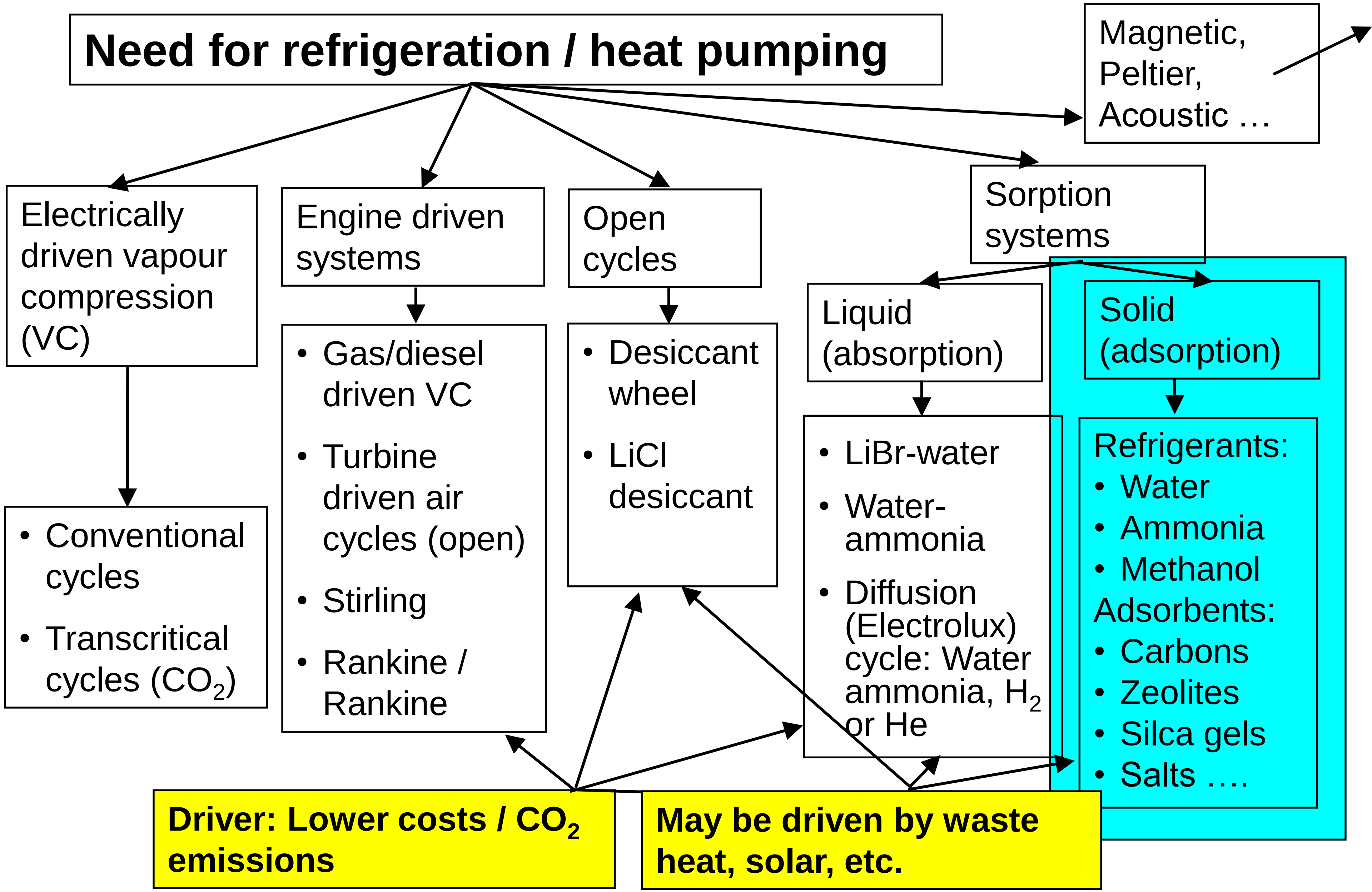
SIRAC
www.sirac.org.uk

Introduction to heat driven (adsorption) cycles

Prof. Bob Critoph

THE UNIVERSITY OF WARWICK

Contents:


Need for refrigeration / heat pumping
Electrically driven vapour compression (VC)
• Conventional cycles
• Transcritical cycles (CO_2)
Engine driven systems
• Gas/diesel driven VC
• Turbine driven air cycles (open)
• Stirling
• Rankine / Rankine
Open cycles
• Desiccant wheel
• LiCl desiccant
Sorption systems
Liquid (absorption)
• LiBr-water
• Water-ammonia
• Diffusion (Electrolux) cycle: Water ammonia, H_2 or He
Solid (adsorption)
Refrigerants:
• Water
• Ammonia
• Methanol
Adsorbents:
• Carbons
• Zeolites
• Silca gels
• Salts ….
Magnetic, Peltier, Acoustic …
Driver: Lower costs / CO_2 emissions
May be driven by waste heat, solar, etc.

Applications:

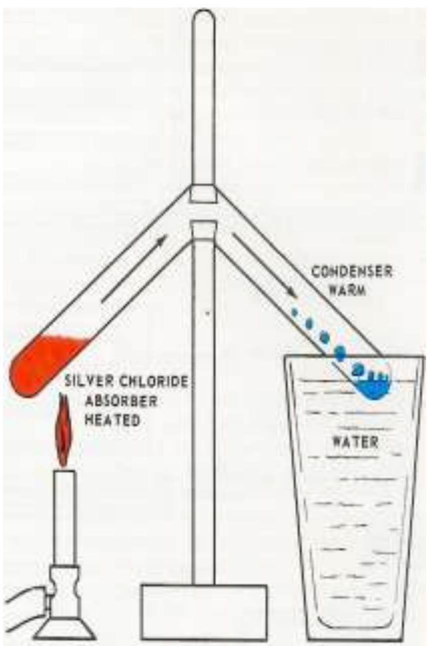
- Heat pumps
- Refrigerators
- Air conditioning

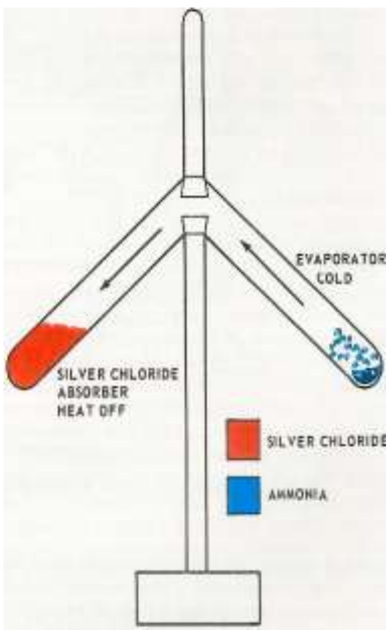
Driven by heat from:

- Fossil fuels
- Bio fuels
- Waste heat
- Solar thermal energy

In the beginning…

It started with Faraday in 1821…





sion to notice some years since with chloride of silver.* When dry chloride of silver is put into ammoniacal gas, as dry as it can be made, it absorbs a large quantity of it; 100 grains condensing above 130 cubical inches of the gas: but the compound thus formed is decomposed by a temperature of 100° F. or upwards. A portion of this compound was sealed up in a bent tube and heated in one leg, whilst the other was cooled by ice or water. The compound thus heated under pressure fused at a comparatively low temperature, and boiled up, giving off ammoniacal gas, which condensed at the opposite end into a liquid.

Liquid ammonia thus obtained was colourless, transparent, and very fluid. Its refractive power surpassed that of any other of the fluids described, and that also of water itself. From the way in which it was obtained, it was evidently as free from water as ammonia in any state could be. When the chloride of silver is allowed to cool, the ammonia immediately returns to it, combining with it, and producing the original compound. During this action a curious combination of effects takes place: as the chloride absorbs the ammonia, heat is produced, the temperature rising up nearly to 100°; whilst a few inches off, at the opposite end of the tube, considerable cold is produced by the evaporation of the fluid. When the whole is retained at the temperature of 60°, the ammonia boils till it is dissipated and re-combined. The pressure of the vapour of ammonia is equal to about 6.5 atmospheres at 50°. Its specific gravity was 0.76.

* Quarterly Journal of Science, vol. V. p. 74.

One of the few commercial machines in production :

REFRIGERANT REQUIREMENTS:

- HIGH LATENT HEAT PER UNIT VOLUME
- CHEMICAL STABILITY
- PRESSURE BETWEEN 1 AND 5 BAR
- NON POLLUTING

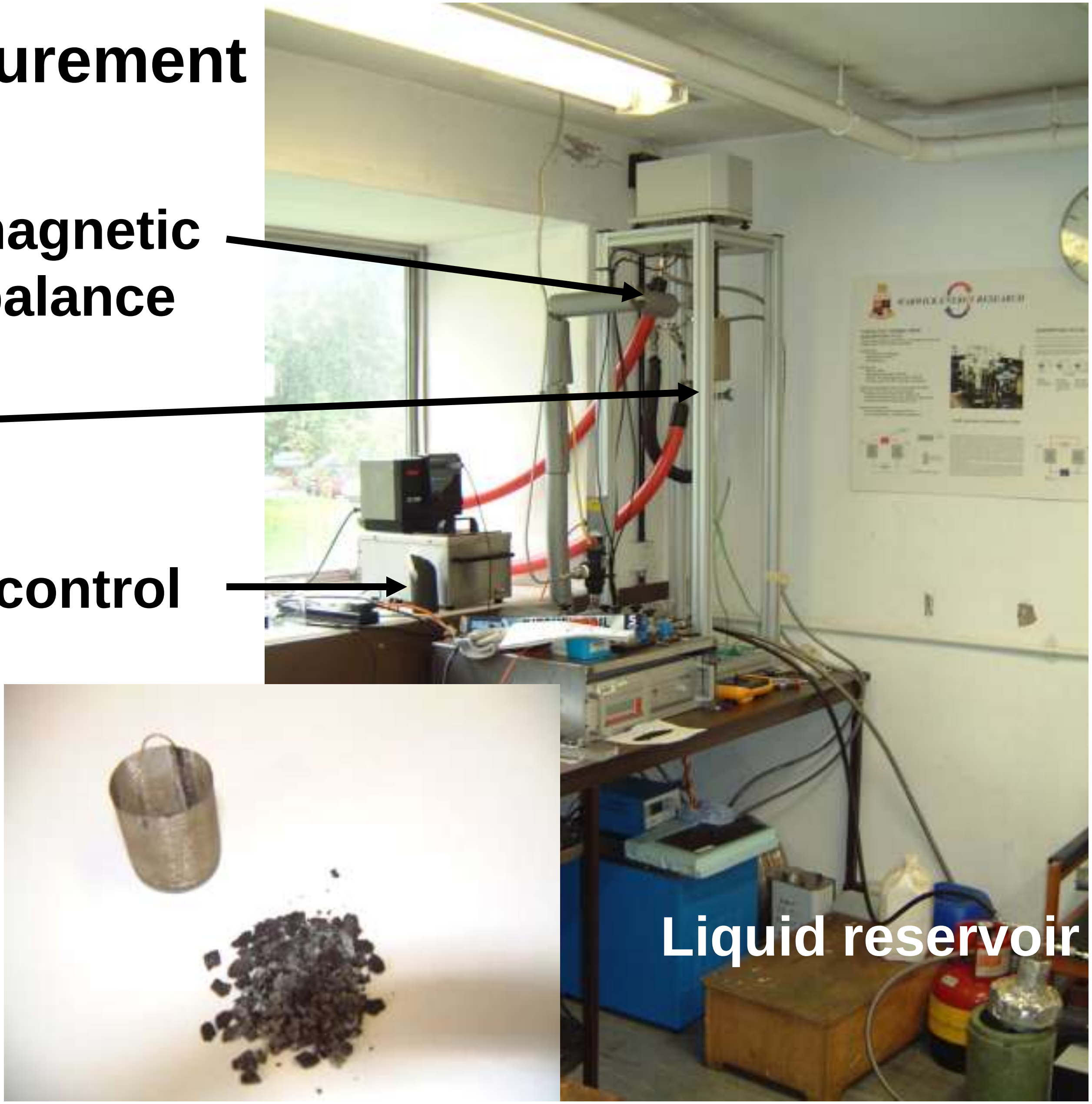
MAIN CONTENDERS:

- WATER
- METHANOL
- AMMONIA

ADSORBENTS:

- **SILICA GEL** **Low temperature lift**
- **ZEOLITES** **Low pore volume, High temperature lift**
- **CARBONS** **High pore volume, Medium lift**

Porosity measurement equipment



Rubotherm magnetic suspension balance

Test vessel

Temperature control

Basket and sample

The (nearly) painless theory…

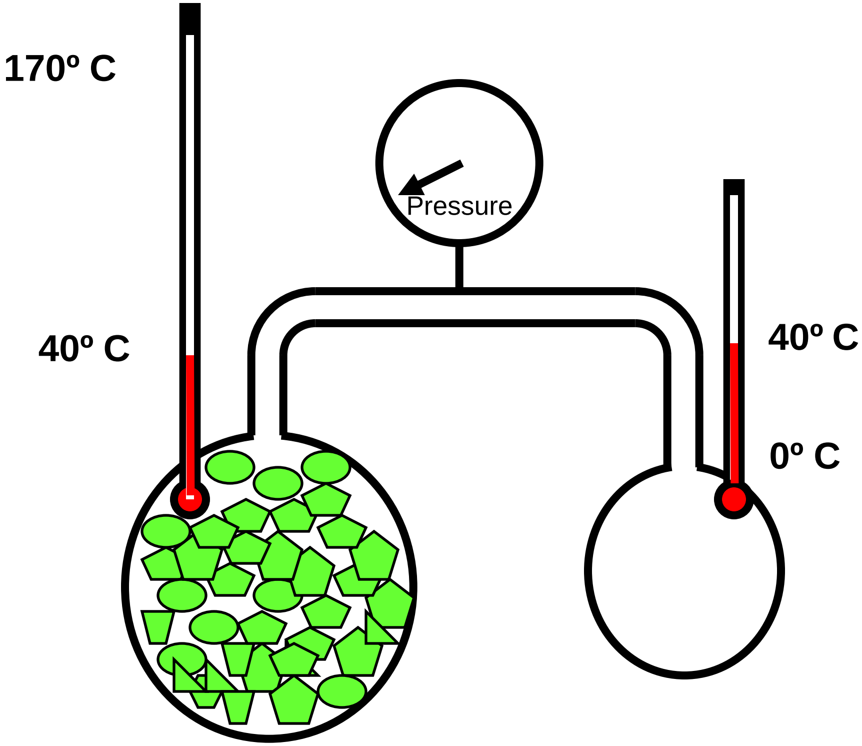
Idealised Adsorption Cycle

Initial State:

Ambient Temperature

Low pressure

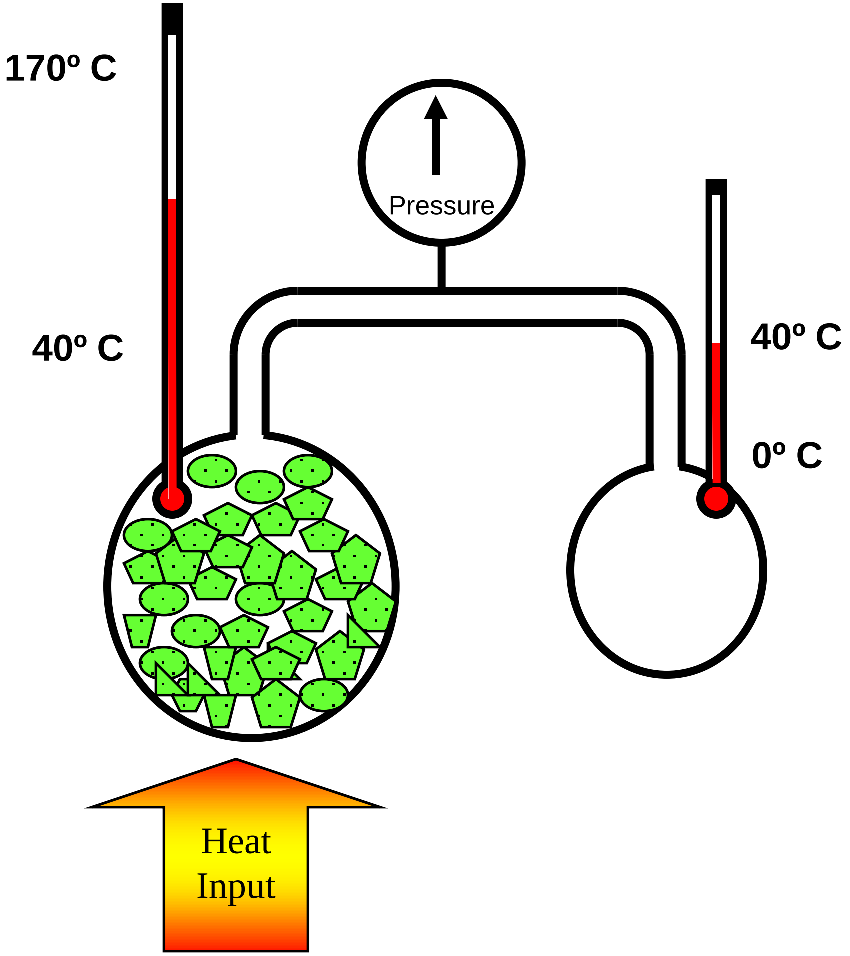
High concentration



Idealised Adsorption Cycle

Process 1

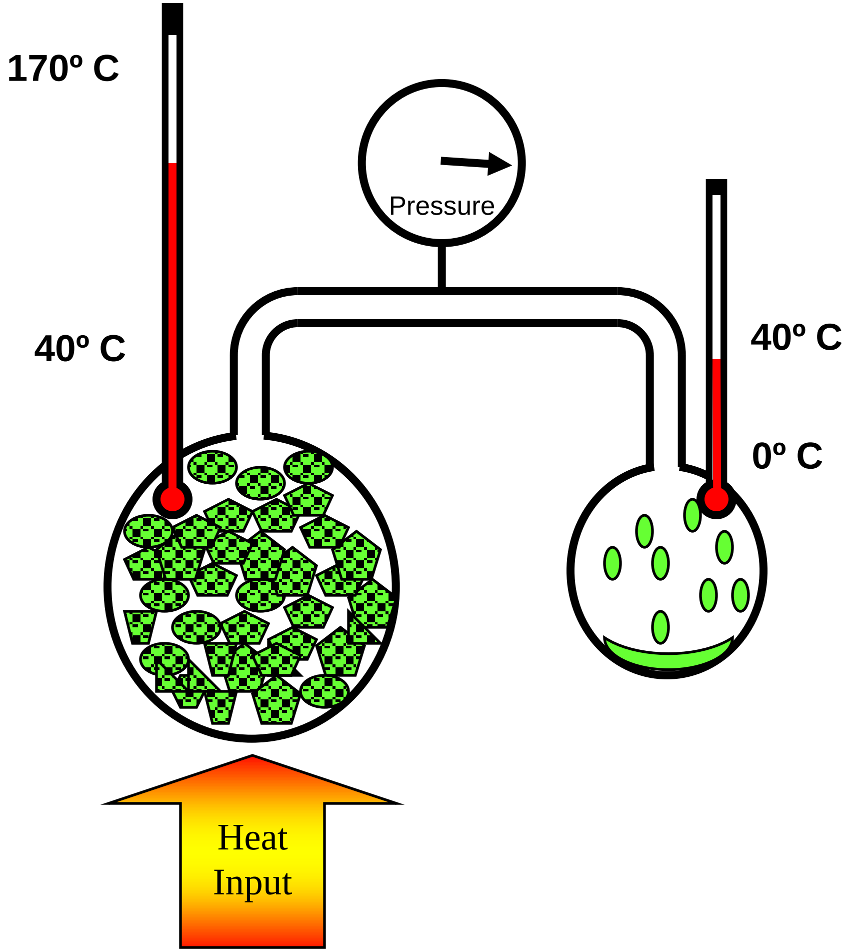
Carbon bed is heated, ammonia is driven off and pressure increases until…



Idealised Adsorption Cycle

Process 2 starts

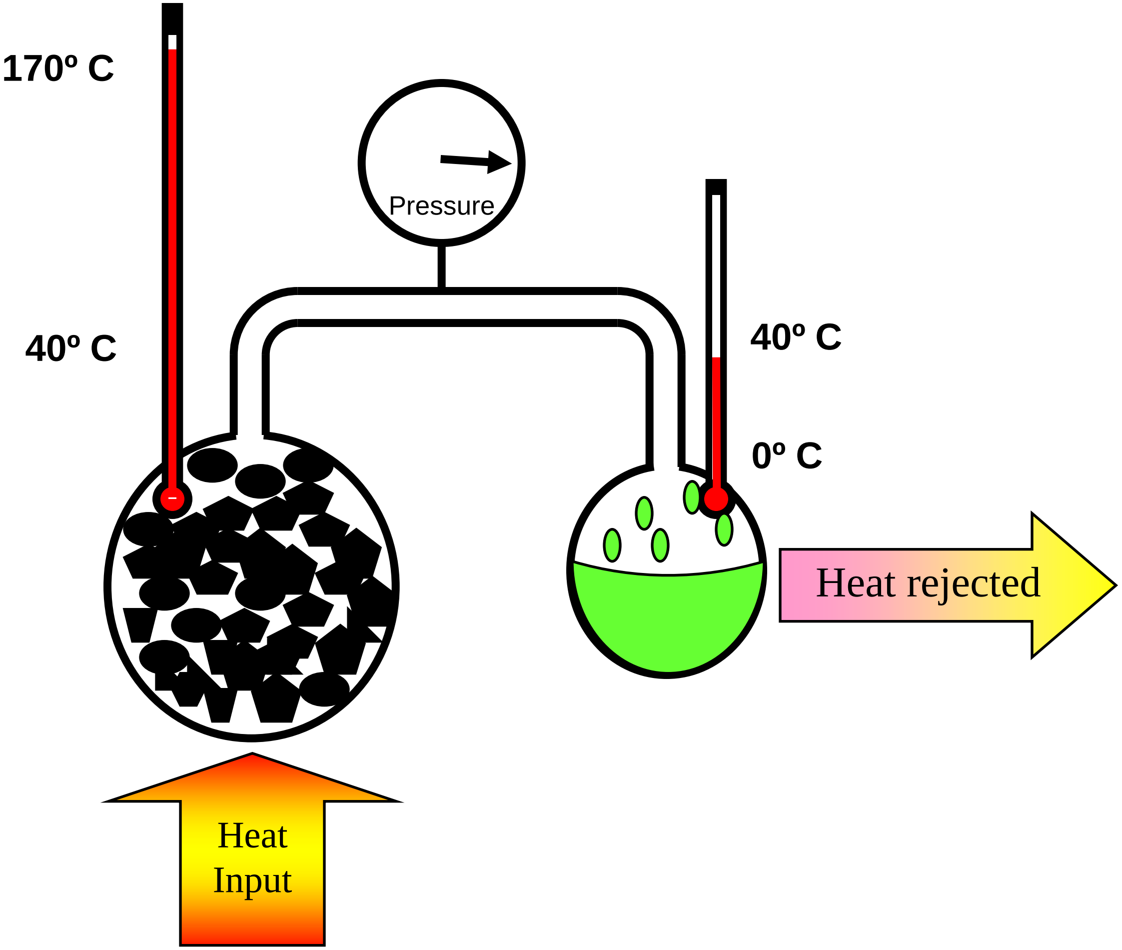
The saturation pressure is reached and ammonia condenses in the right hand vessel at ambient temperature.



Idealised Adsorption Cycle

Process 2 continues

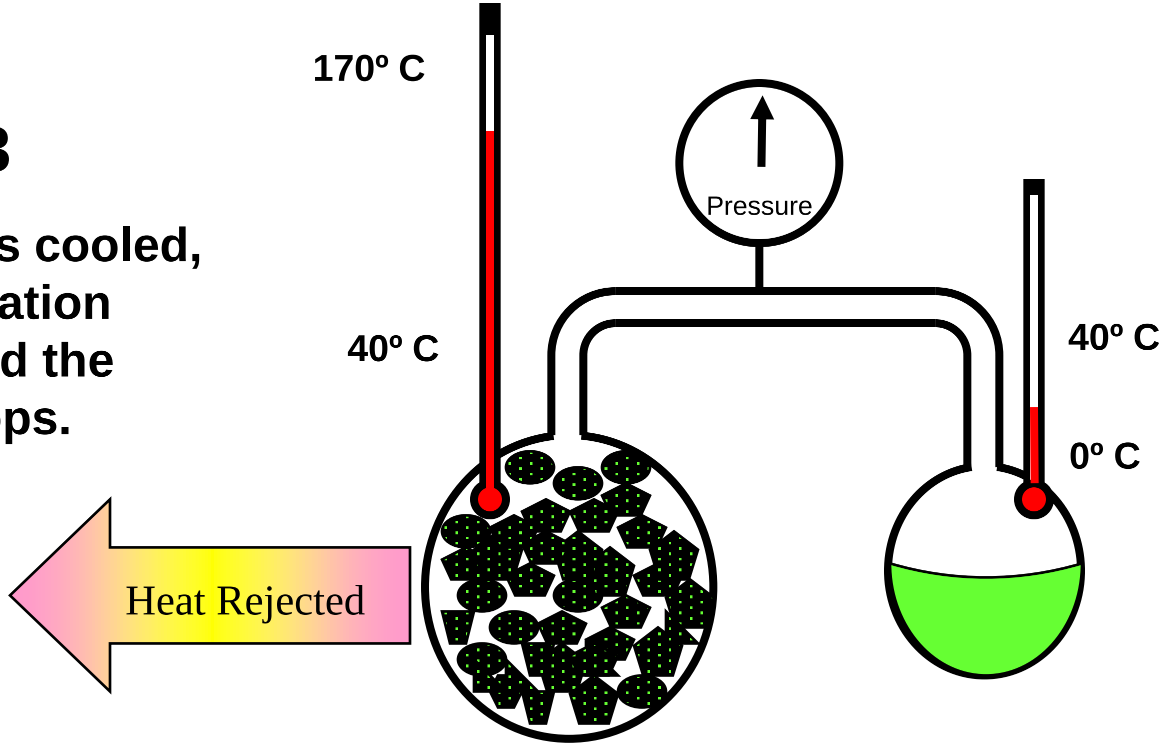
More ammonia is driven out from the carbon and condensed in the right hand vessel



Idealised Adsorption Cycle

Process 3

The carbon is cooled, the concentration increases and the pressure drops.

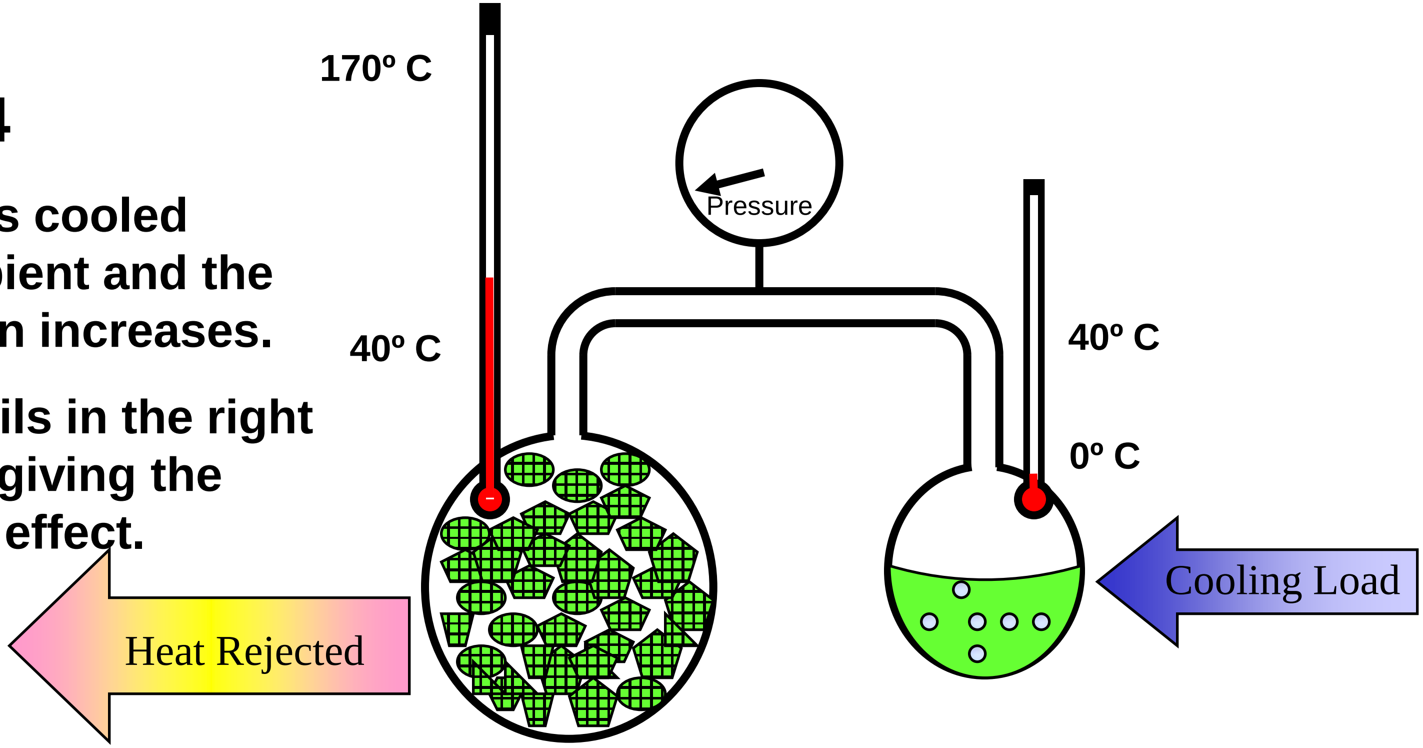


Idealised Adsorption Cycle

Process 4

The carbon is cooled towards ambient and the concentration increases.

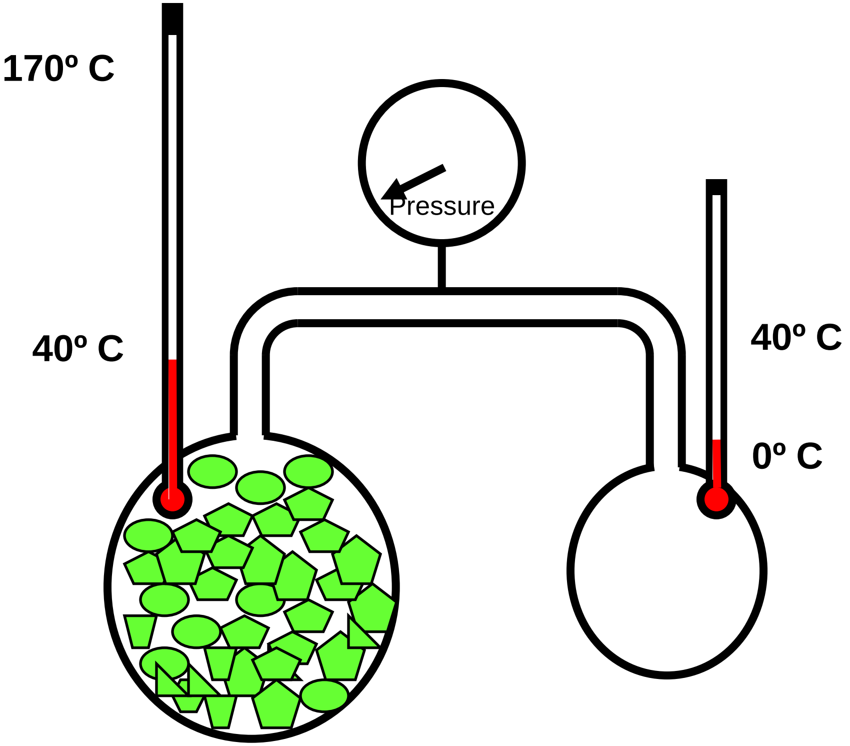
Ammonia boils in the right hand vessel giving the refrigerating effect.



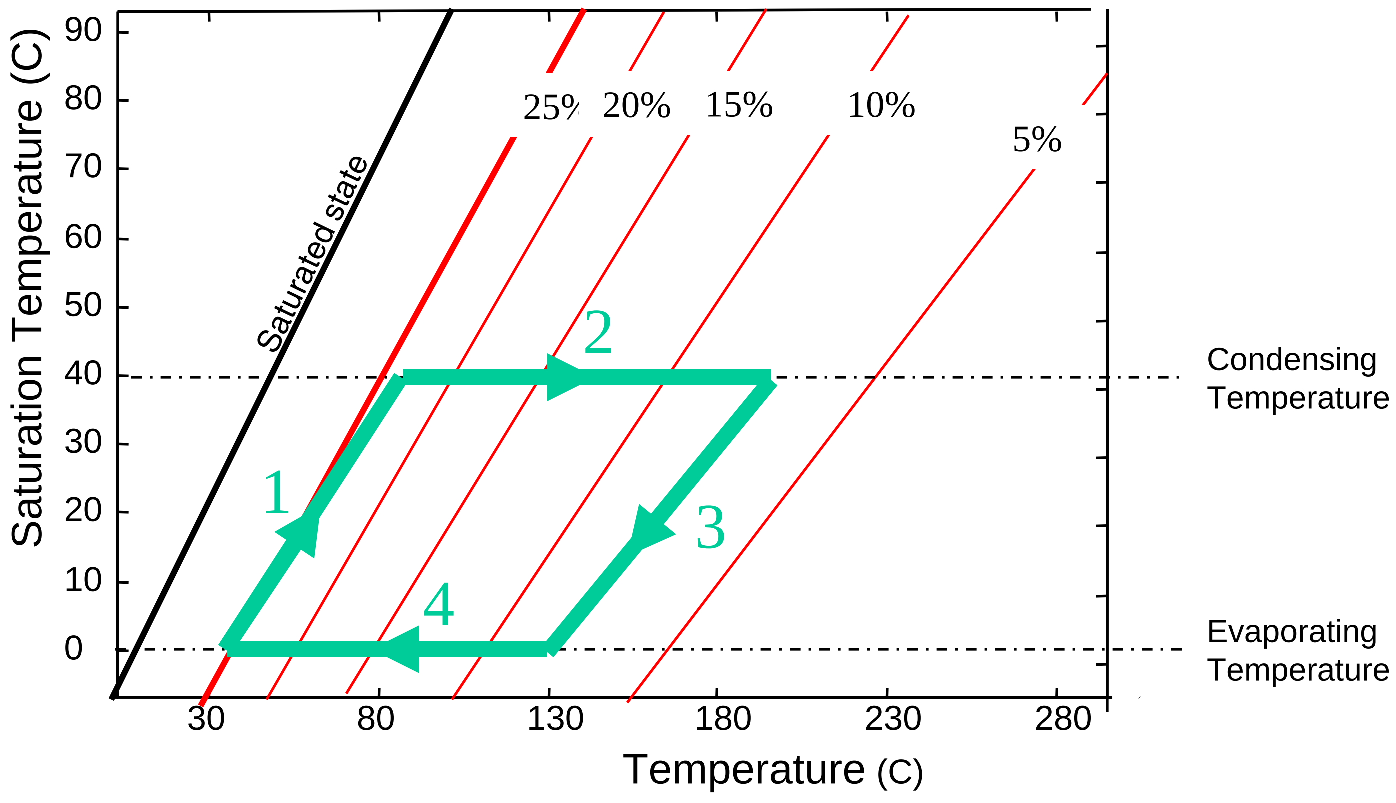
Idealised Adsorption Cycle

End of Process 4:

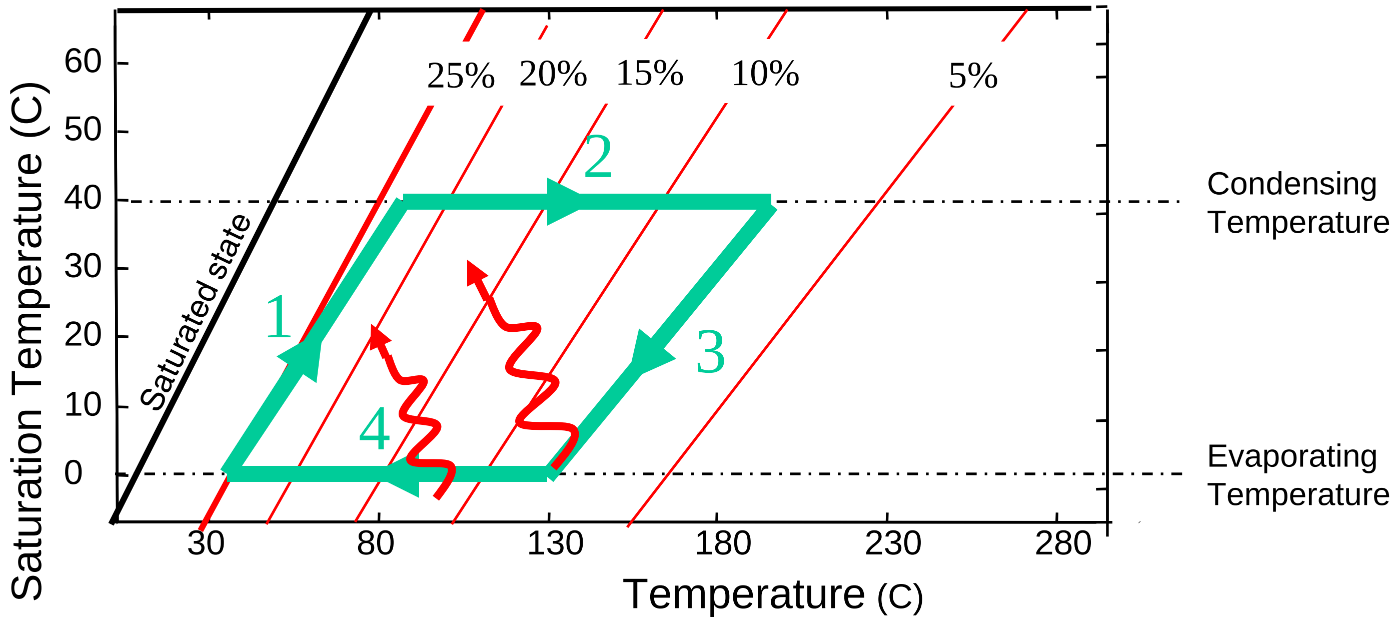
The system is returned to the starting condition



Representation of a simple cycle on the pressure – temperature – concentration diagram



Thermal Regeneration



Heat must be rejected during processes 3 and 4 where the carbon is cooled.

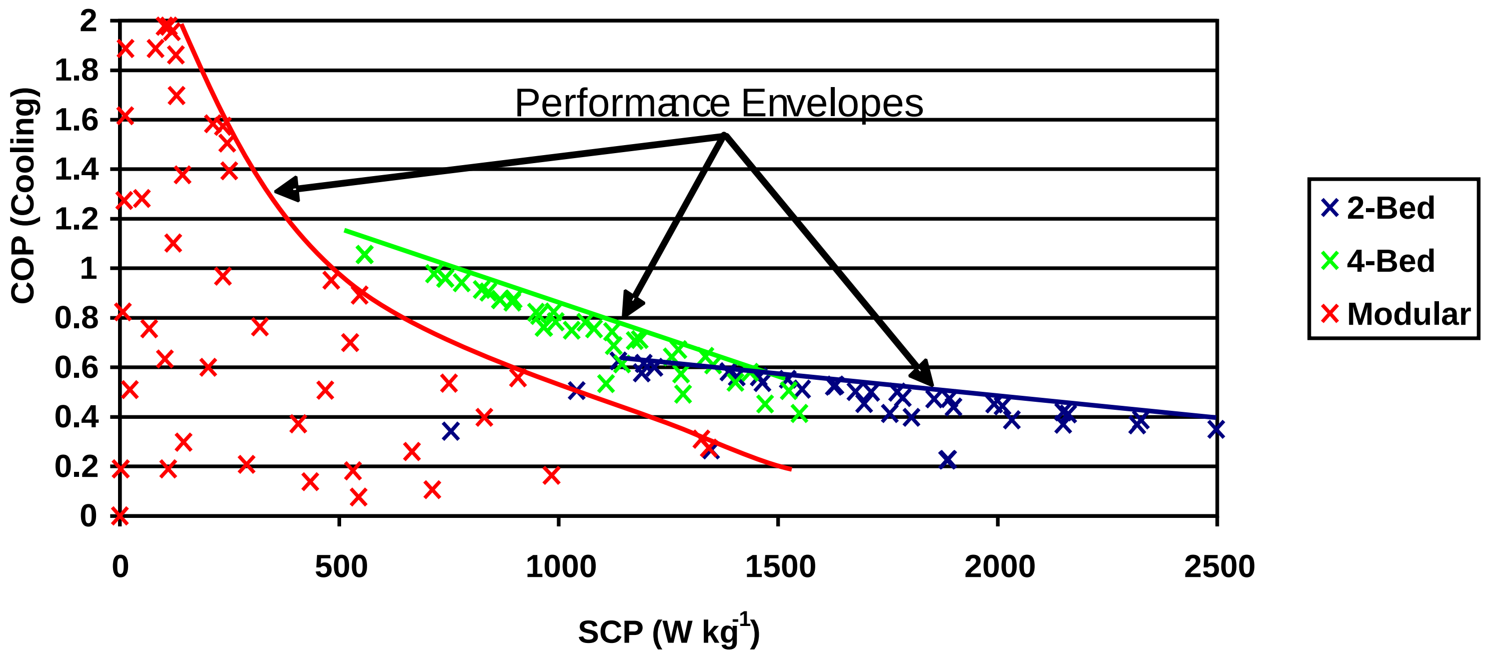
Some of that heat may be used in processes 1 and 2 where the carbon is heated.

This ***thermal regeneration*** gives high efficiency.

Cycle Selection

Two Main Heat Recovery Methods for Adsorption Cycles:

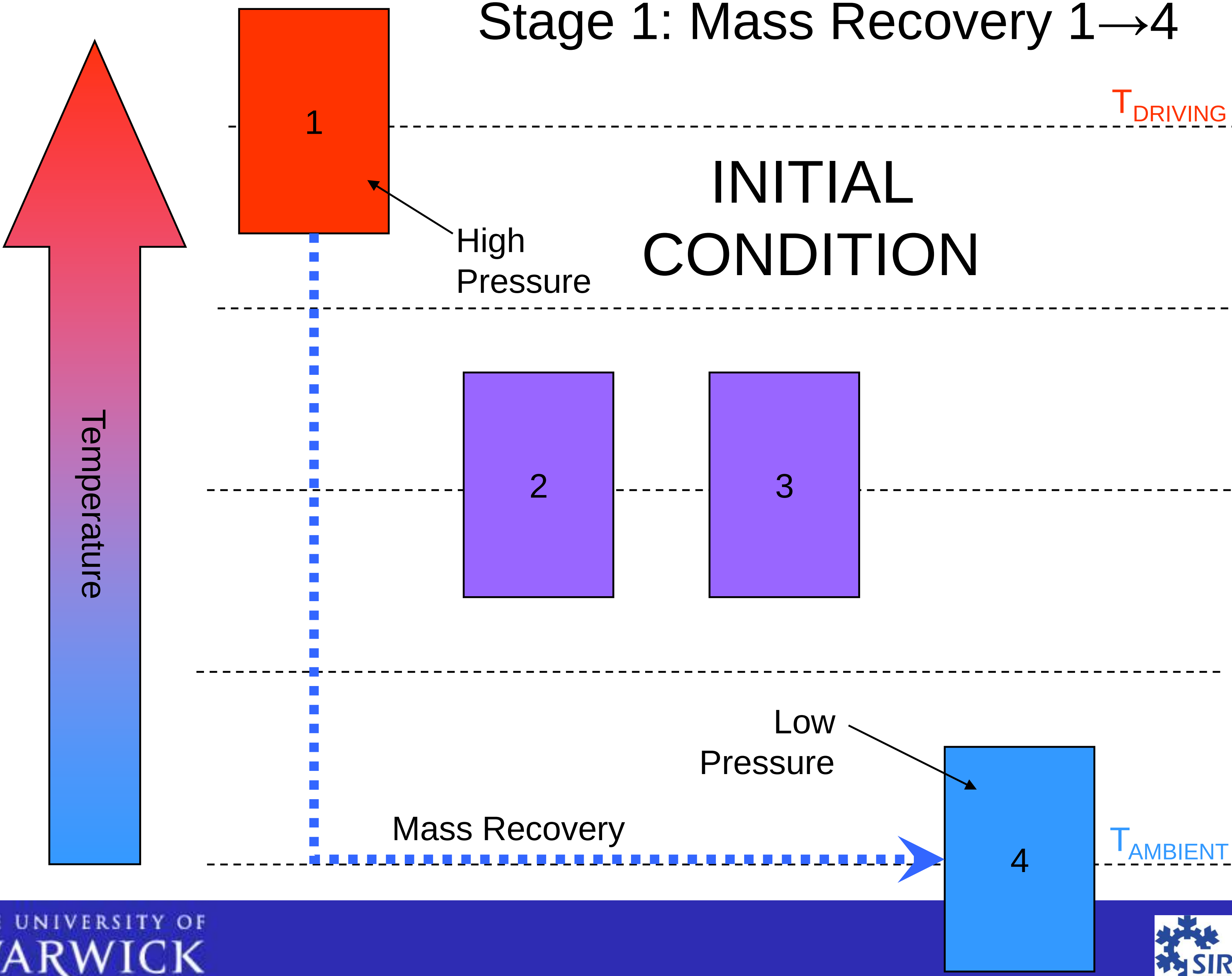
- **Thermal Wave (Performance envelope in Red Below)**
- **Multiple-Bed (Four-Bed In Green, Two-Bed In Blue)**



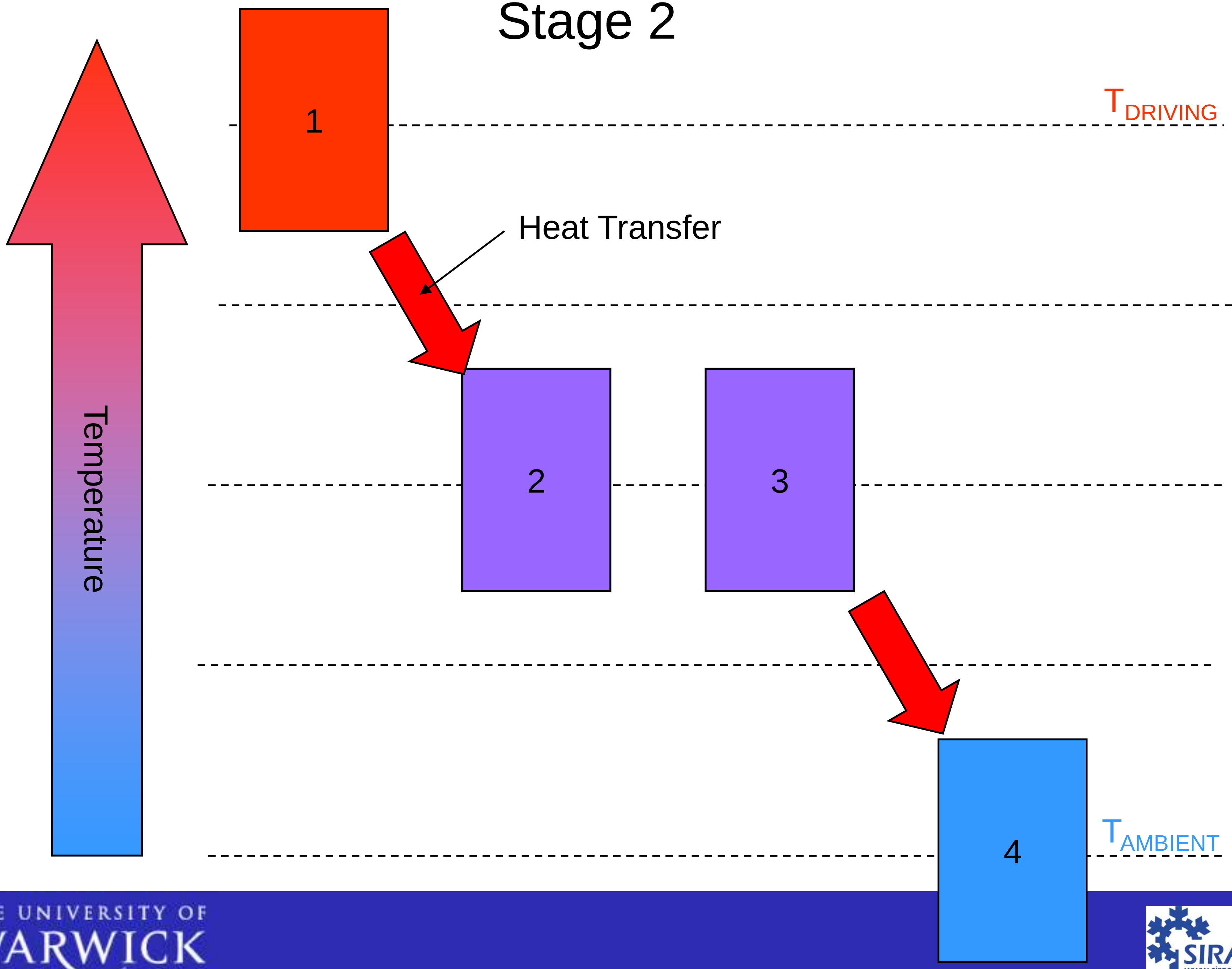
Four Bed Adsorption Cycle

Illustration of a Four-Bed Adsorption Cycle with Mass Recovery

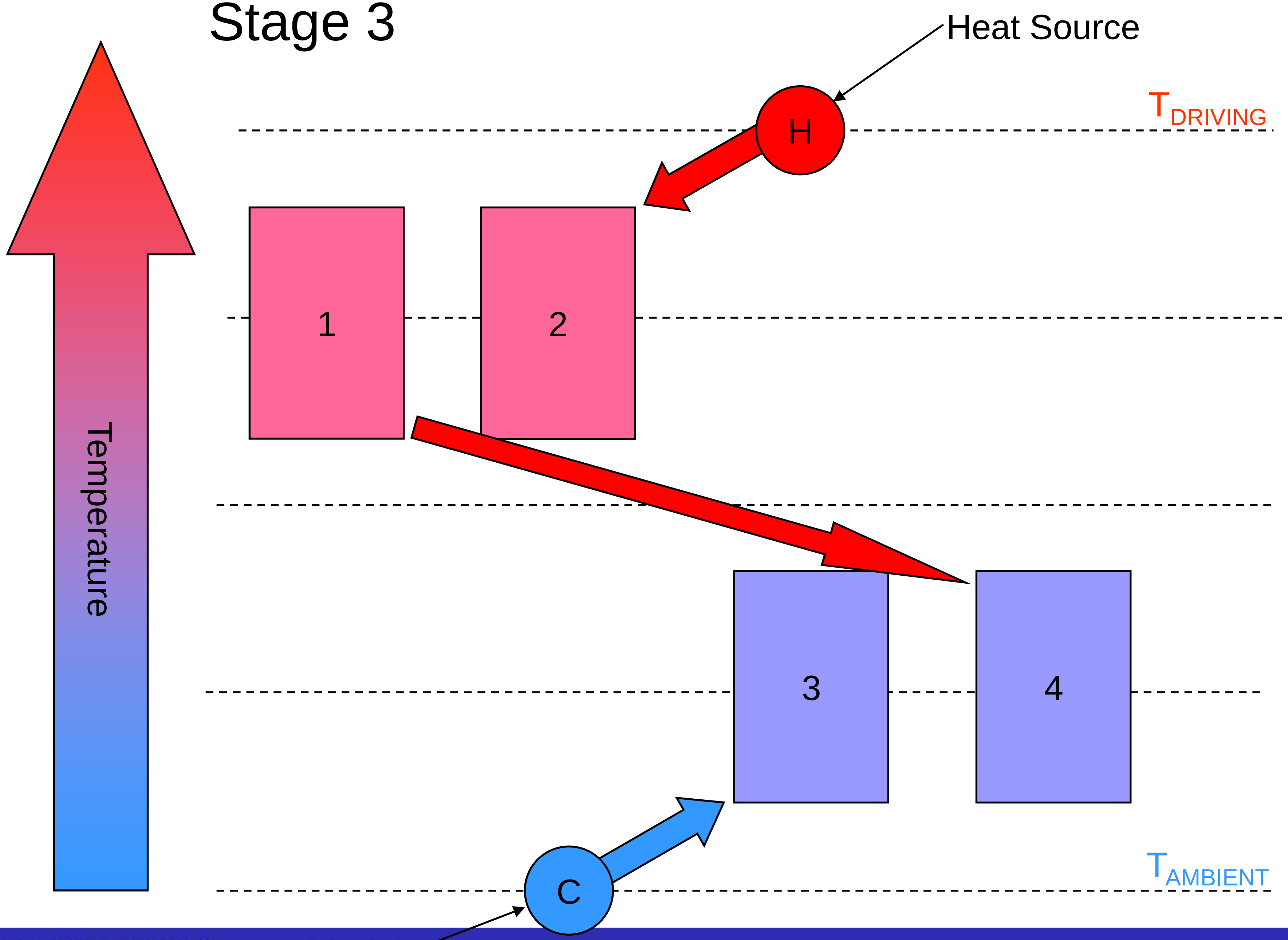
Stage 1: Mass Recovery 1→4



Stage 2

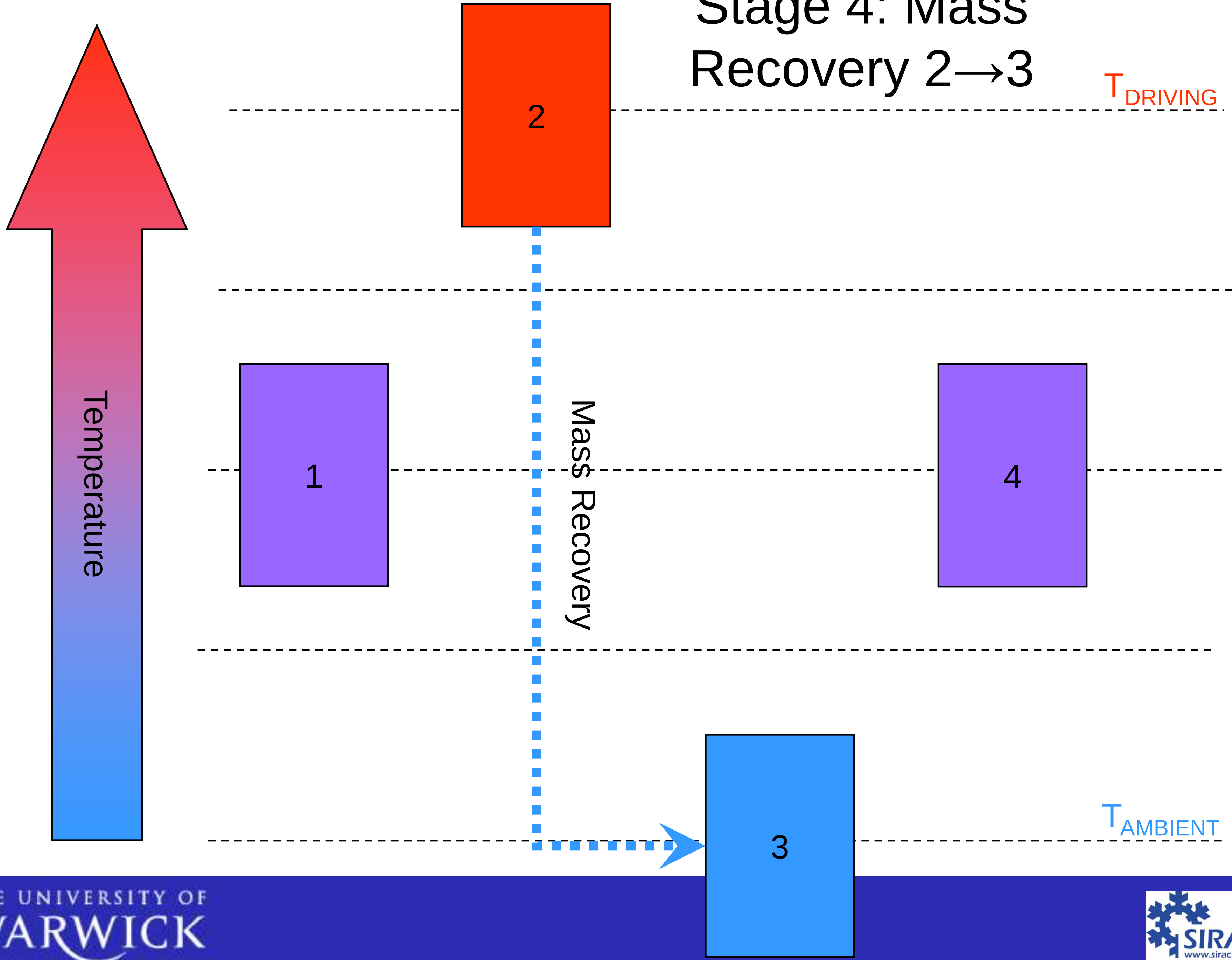


Stage 3

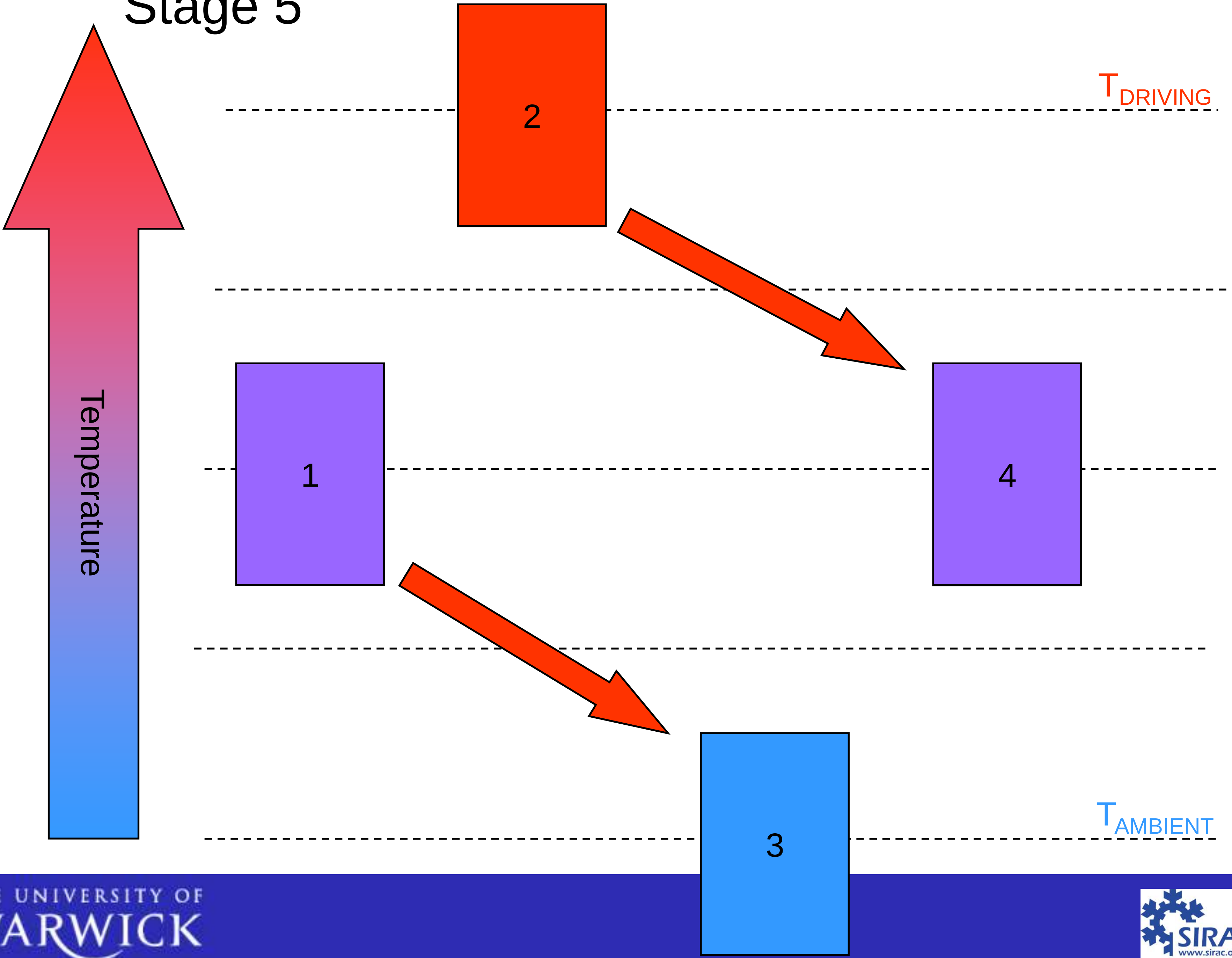


Heat Source
T DRIVING
H
1
2
Temperature
3
4
T AMBIENT
C
Cold Sink

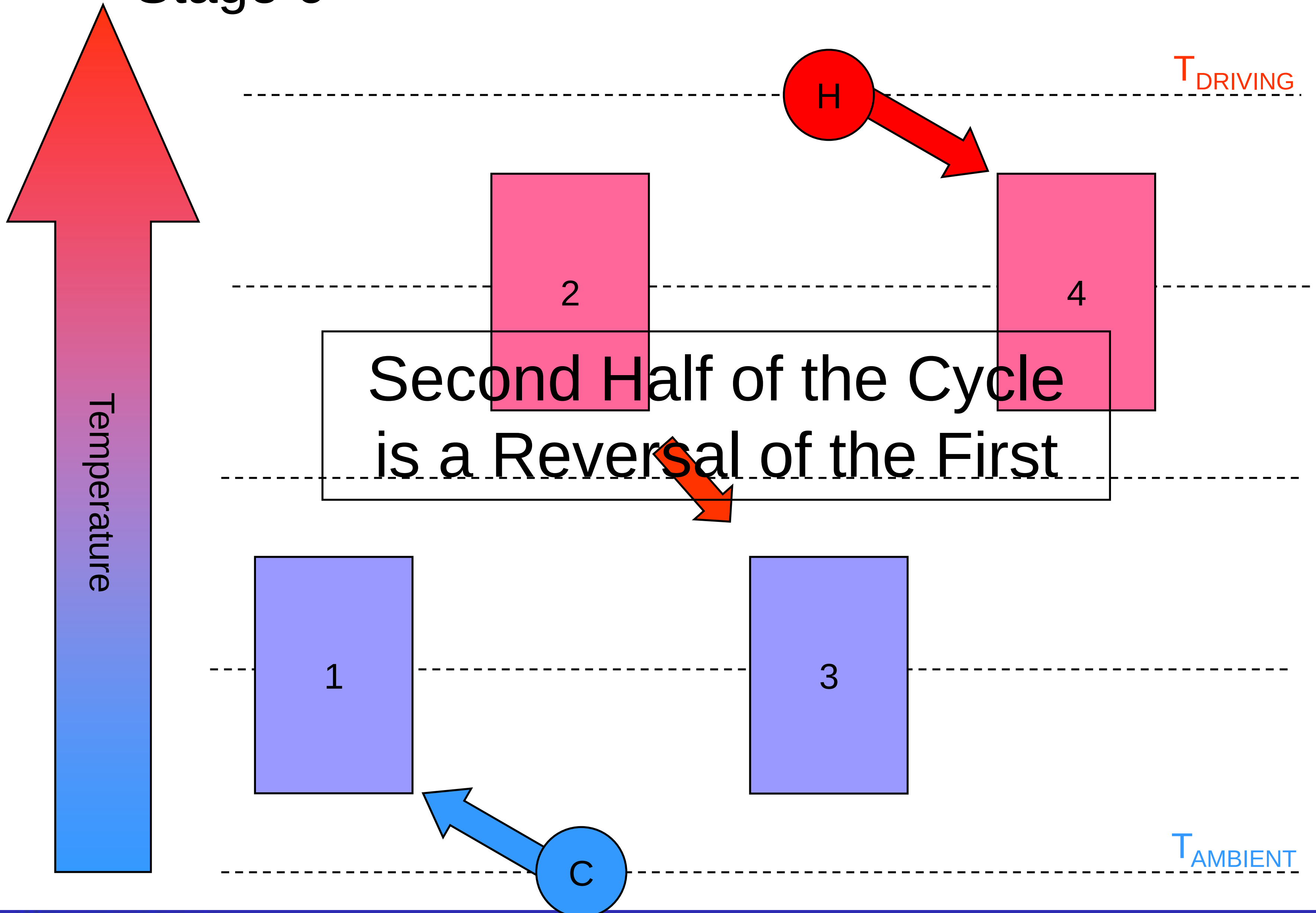
Stage 4: Mass Recovery 2→3



Stage 5



Stage 6


T DRIVING
H
2
4
Second Half of the Cycle
is a Reversal of the First
Temperature
1
3
T AMBIENT
C

PROBLEMS FACING ADSORPTION MACHINES:

- **Poor heat transfer**
  - ➡ **low specific power**
    - ➡ **high capital cost**
- **Simple cycle has low COP**
  - ➡ **high running cost**
- **Discontinuous processes**
  - ➡ **unsteady output**

PROBLEMS SPECIFIC TO AMMONIA :

- **Toxicity**
- **No copper or brass**

ADVANTAGES OF ADSORPTION MACHINES:

- **Rugged, not sensitive to vibration, orientation**
- **Regenerative cycles have a high COP**

ADVANTAGES OF AMMONIA :

- **High pressure, so permeability of sorbent is not critical**
- **Can be easier to engineer than sub-atmospheric systems**

Challenges common to all our research:

1. Getting heat in and out of a low conductivity granular bed.
2. Doing it with zero cost and zero mass!

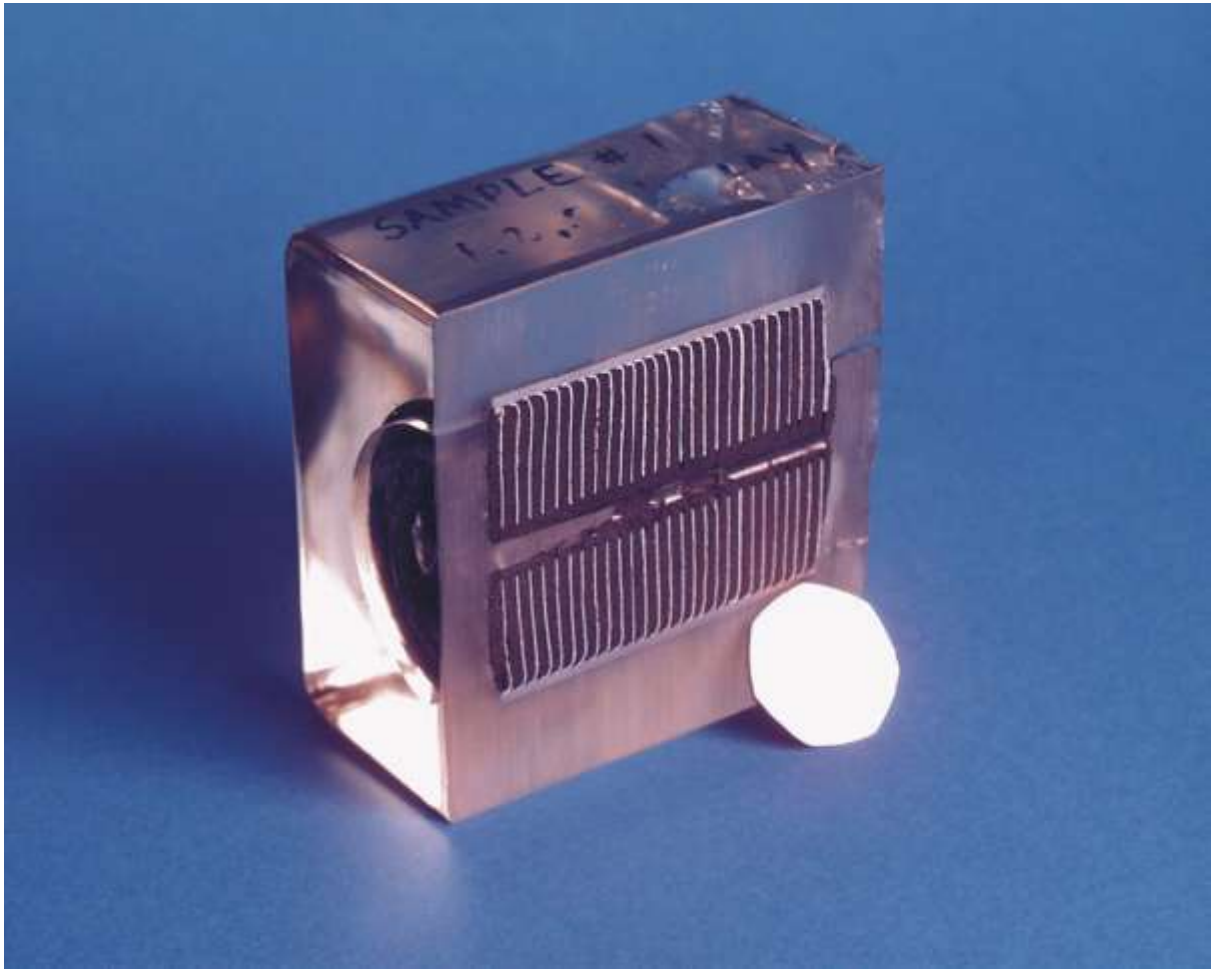
Previous approaches at Warwick :

1. **Monolithic carbon generators**
2. Multiple-Bed regenerative cycle
3. Plate heat exchanger bonded to thin layers of adsorbent.

GRANULAR CARBON

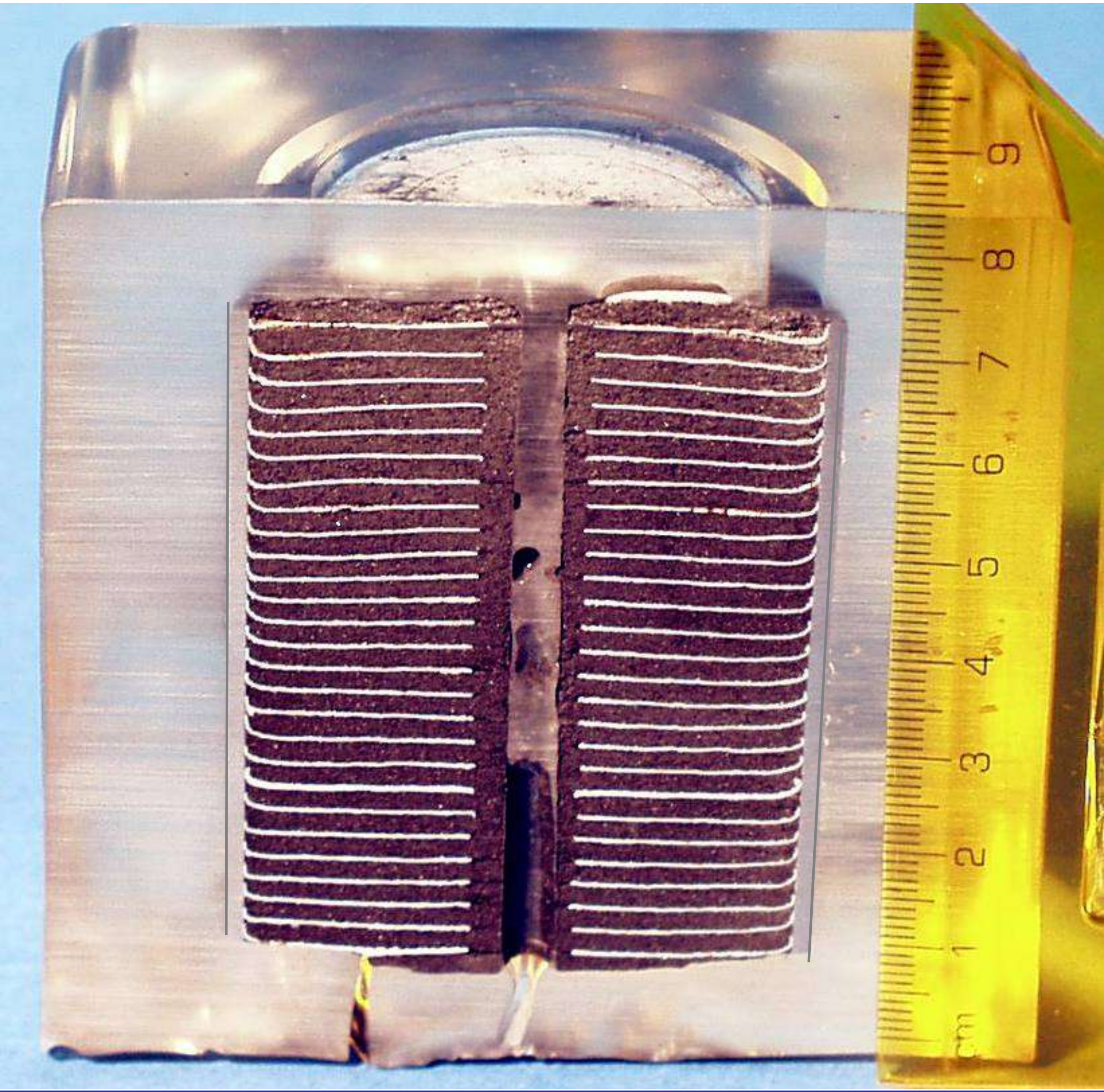
MONOLITHIC CARBON

Carbon- Aluminium Laminate



Carbon- Aluminium Laminate

Typical conductivity of monolithic carbon : 0.5 W/mK



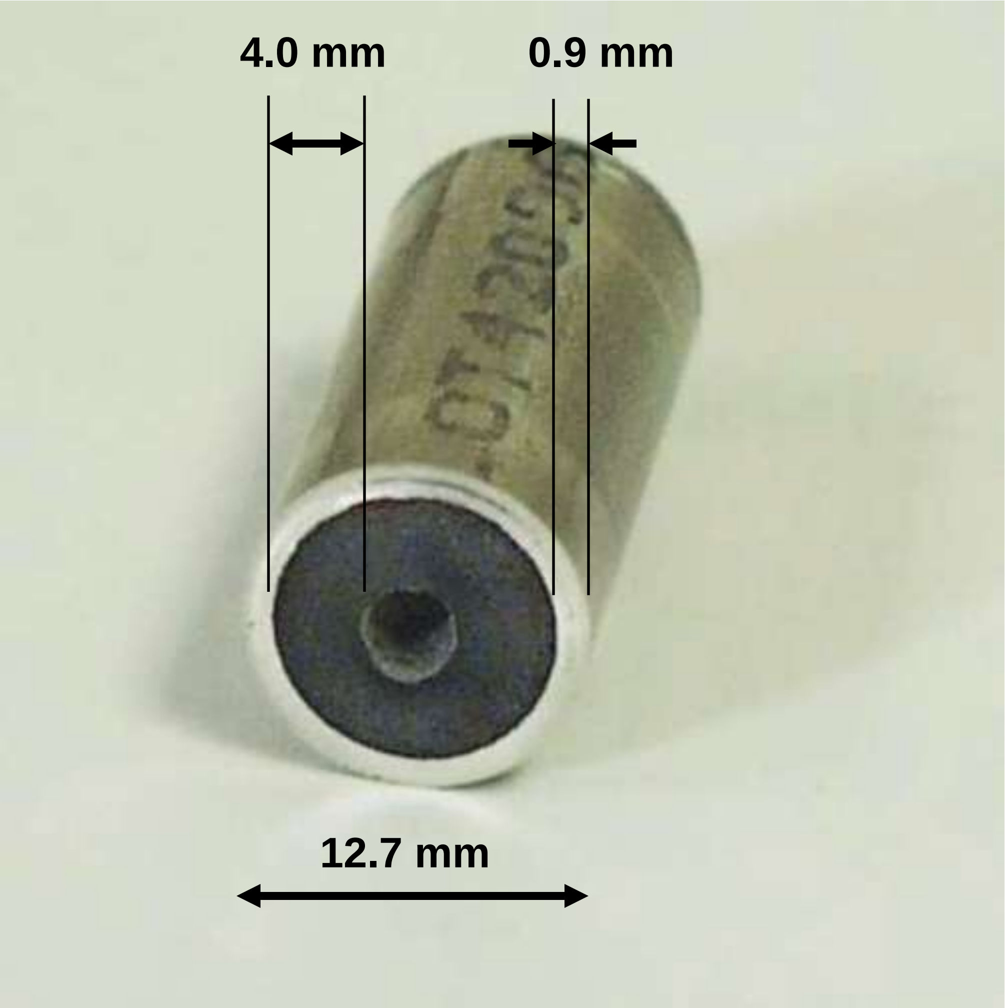
Typical radial conductivity of new carbon - aluminium laminate: 20 W/mK

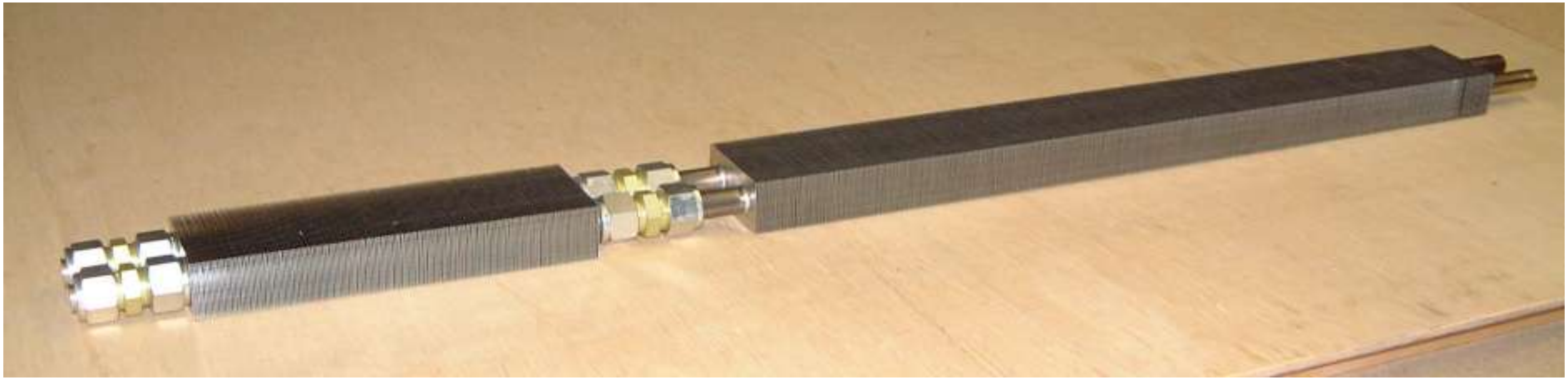
Previous approaches at Warwick :

1. Monolithic carbon generators
2. **Multiple-Bed regenerative cycle**
3. Plate heat exchanger bonded to thin layers of adsorbent.

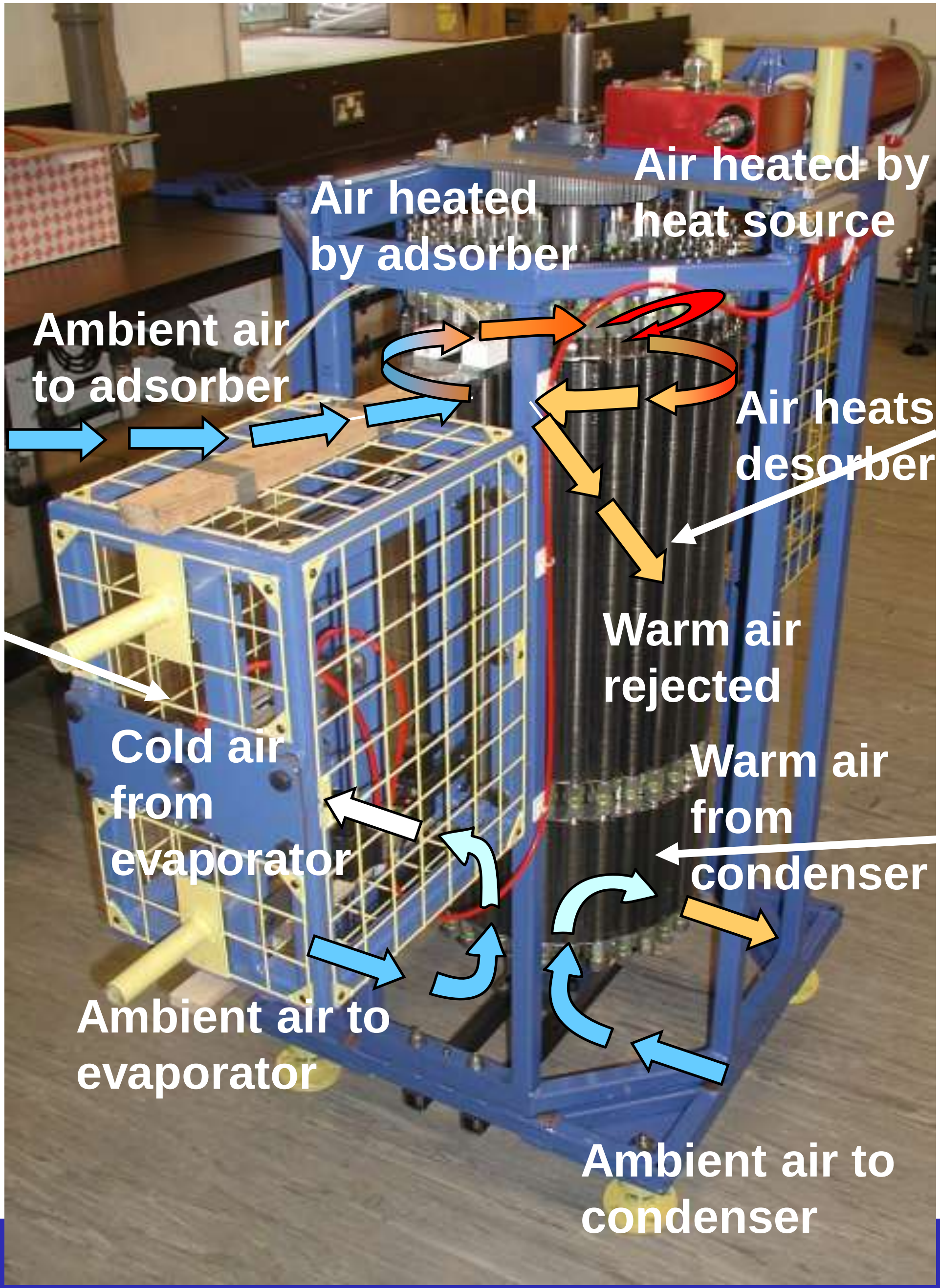
A patented cycle based on modular generators lined with monolithic carbon

Initial carbon-lined tube





Double sorption module



THE UNIVERSITY OF WARWICK

SIRAC www.sirac.org.uk

Complete machine – Outer cladding in place

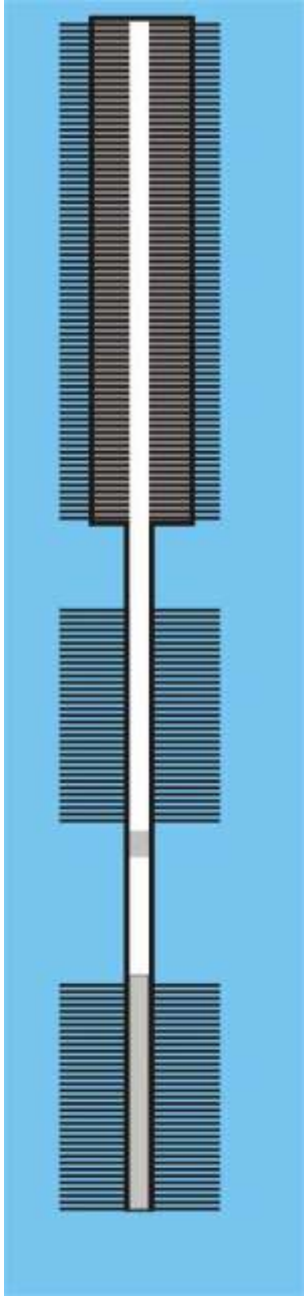
The realisation that the mechanical complexity outweighed the benefits of the 'counterflow' design, lead us to a low-cost 'cross-flow' concept…

VARIATIONS ON MODULE DESIGNS:

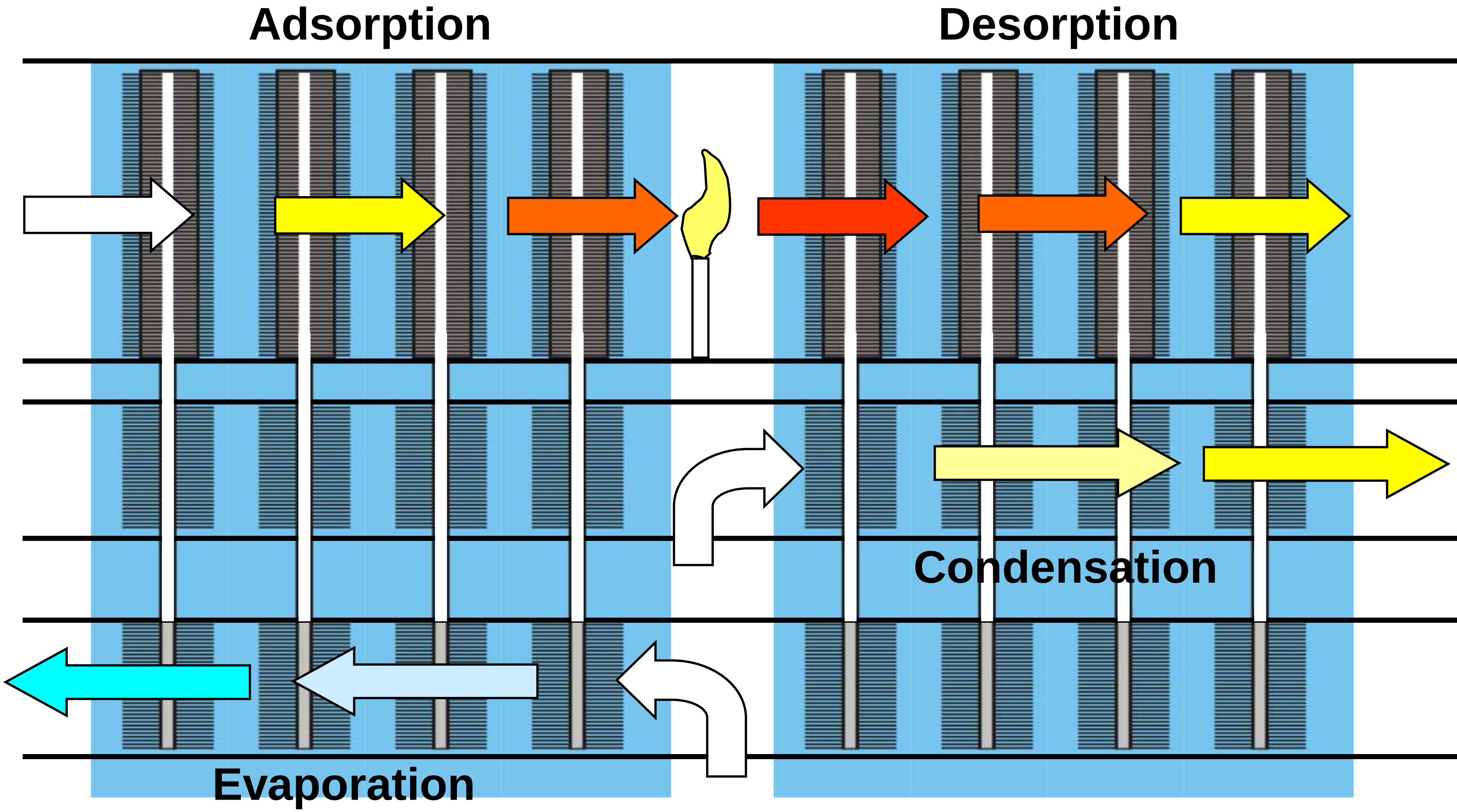
Advanced module (separate condenser and evaporator)

Fixed beds – Being used on 'SOCOOL' tri-generation project

Module with separate evaporator, receiver and condenser

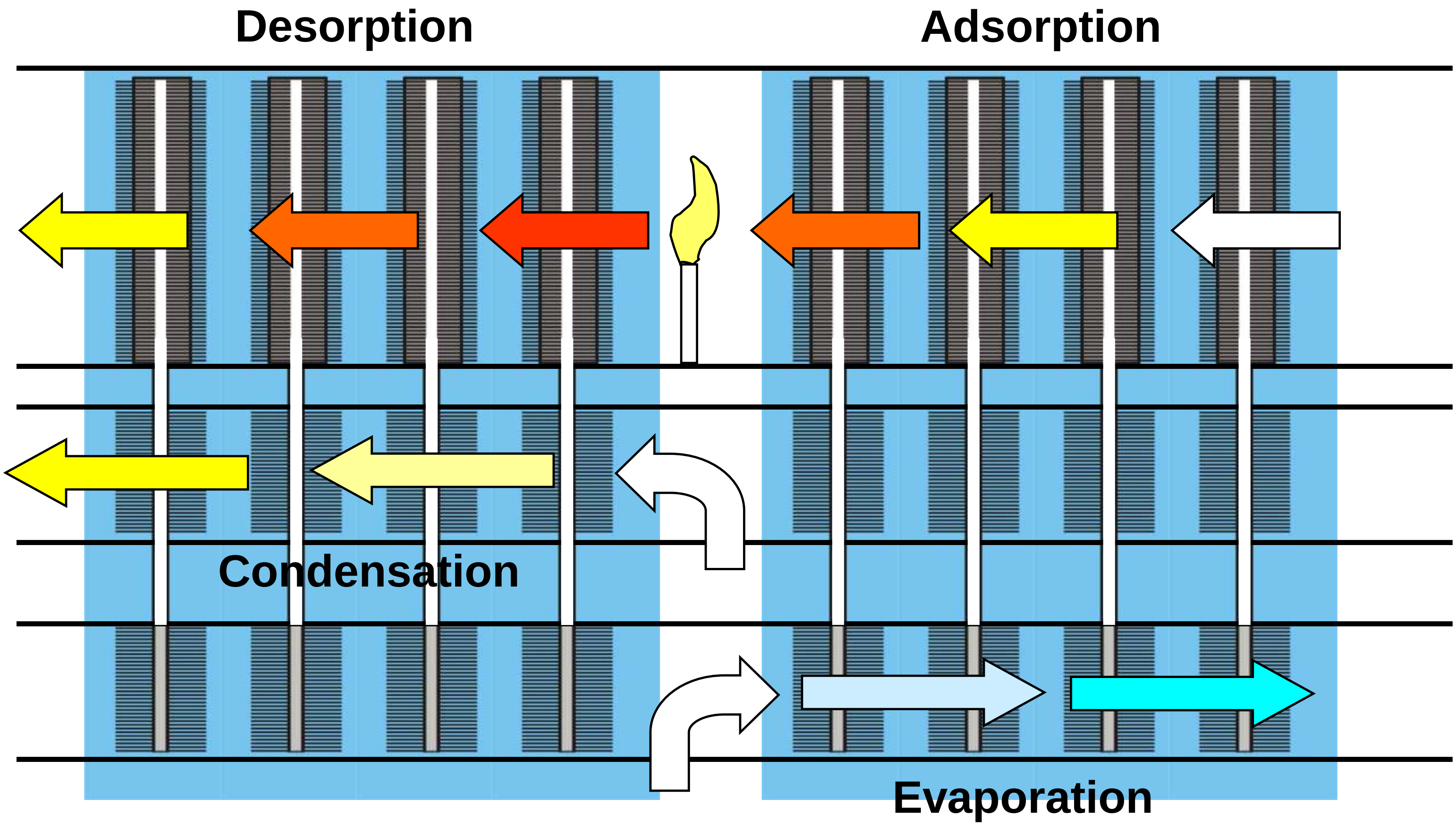


FIXED MODULAR BED CONFIGURATION



Phase 1

FIXED MODULAR BED CONFIGURATION



Phase 2

‘Spinner’ project using the fixed bed design

The advantages are those of simplicity – the only moving parts are fans.

A 1–2 kW air conditioner for laboratory demonstration was built in early 2006.

‘Spinner’ project

Generator section

Condenser section

Receiver section

Evaporator section

‘Spinner’ project

Assembled prototype without fans

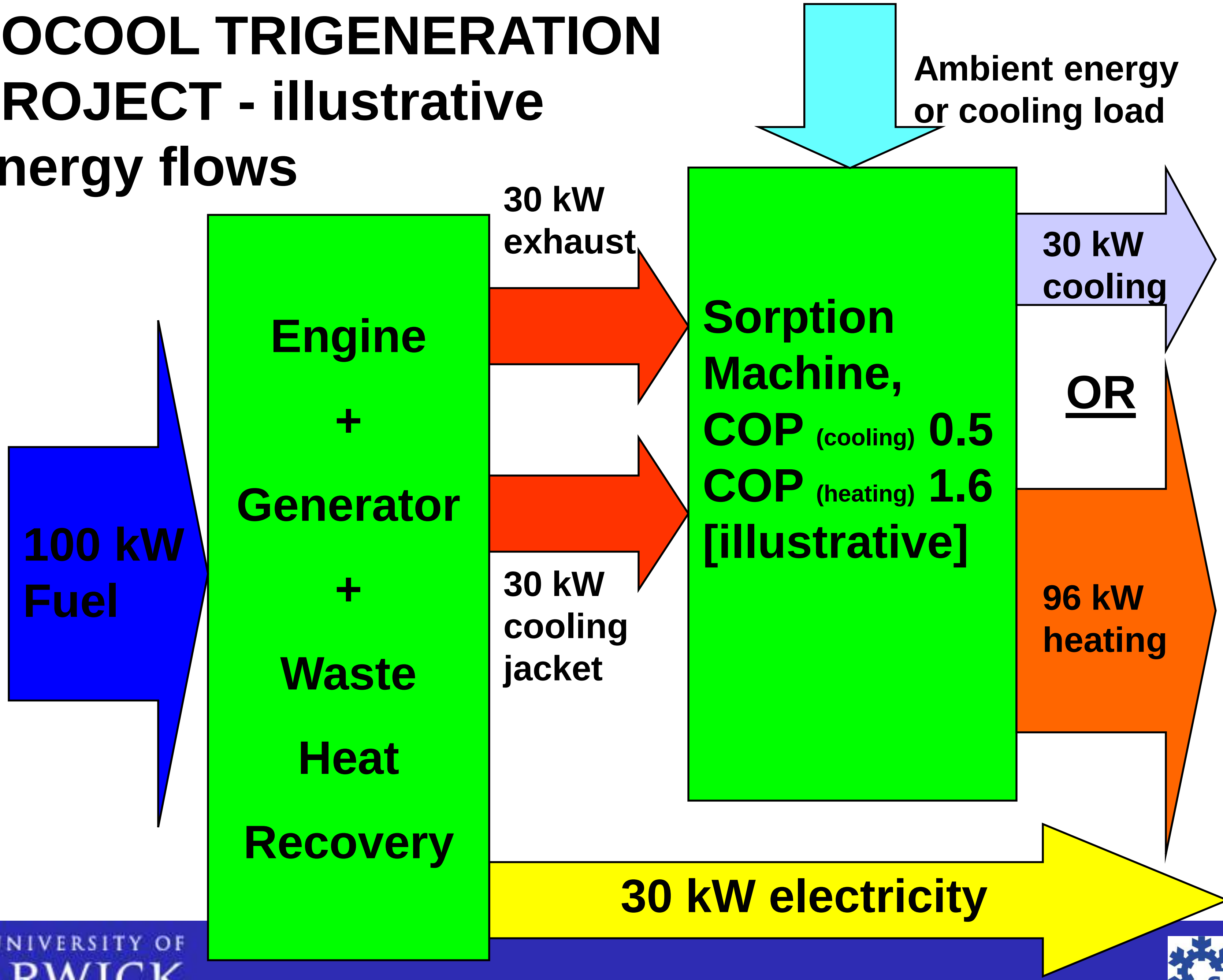
Advantages :

- **Sealed modules are low-cost and safe**
- **No ammonia valves or controls**
- **Only moving parts are the fans**

Disavantages :

- **More modules needed than for rotating system**

SOCOOL TRIGENERATION PROJECT - illustrative energy flows



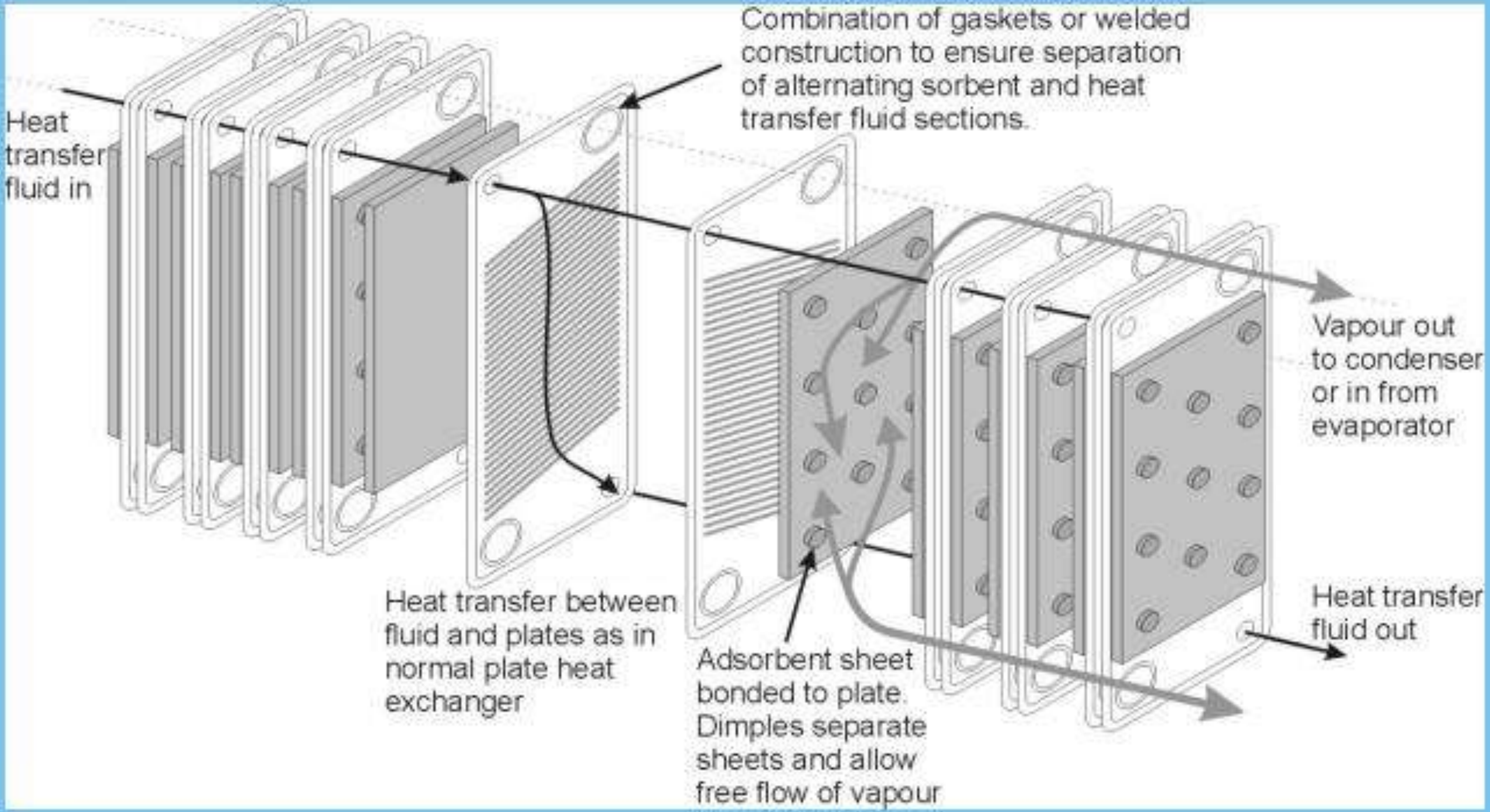
Single module under test, January 2005

5 kW SOCOOL prototype before delivery to Italy

THE COMPLETE UW SOCOOL MACHINE INSTALLED AT CRF

Previous approaches at Warwick :

1. Monolithic carbon generators
2. Multiple-Bed regenerative cycle
3. **Plate heat exchanger bonded to thin layers of adsorbent.**



Has been investigated in a group project during 2003/4

Inlet Temperature 200C

Condensing temperature 30 C

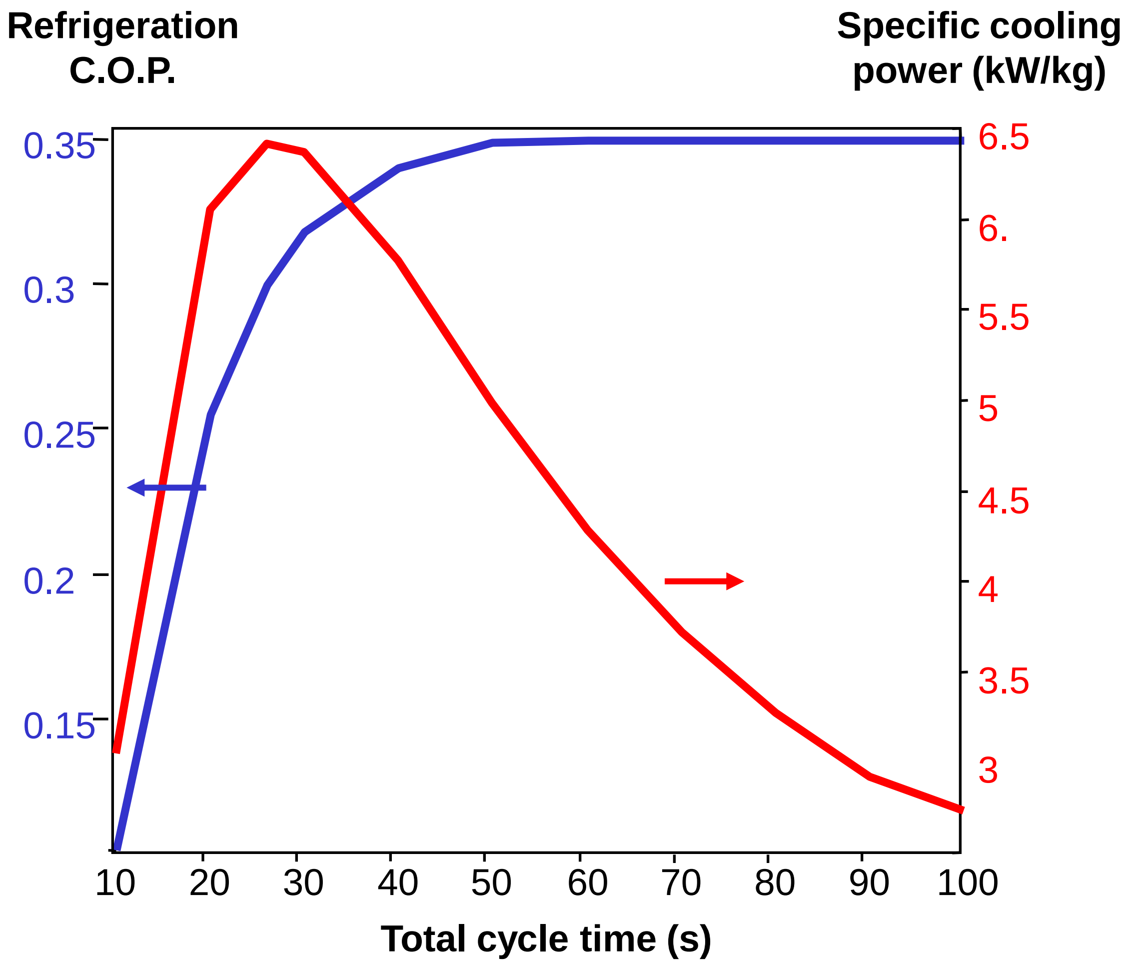
Evaporating temperature 15 C

Carbon thickness 1mm

Wall thickness 0.1mm

Fluid channel thickness 0.25mm

h=1080 W/m² K



This is two orders of magnitude more compact than commercially available adsorption refrigerators

THE UNIVERSITY OF WARWICK

SIRAC www.sirac.org.uk

Advantages

- **VERY compact**
- **Low ammonia mass**

Disadvantages

- **Not yet demonstrated – some technical risks (seals, thermal shock)**
- **Liquid-liquid heat transfer may not suit all applications**

This lead to an EU-funded project, 'TOPMACS', aimed at heat operated car/truck air conditioning.

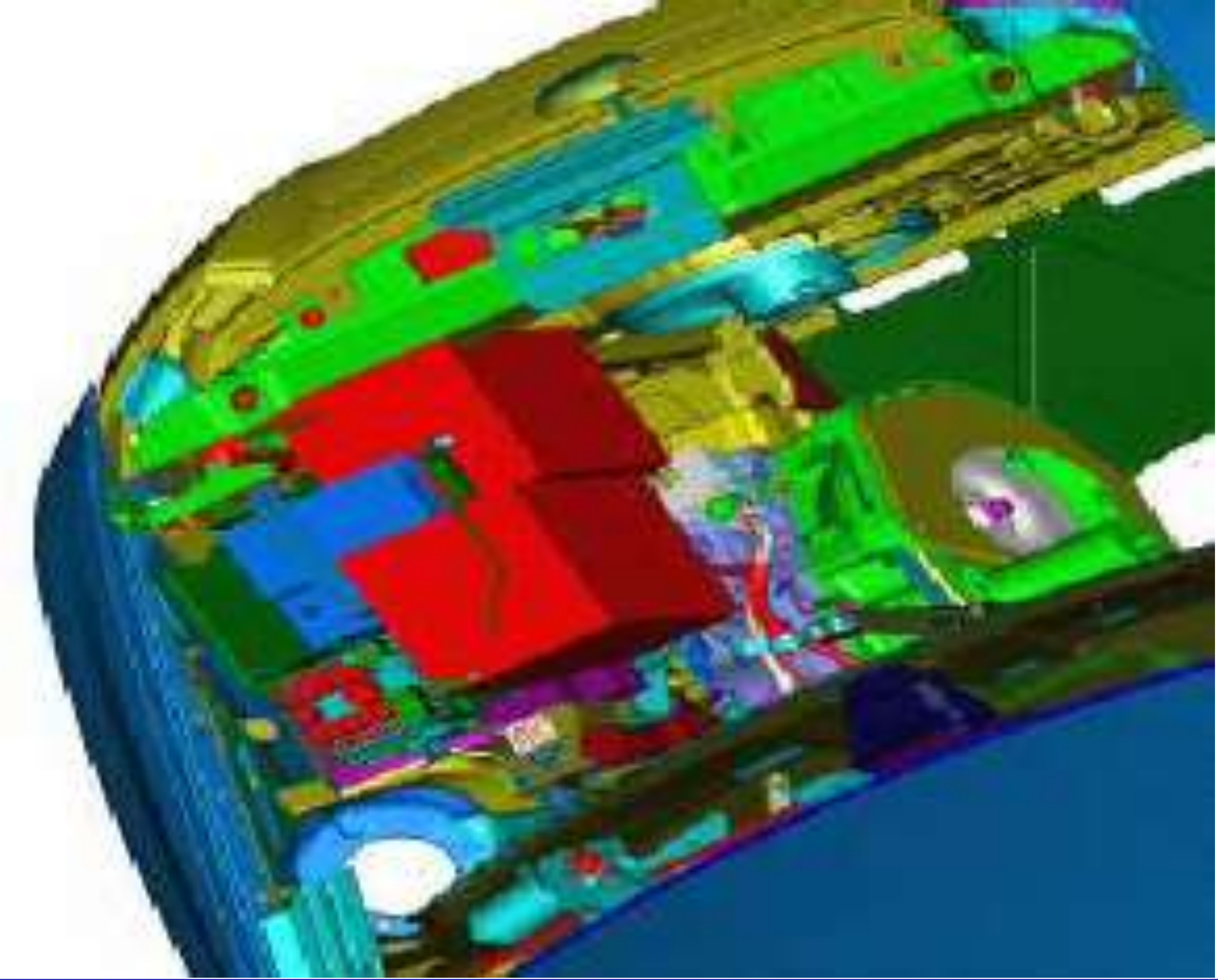
It was coordinated by CRF and started in March 2005.

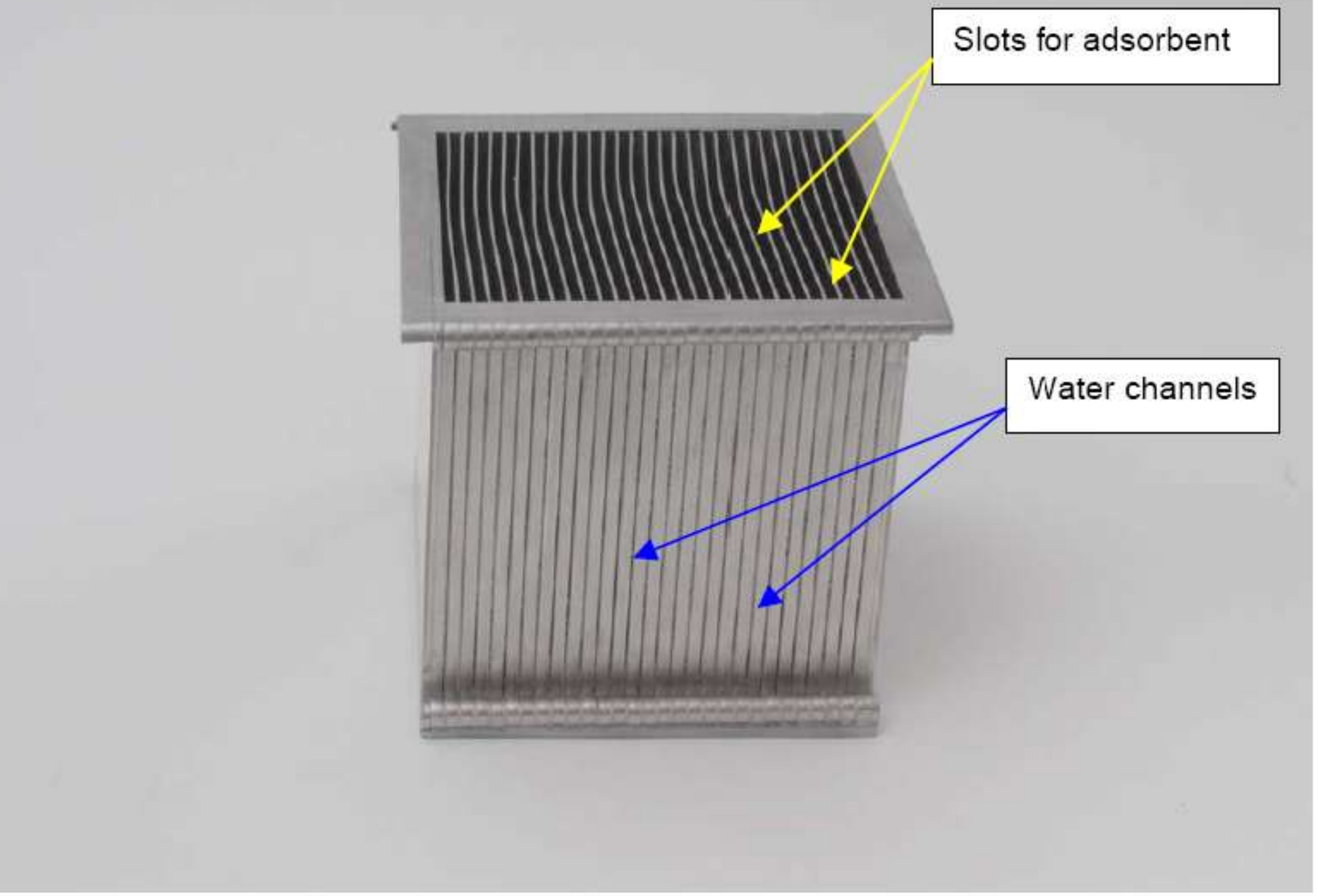
We collaborated with Chemviron Carbon and Bodycote to work on a novel brazed plate generator design.

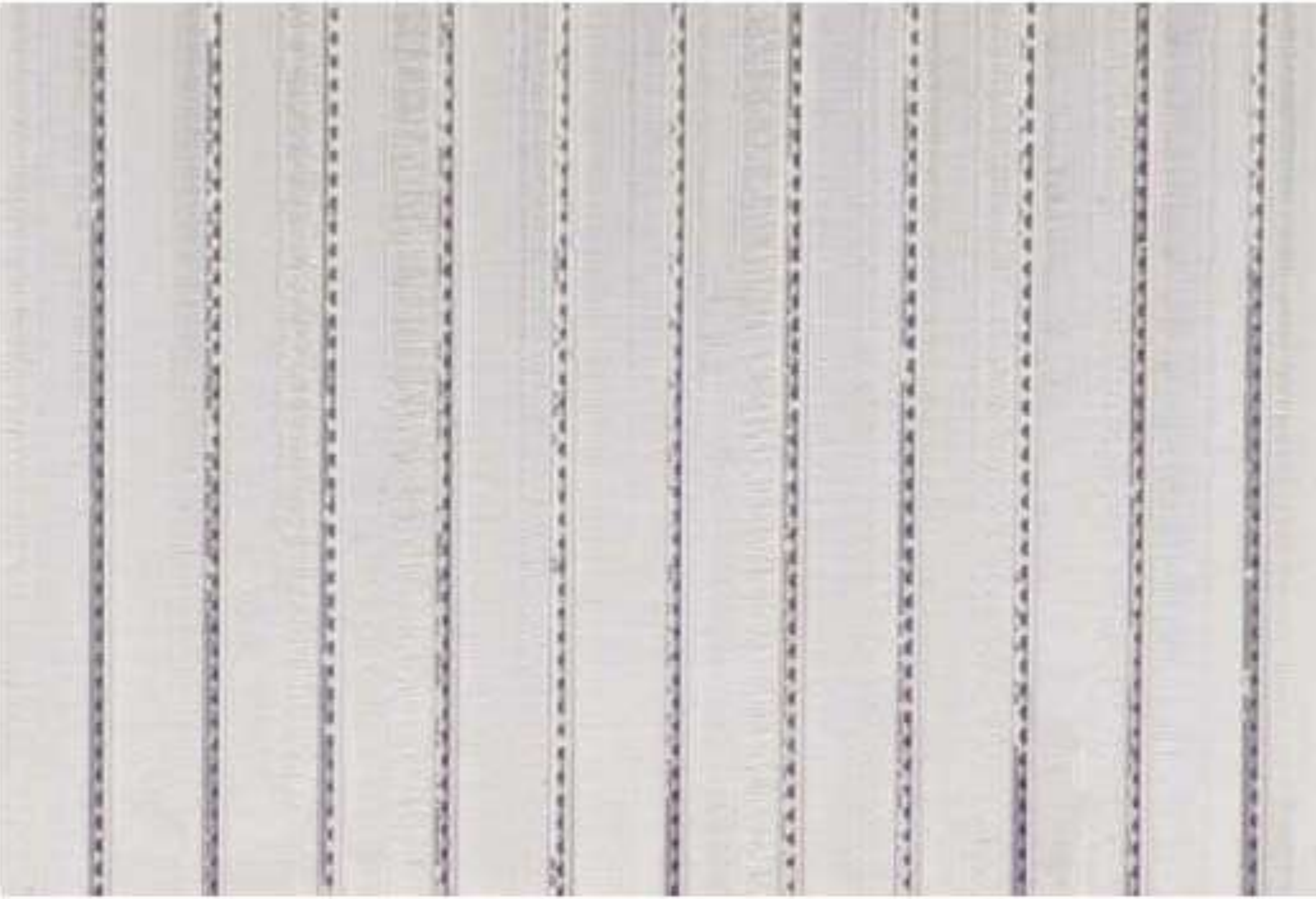
Two applications:

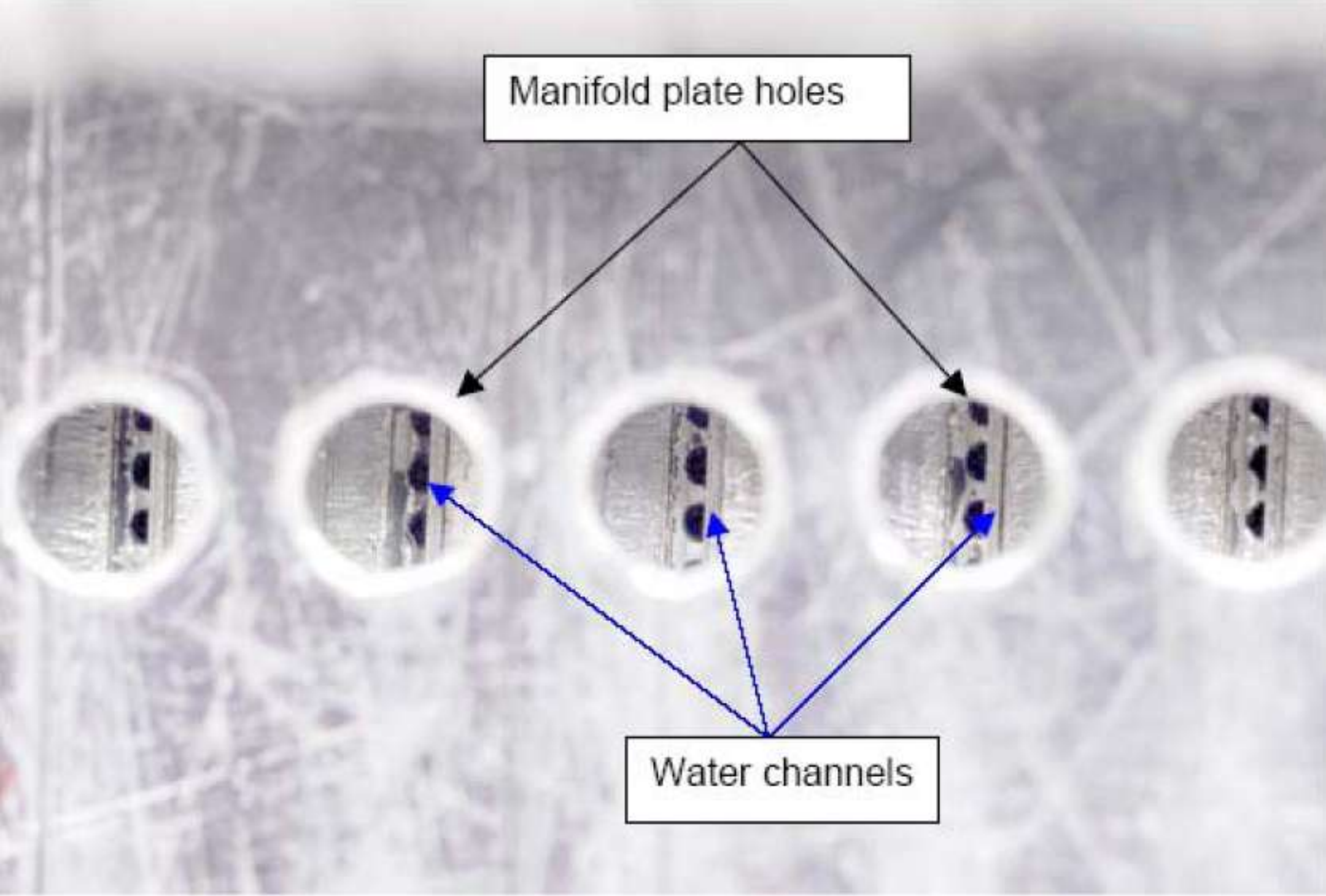
- **C-Class car (2 -3 kW)**
- **Long distance truck**

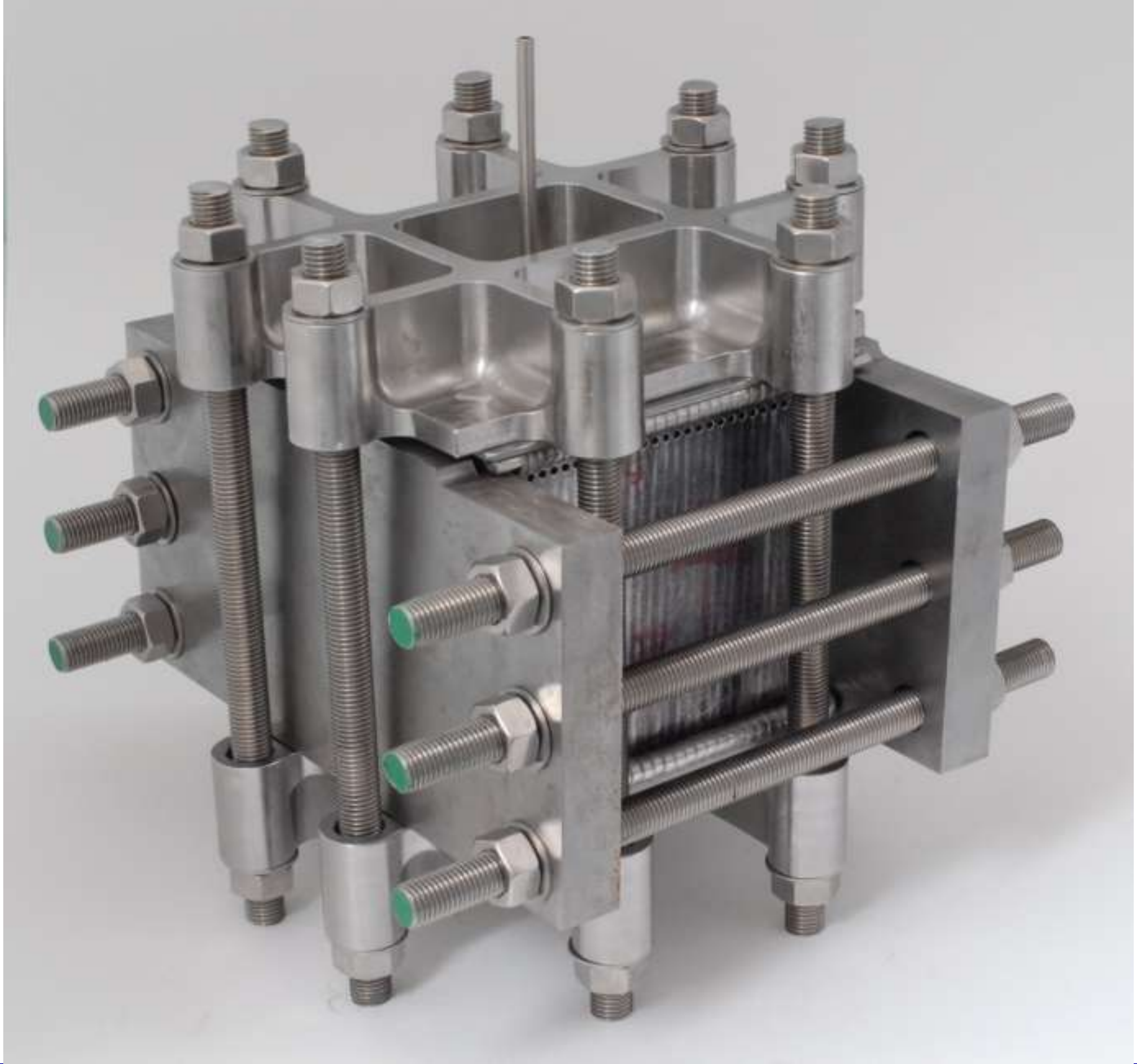
The car application has a potential fuel consumption reduction of 8% in southern European climates.




Slots for adsorbent
Water channels

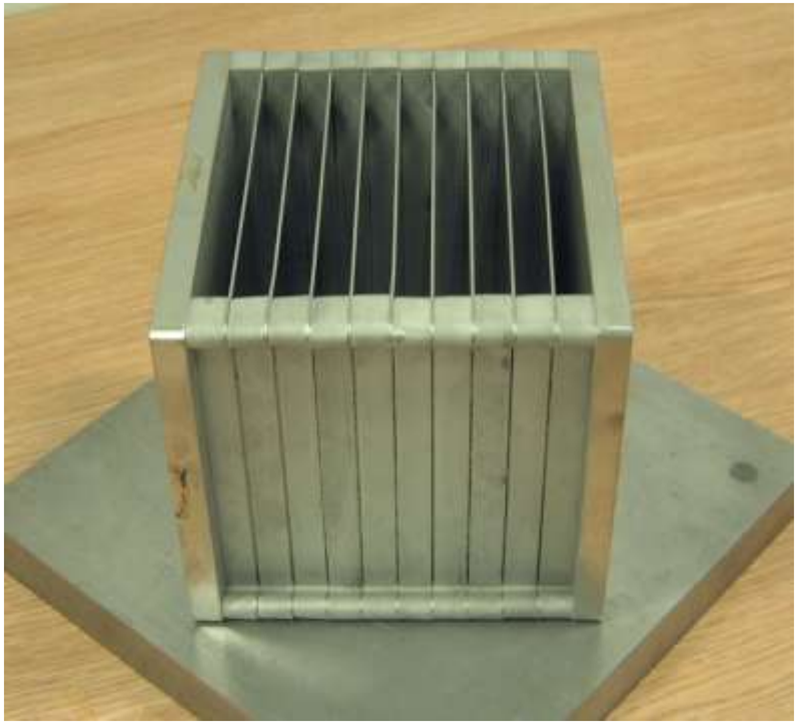



Manifold plate holes
Water channels



Sorption Generator Design

Plate Heat Exchanger – 12mm shim spacing design used with aluminium fins



We are actually using the plate technology in three separate projects:

- Gas fired heat pumps
- Solar powered refrigeration
- Car air conditioning

More on that from my colleagues later…

Laboratory Prototype 2-bed heat pump (10kw heating) tested successfully.

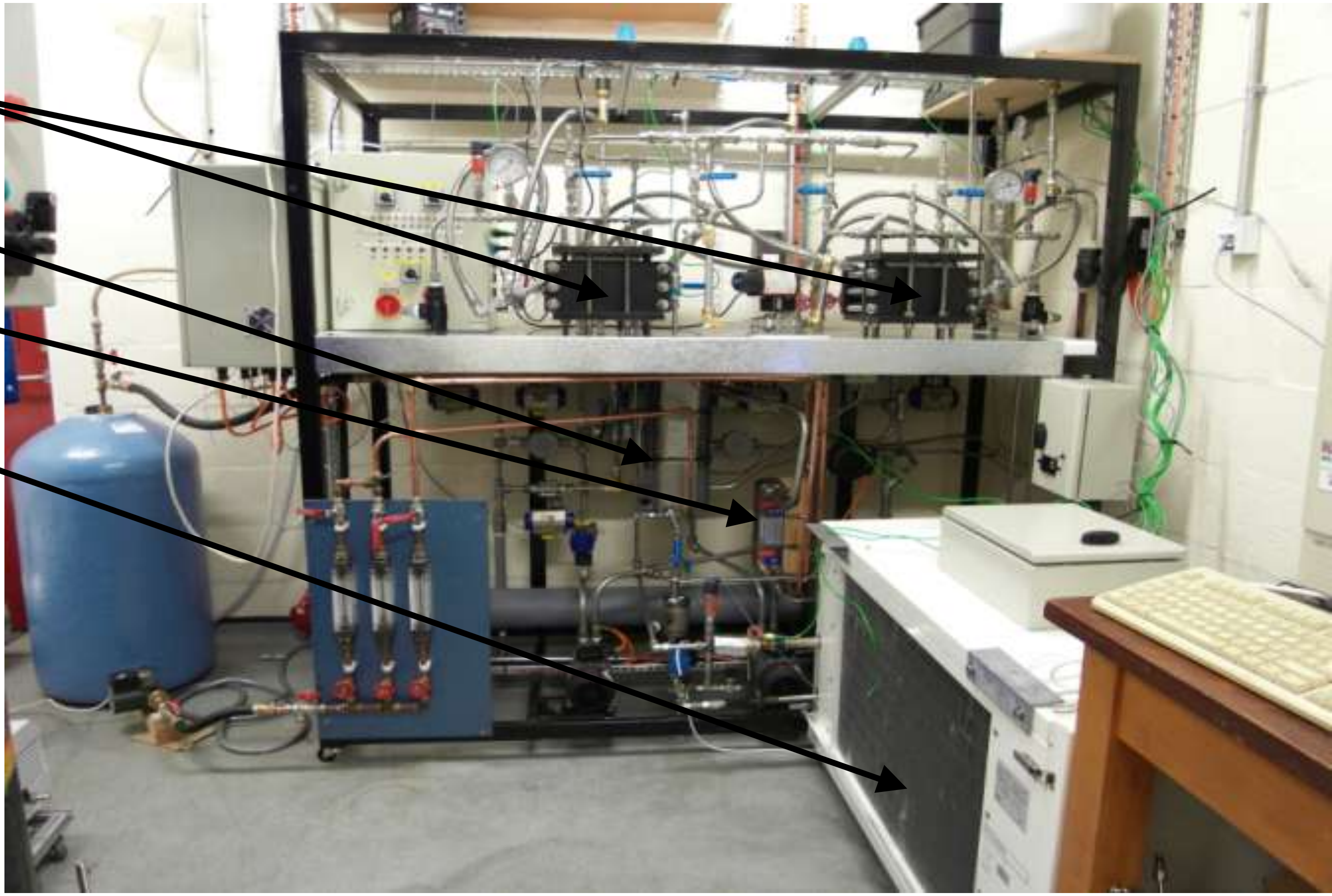
Sorption generators

Condenser

Cooler

Air-ammonia evaporator

We <u>can</u> fit this in a small space…



Achieved:

- All major components installed
- New adsorbent tested
- Control algorithm chosen
- Water loops installed

To do :

- New generators to be completed and filled with carbon
- Test in laboratory with electric heating
- Deliver for testing in Arizona

ATMI Solar refrigerator

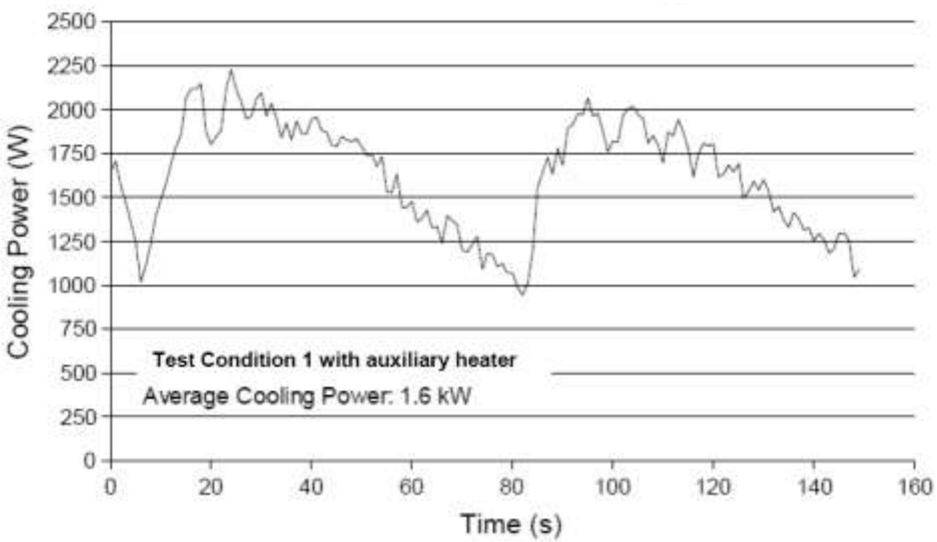
Car Air Conditioning Project Summary:

- Successful demonstration of plate heat exchanger concept
- Short cycle times
- Accurate performance predictions
- Power density –

  SOCOOL 2.5 W/litre

  Sortec 4 W/litre

  Latest machine **63 W/litre**



New development :-

Sorption Energy

Commercialisation

Sorption Energy formed to spin technology out of University of Warwick for commercial success

H2O Venture Partners acting as commercialisation partner to bring quality business skills

- Engaging full time with Sorption Energy until first significant (£multimillion) funding round

Now engaging with vehicle builders and Tier1 suppliers

- Validation of market concept
- Understanding of market and timelines
- Support and advice on in-vehicle demonstrator

CALEBRE and FoF to develop gas fired heat pump technology

Watch this space…

Thank you!