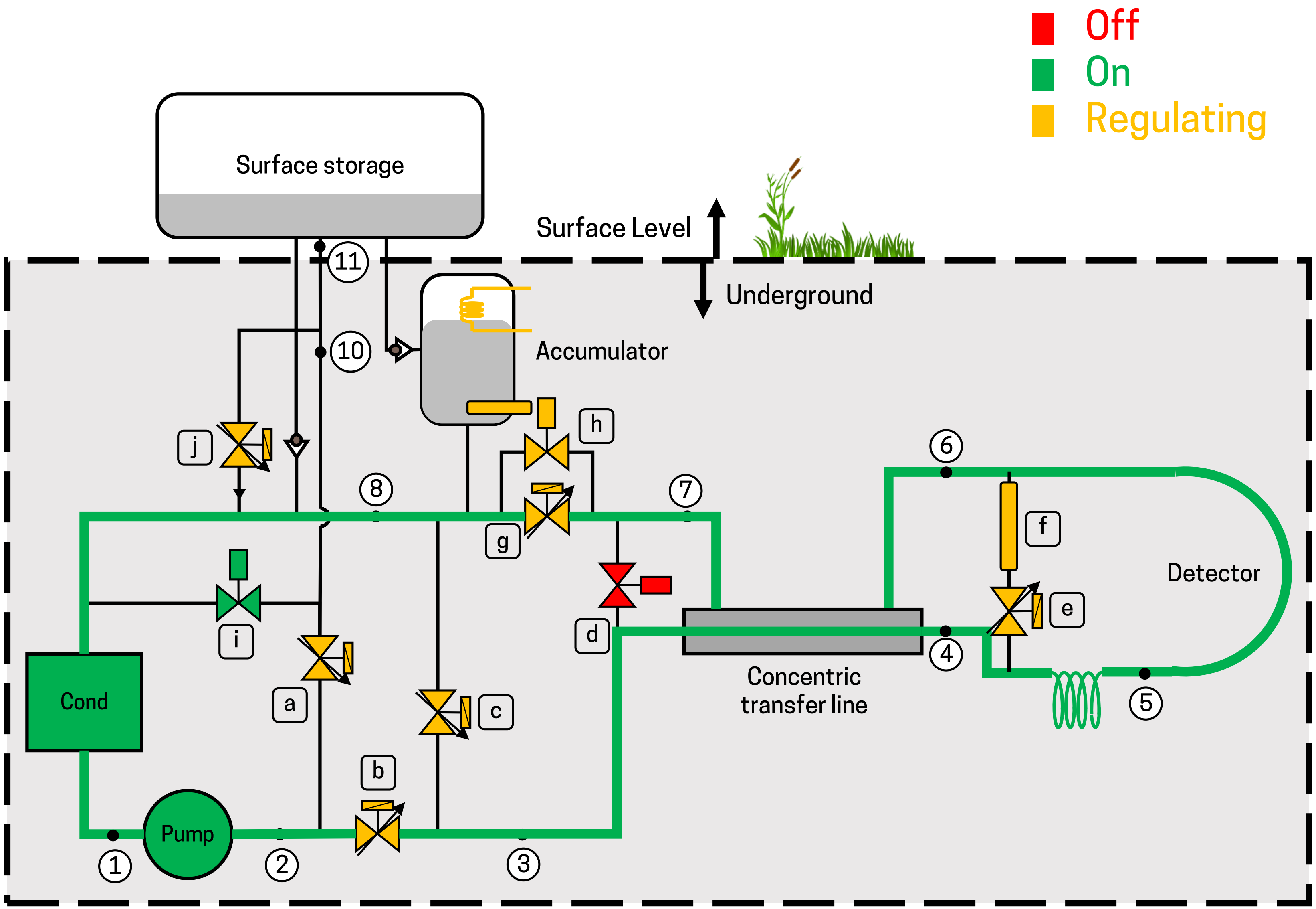
New startup

- Step 4: Accumulator control
- Time to fill up the Accumulator
- Surface storage valves fill up the vessel



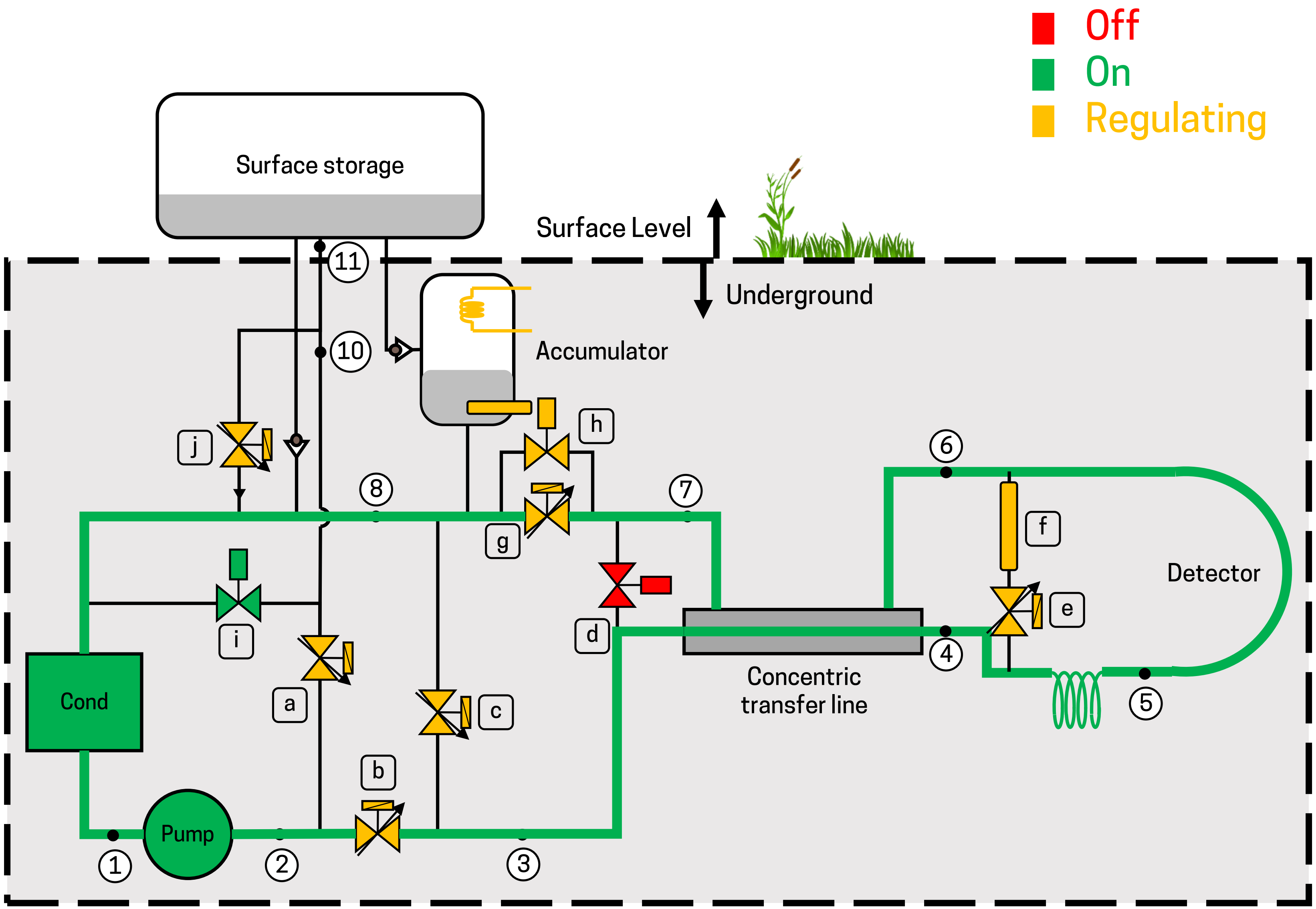
# New startup

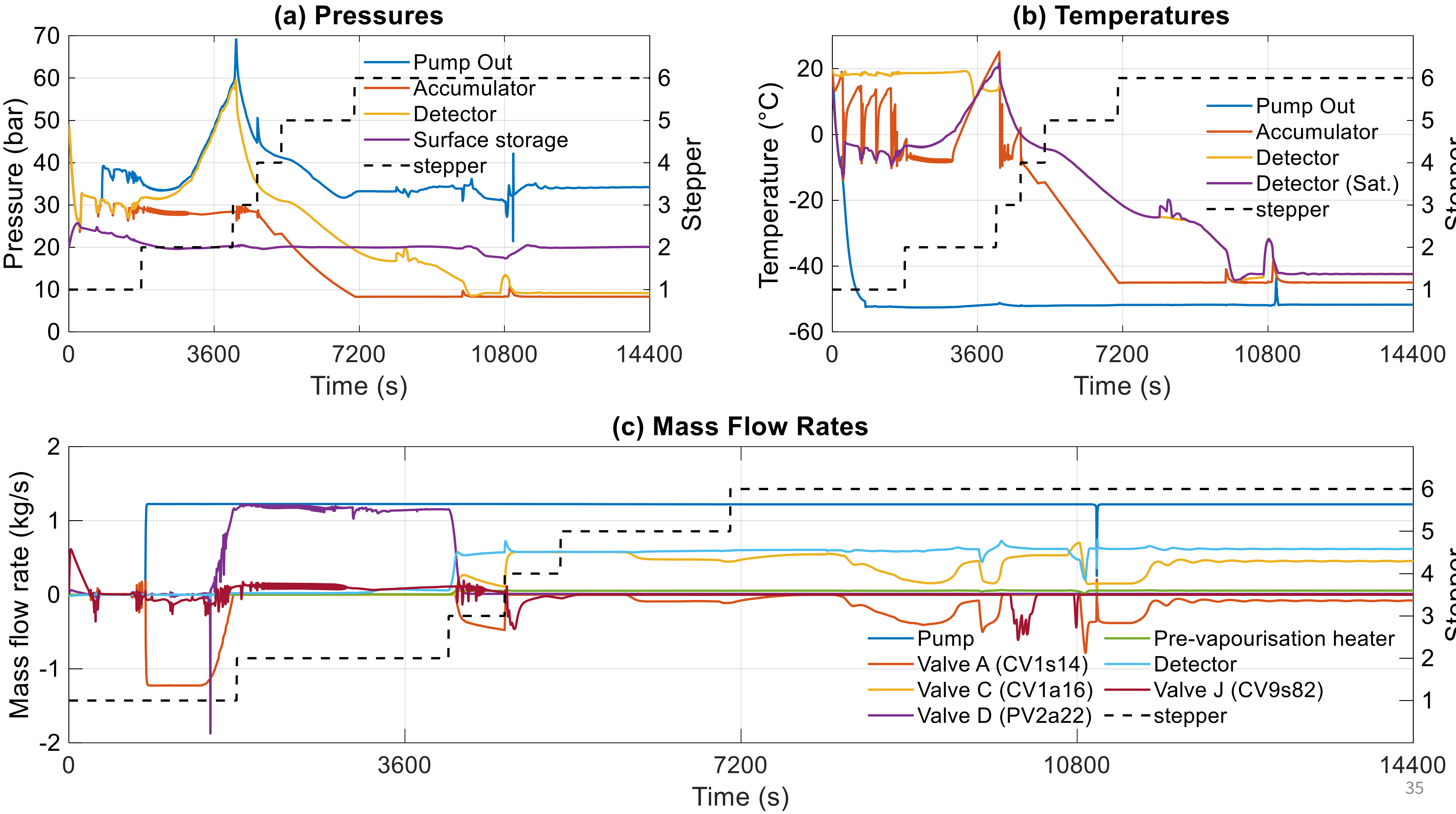
- Step 5: Detector cooldown
- Detector is liquid
  - No danger of thermal shock
- Accumulator is regulating
- ∴ we are ready to cool down
- Pre-vapourisation heating may be turned on now
  - Level control brings back Accumulator level



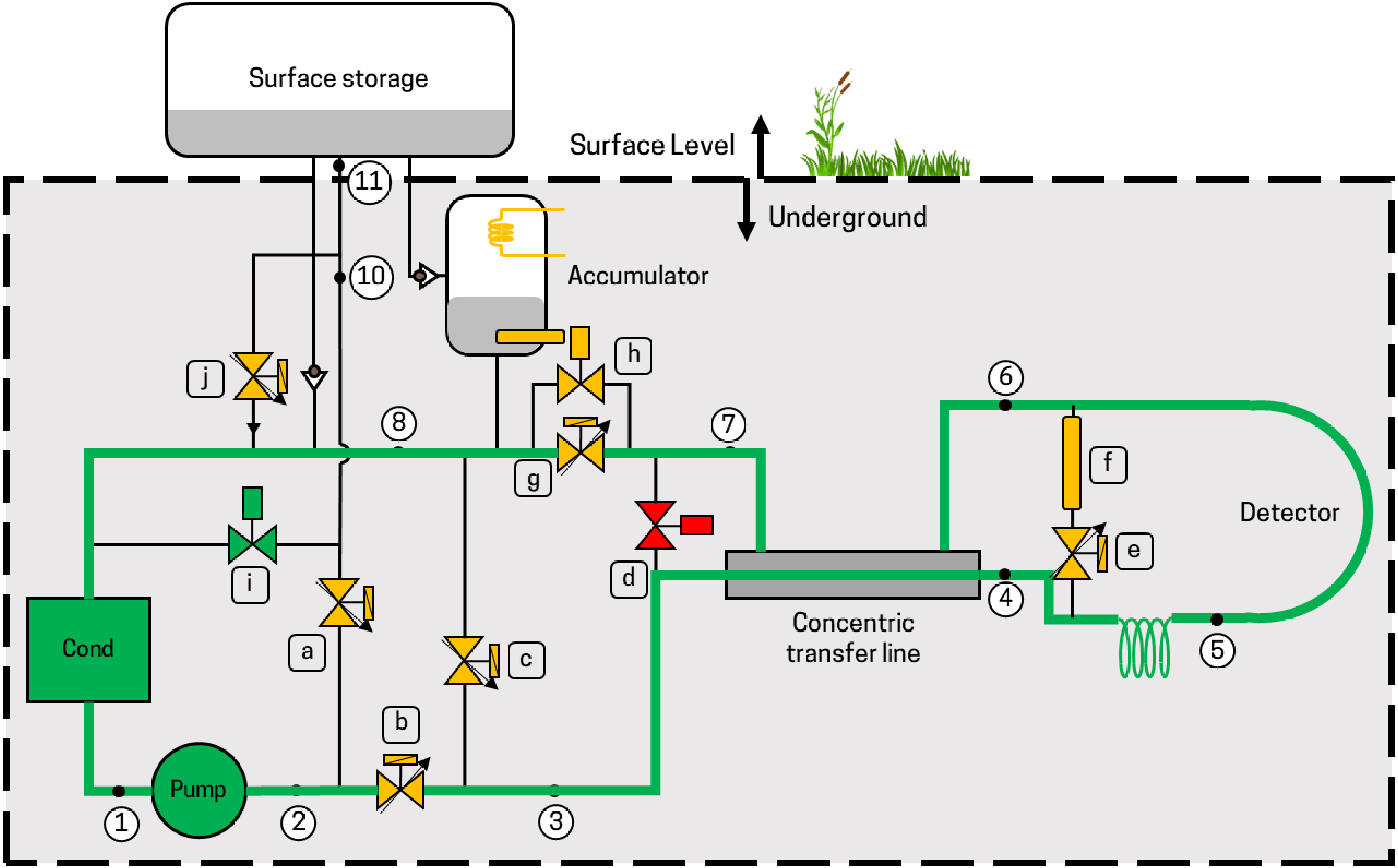
## New startup

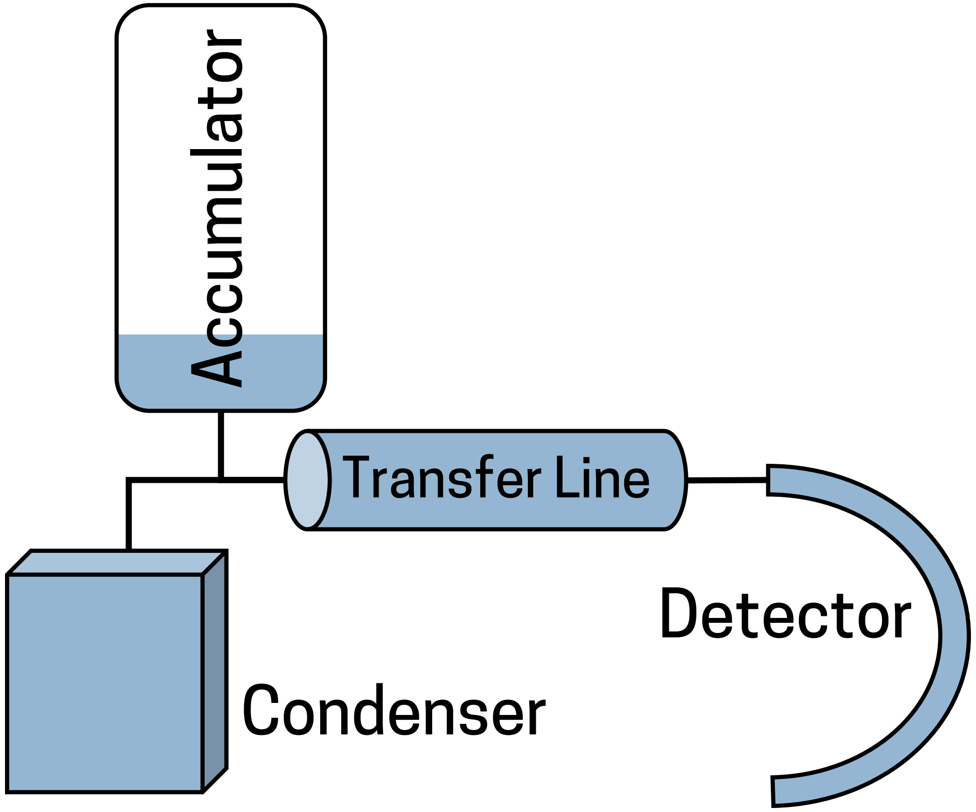
- Step 6: Detector power allow
- All done from CO2 side
- Detectors can turn on power when they like



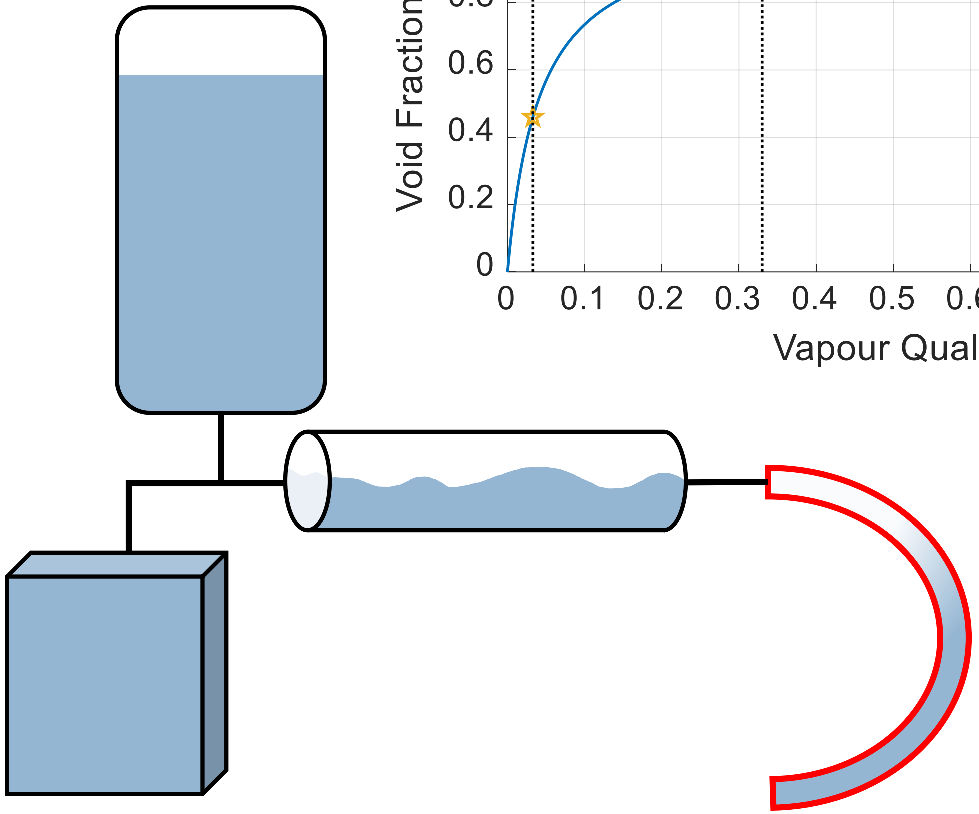


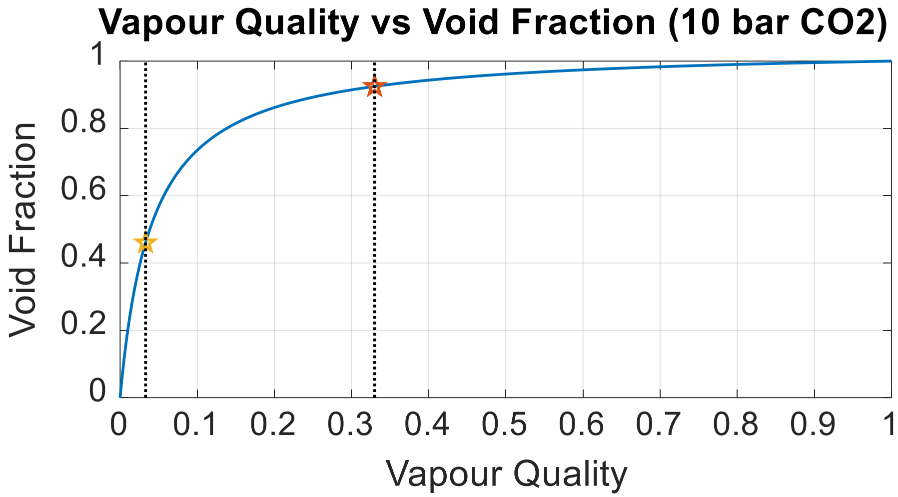
(a) Pressures
Pressure (bar)
Stepper
Time (s)
Pump Out
Accumulator
Detector
Surface storage
stepper
(b) Temperatures
Temperature (°C)
Stepper
Time (s)
Pump Out
Accumulator
Detector
Detector (Sat.)
stepper
(c) Mass Flow Rates
Mass flow rate (kg/s)
Stepper
Time (s)
Pump
Valve A (CV1s14)
Valve C (CV1a16)
Valve D (PV2a22)
Pre-vapourisation heater
Detector
Valve J (CV9s82)
stepper


Surface storage
Surface Level
Underground
11
10
Accumulator
h
j
8
7
6
g
f
Detector
i
d
e
4
Cond
a
c
Concentric
transfer line
5
b
Pump
1
2
3




Power-on



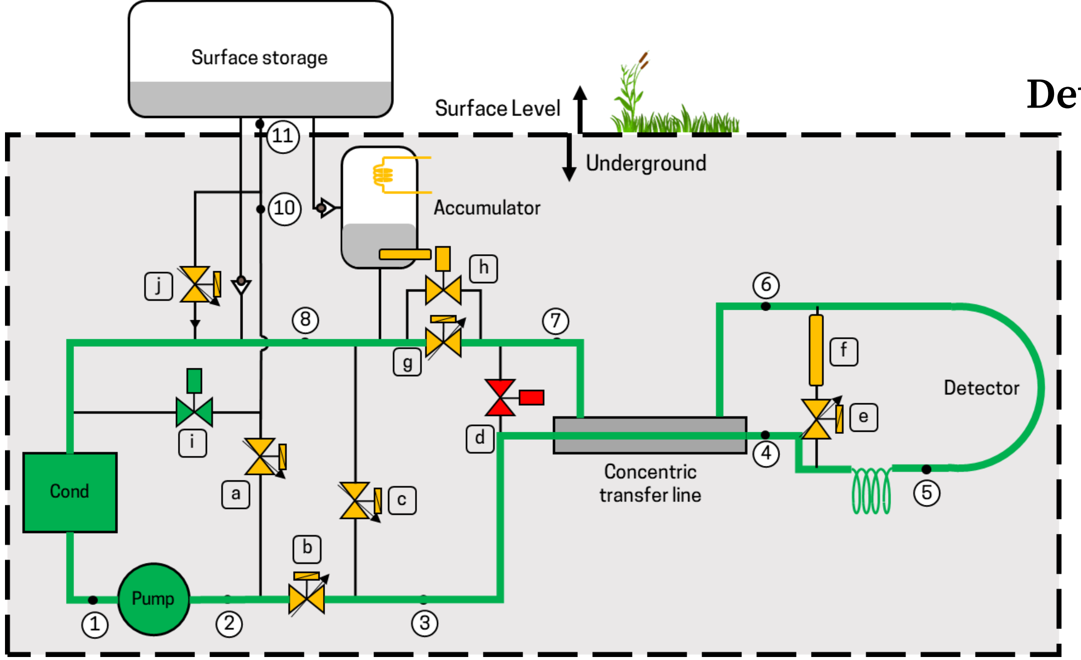



Initial:

- Fully liquid transfer line
- Accumulator mostly empty

Power-on:

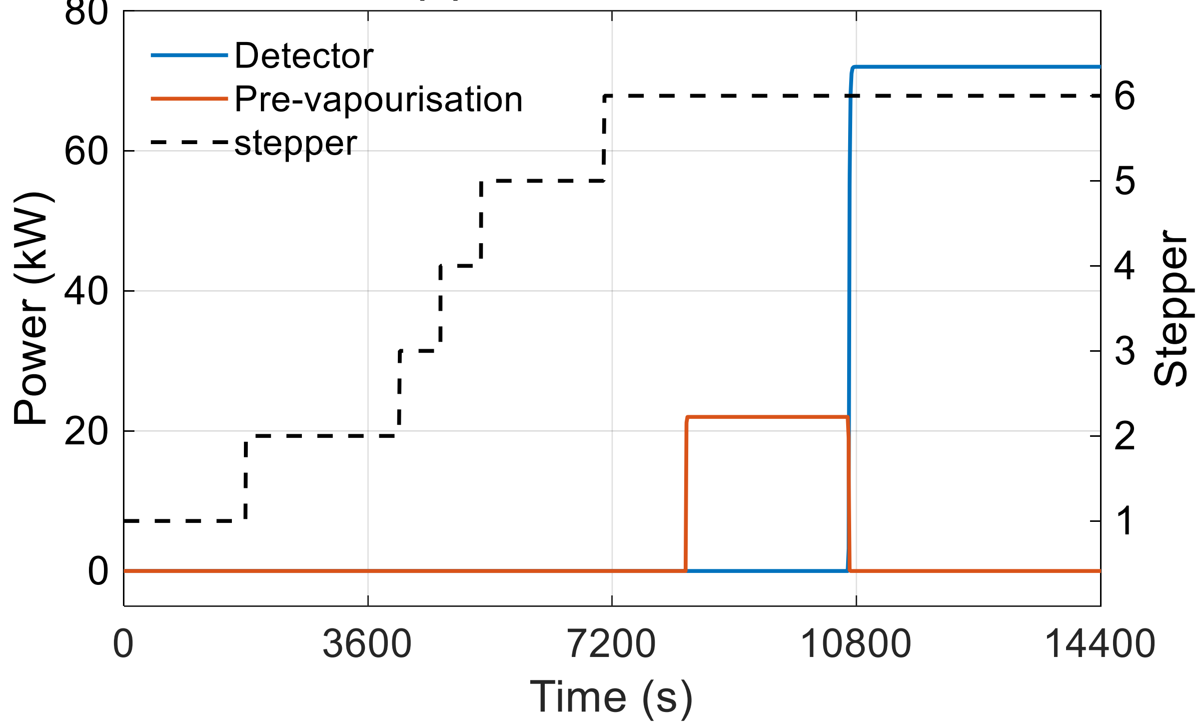
- Vapour travels faster than liquid
- Pump is constant volumetric flow rate
- Liquid displaced into accumulator



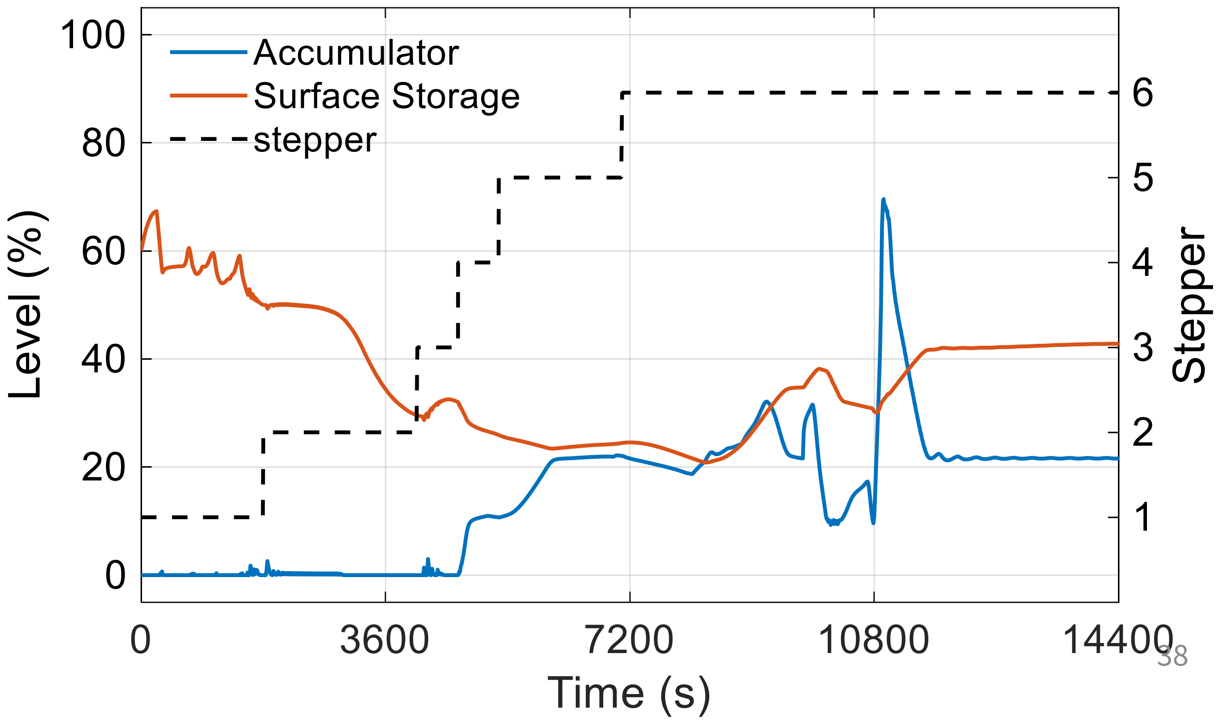

## Detector power-on

- Level controller not finely tuned for the moment
- Surface storage rise gives a better indication
- The second rise on the Accumulator at 3 hours (10800 seconds) suggests pre-vapourisation works well.

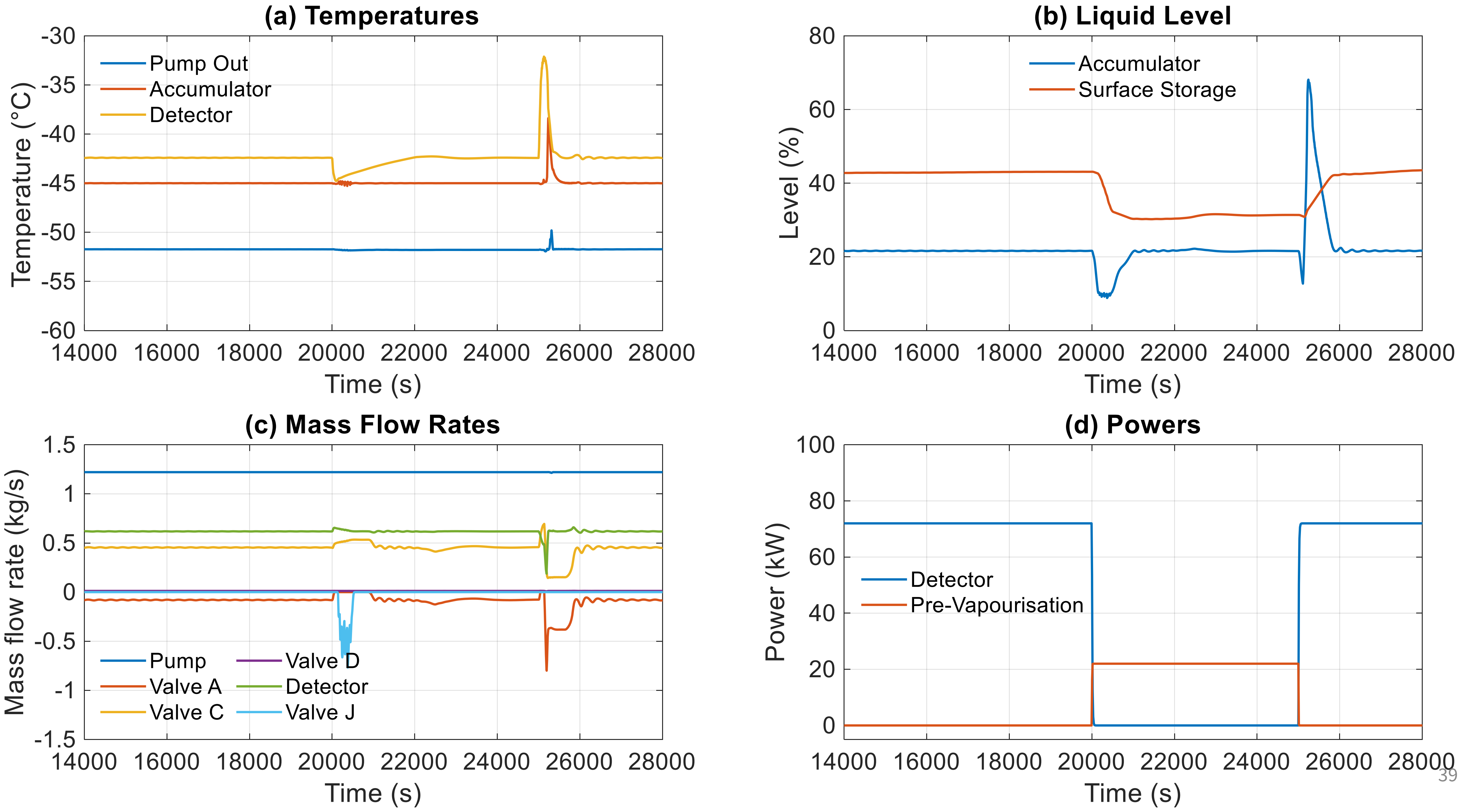
**(a) Detector Power**

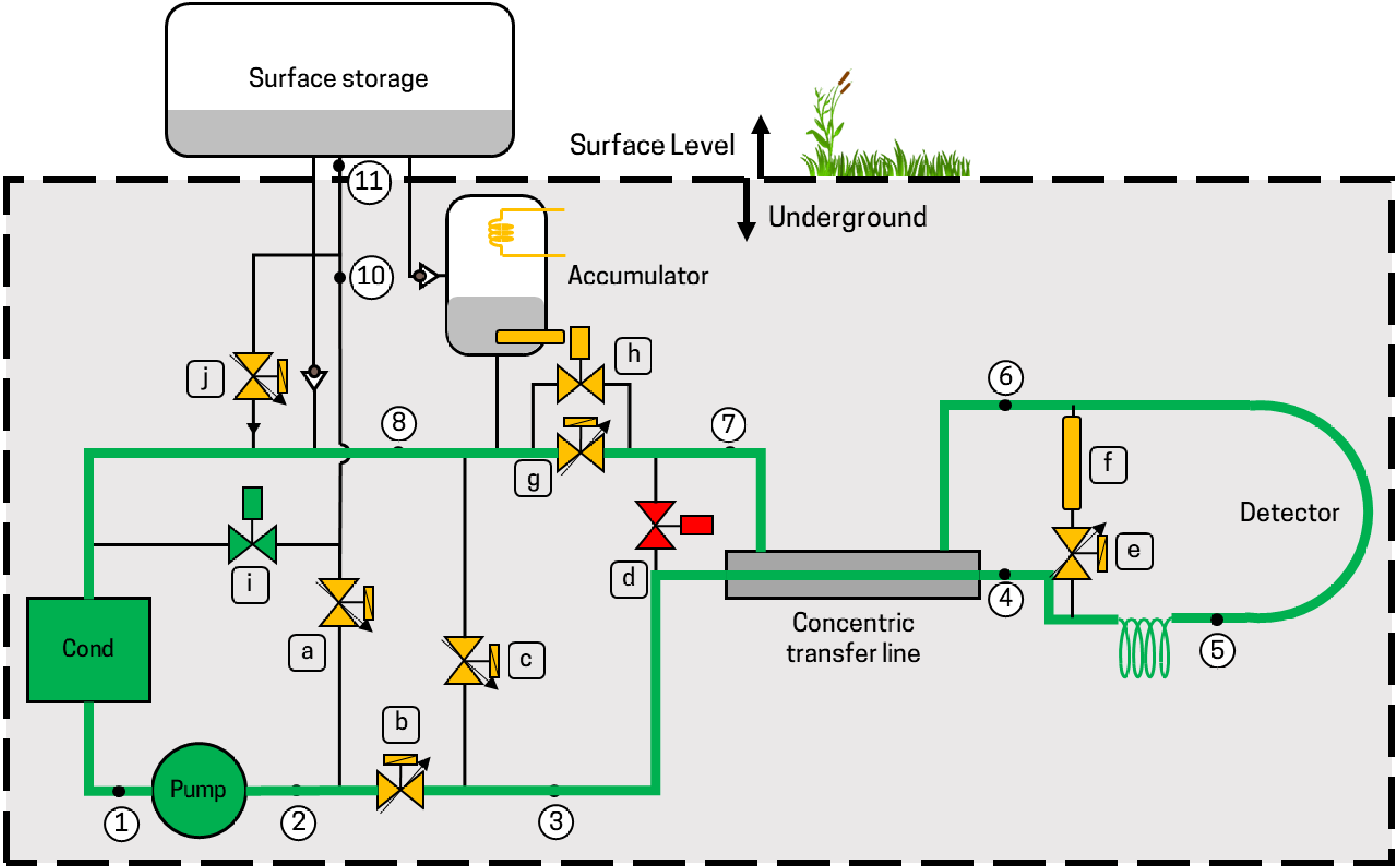



**(b) Liquid Level**



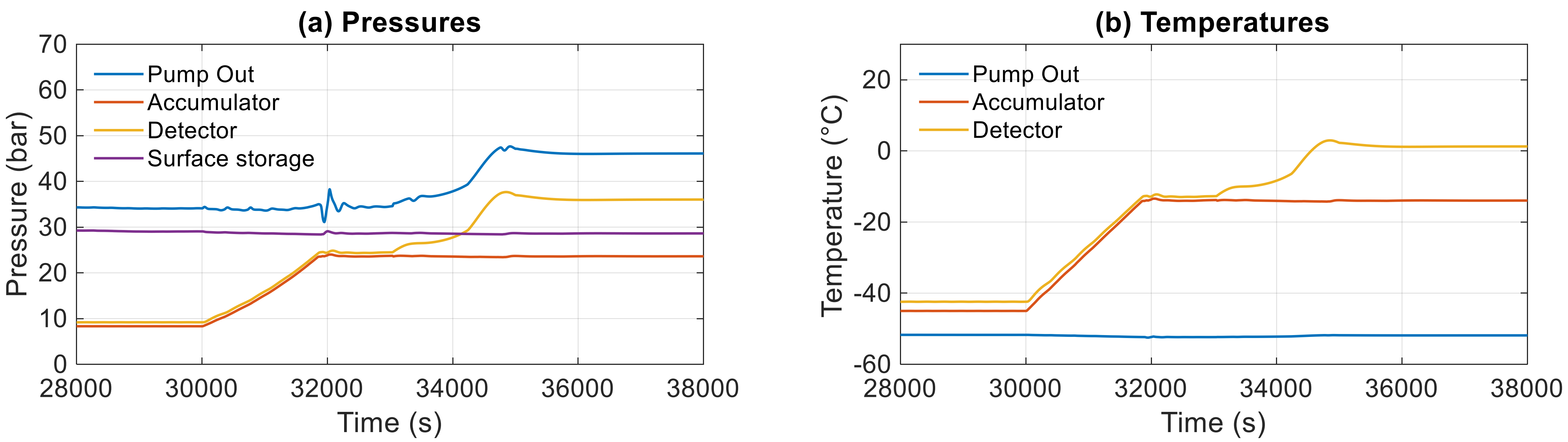
# Detector power-off





Surface storage
Surface Level
Underground
Accumulator
11
10
j
8
h
7
6
g
f
i
d
Detector
e
Cond
a
c
4
Concentric transfer line
5
b
Pump
1
2
3

- Accumulator cannot take us all the way there
- Accumulator pressure must stay *below* surface storage pressure
  - Otherwise, how do we send refrigerant down?
- Back pressure regulator has to do the rest of the job
- Safety concern: If BPR fails, we fall immediately to Accumulator pressure
- Mitigation: Try to find a surface storage that can operate at high pressure



# Conclusions

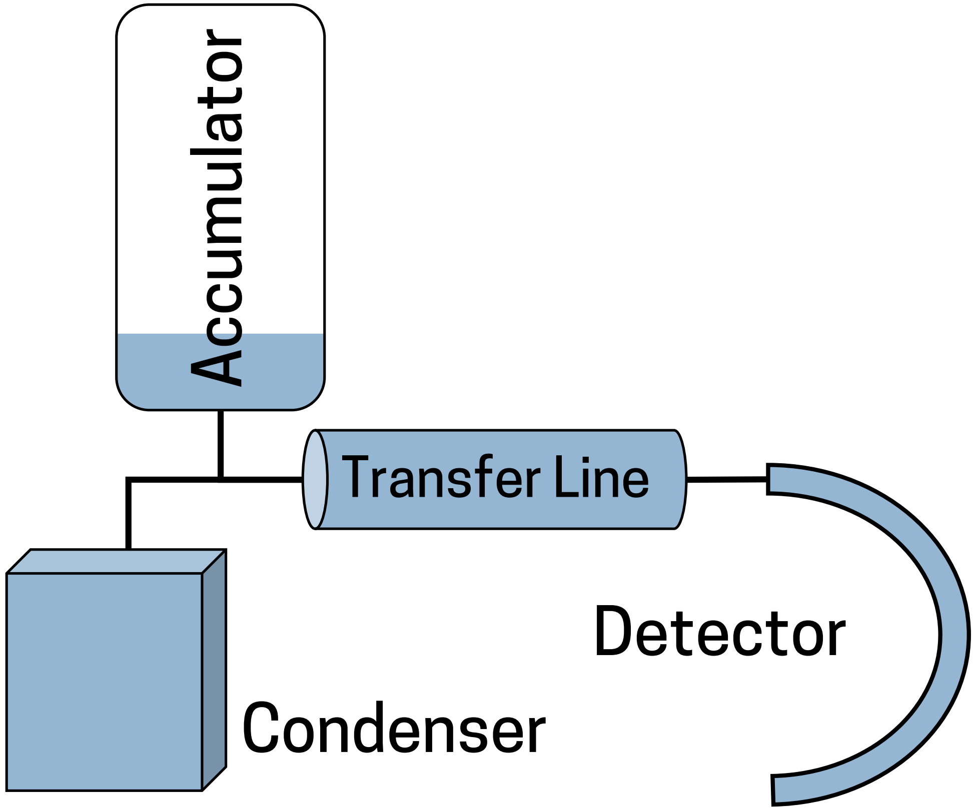
- New systems → significantly so
- System control is undergoing big changes
- Simulations can help provide answers on Phase-2 system behaviour
- Future work: better detector models, spare plant handover, quick restart mode, virtual commissioning setup, operator training, co-simulation with modelica chiller model…

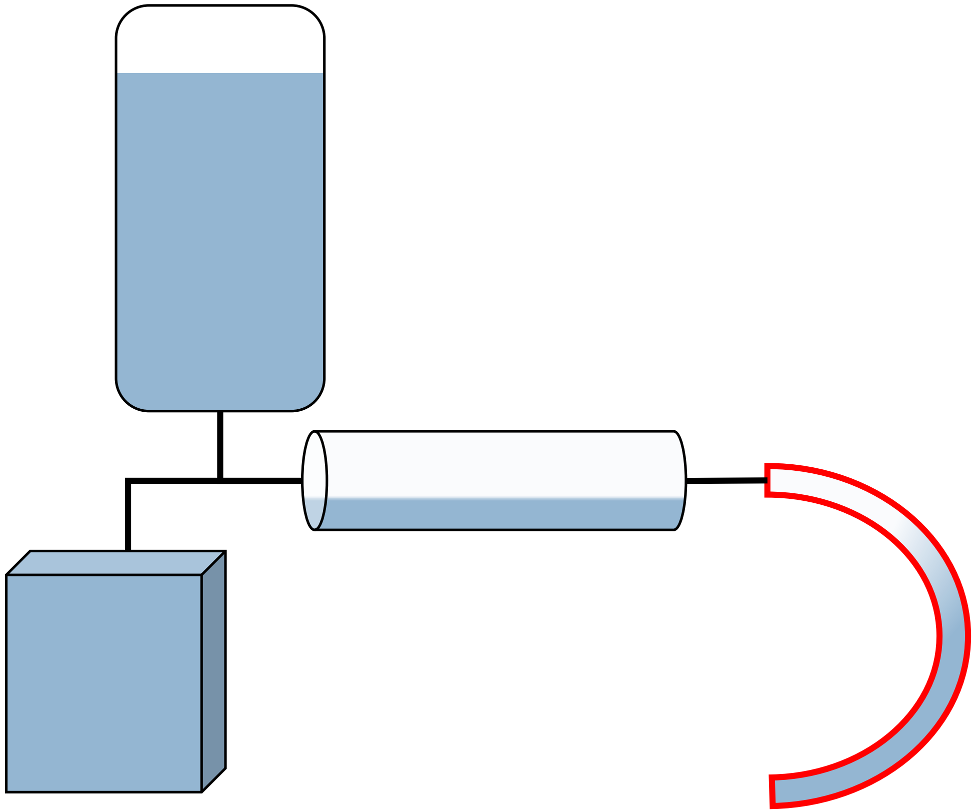

That's all Folks!

# Accumulator Simulations

Sizing and pre-vapourisation

# Accumulator sizing



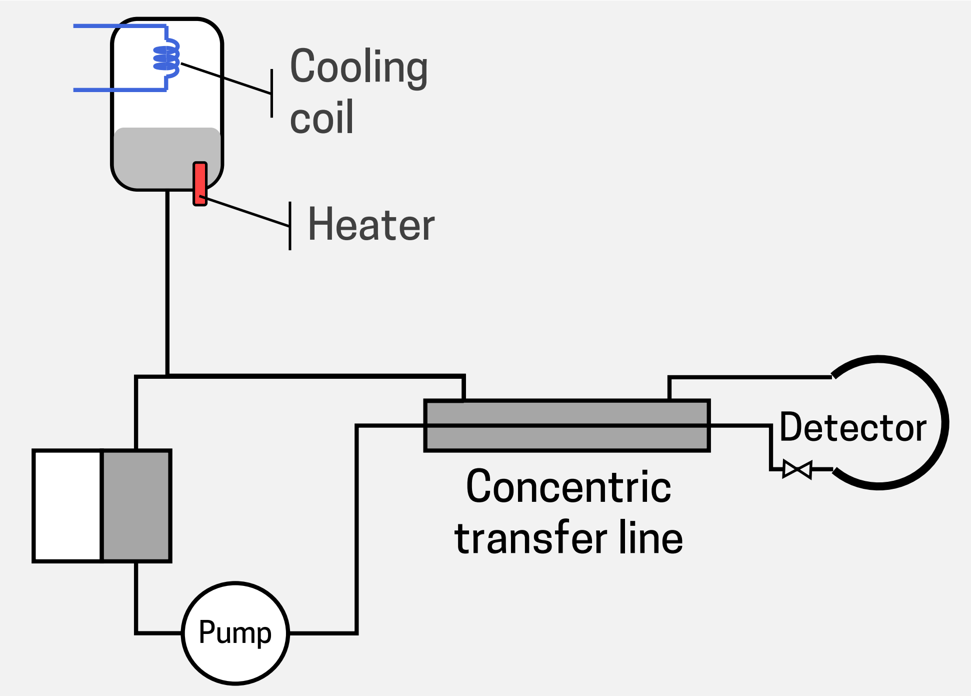
Initial:

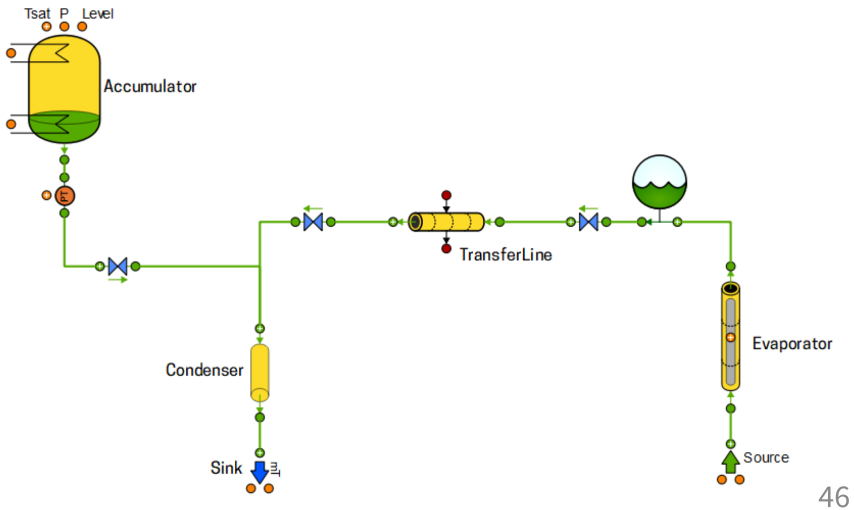
- Fully liquid transfer line
- Accumulator mostly empty

At power-on:

- Vapour travels faster than liquid
- Liquid displaced into accumulator

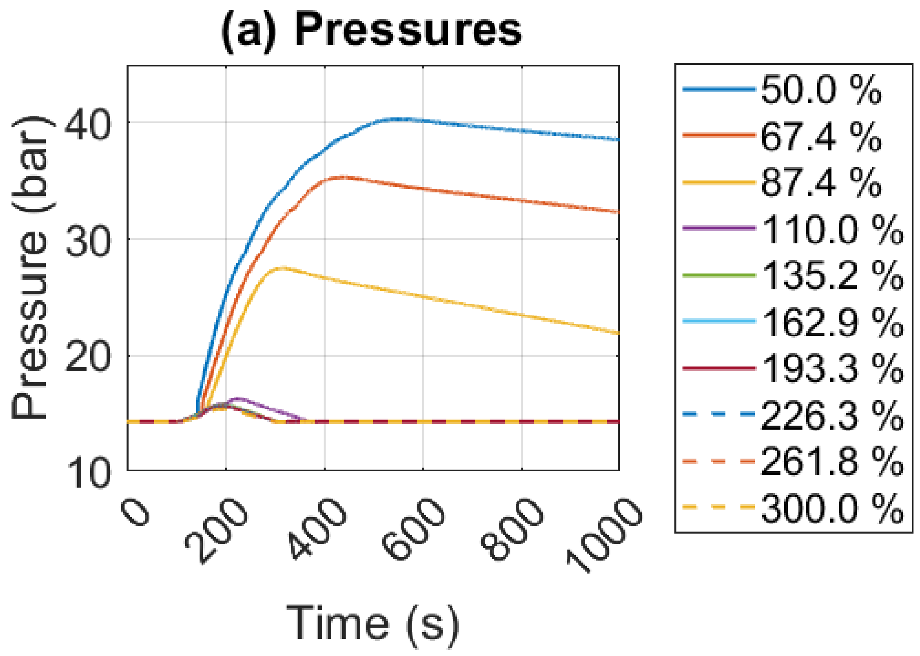
- Parametric simulation on Accumulator volume
  - 10 sizes studied
  - Ranging from 50% to 300% of TL volume
- 70 kW evaporator heat load
  - Turned on after 100 seconds
- 100 m long transfer line
  - Divided into 10 m segments
- 70 g/s of CO2 flow

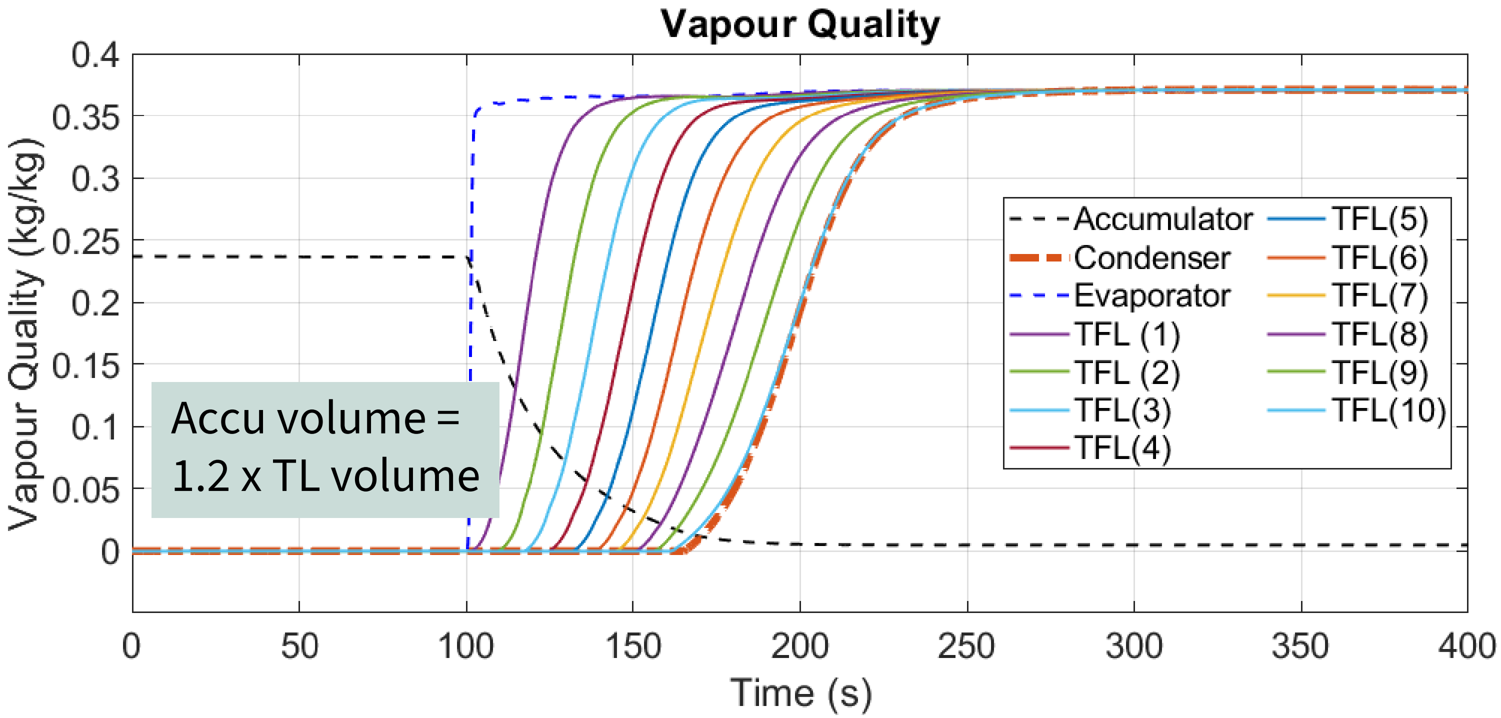


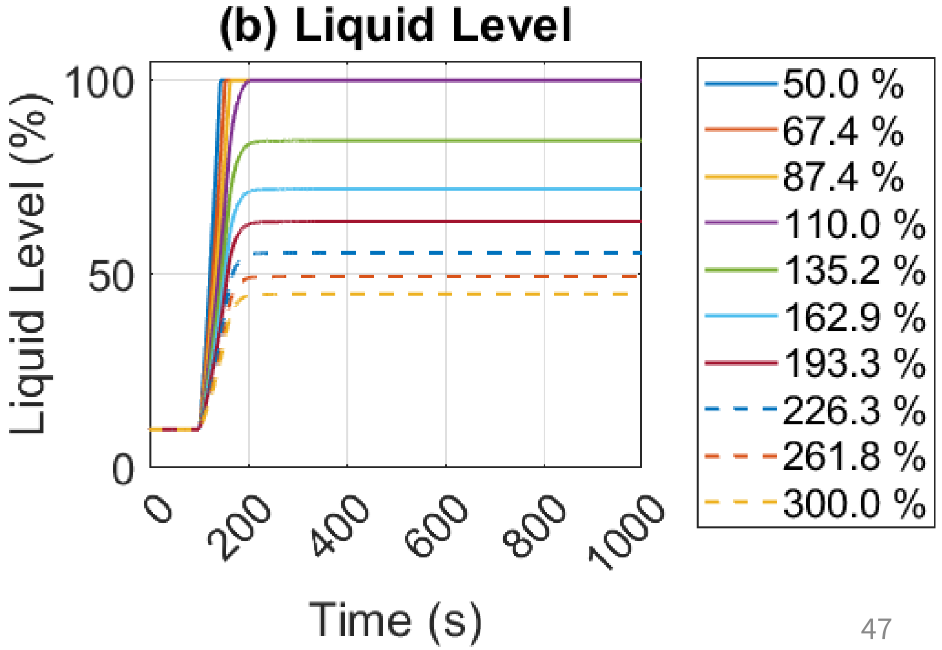



# Accumulator sizing simulation

- 110% of TL return volume
  - Accu just gets full
  - ~120% of TL volume likely sufficient
- Steady-state once vapour front arrives at the Condenser



$$\mathrm{Sc} = \frac{\nu}{\mathscr{D}_{AB}} = \frac{\mu}{\rho \mathscr{D}_{AB}}$$

- Péclet number, Pe = Re.Pr
- Ratio of advection to diffusion
- Convective systems usually have *huge* Peclet numbers
- Downstream parameters have negligible influence on upstream parameters
- Additionally, Diffusion coefficient decreases with lowering temperature and decreases with increasing pressure