Adsorption Refrigeration Research at Warwick

Prof. R.E. Critoph

Contents:

1. Background
2. Previous research projects
3. Current projects and future plans

Background:

We are focussed on adsorption cycles for:

- Heat pumps
- Refrigerators
- Air conditioning

Driven by heat from:

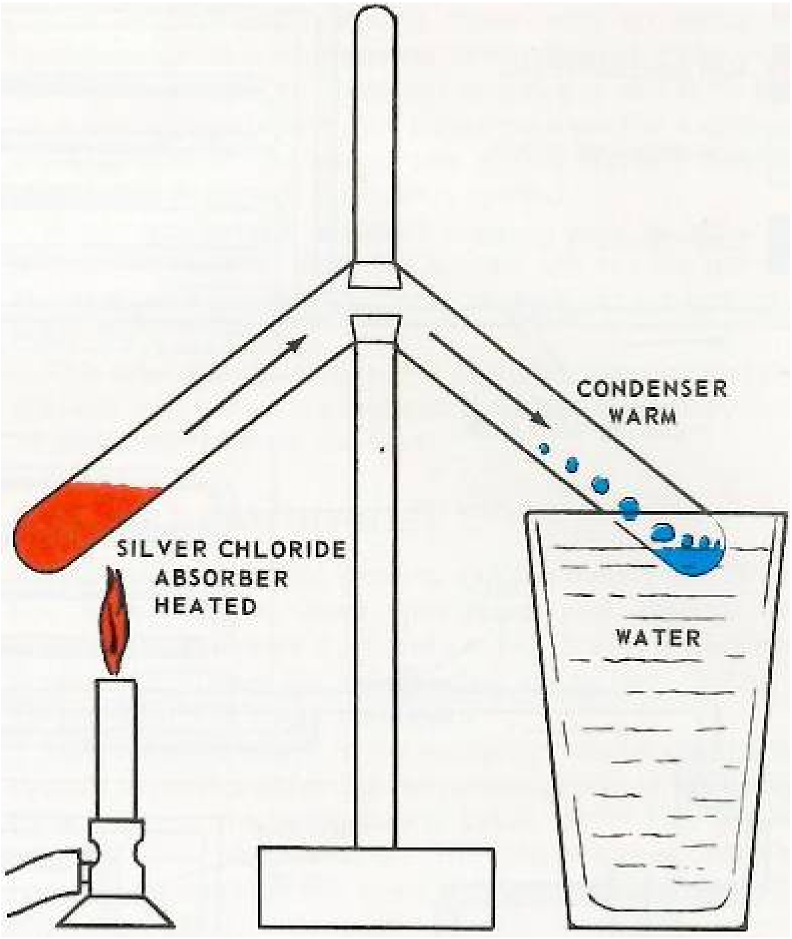
- Fossil fuels
- Bio fuels
- Waste heat
- Solar thermal energy

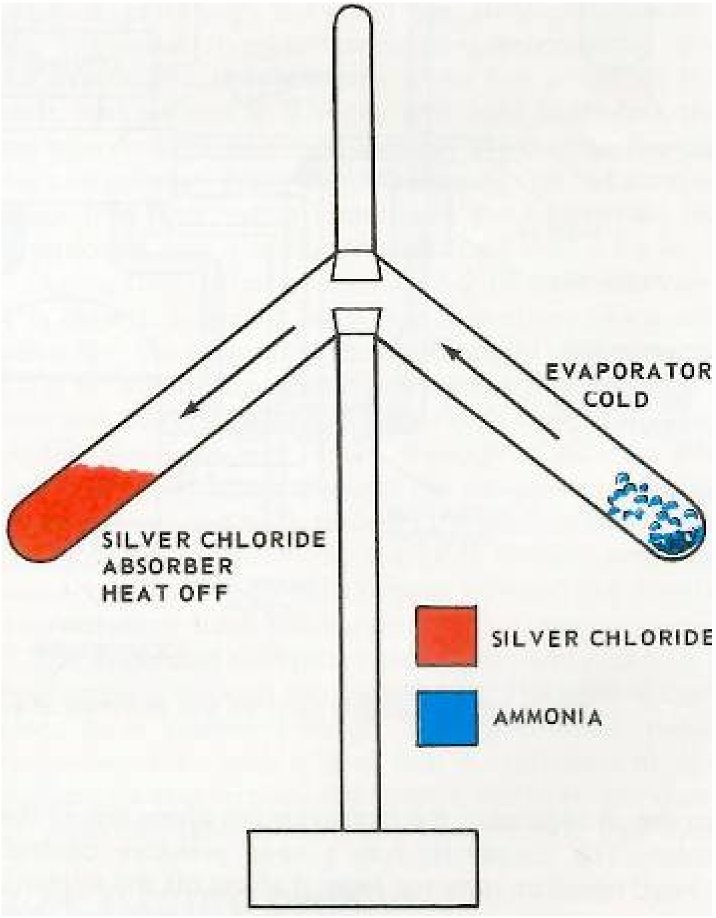
These machines adsorb refrigerant into a solid as the basis of a refrigeration cycle.

It all started with Faraday in 1821…

Adsorption refrigerators and heat pumps

These machines ADsorb the refrigerant into a solid rather than ABsorbing it into a liquid. <u>It is a discontinuous (batch) process</u>





One of the few commercial machines in production :

Background

- Adsorption refrigeration research at Warwick began in 1986
- We prefer to utilise ammonia as a refrigerant
- We have investigated zeolites and salts but still tend to prefer active carbons

The reasons for our use of ammonia:

- High pressure, so permeability of sorbent is not critical, pressure drops not a problem
- Can be easier to engineer than sub-atmospheric systems
- Good latent heat (although not as good as water)
- With regenerative cycles, the COP can be satisfactory

Challenges common to all our research:

1. Improving heat transfer in the adsorbent bed, both to reduce the cycle time / size and to use regenerative cycles.
2. Doing it with zero cost and zero mass!

Facilities:

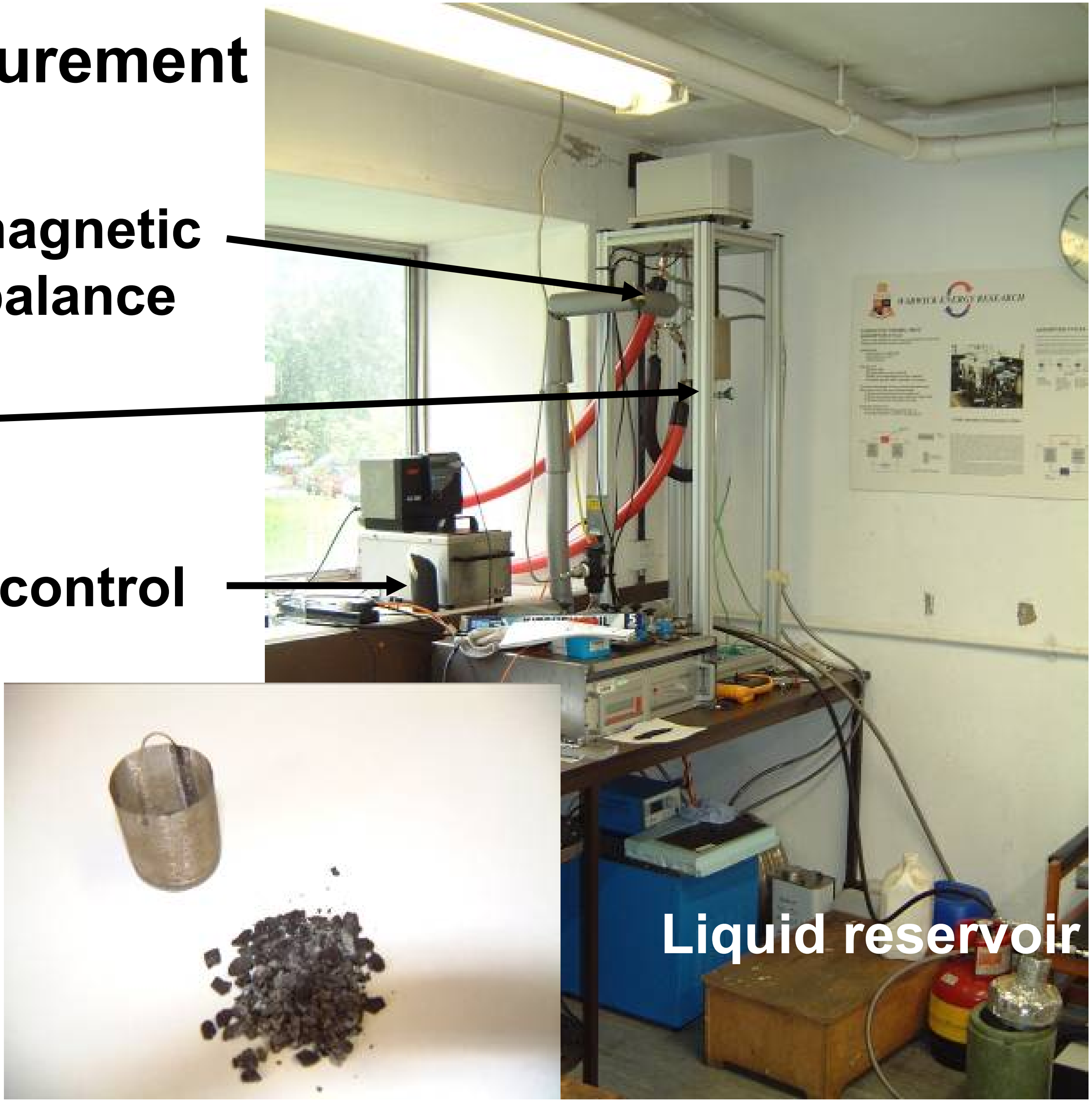
1. Porosimetry.
2. Thermal conductivity measurement.
3. Permeability measurement.

Porosity measurement equipment

Rubotherm magnetic suspension balance

Test vessel

Temperature control

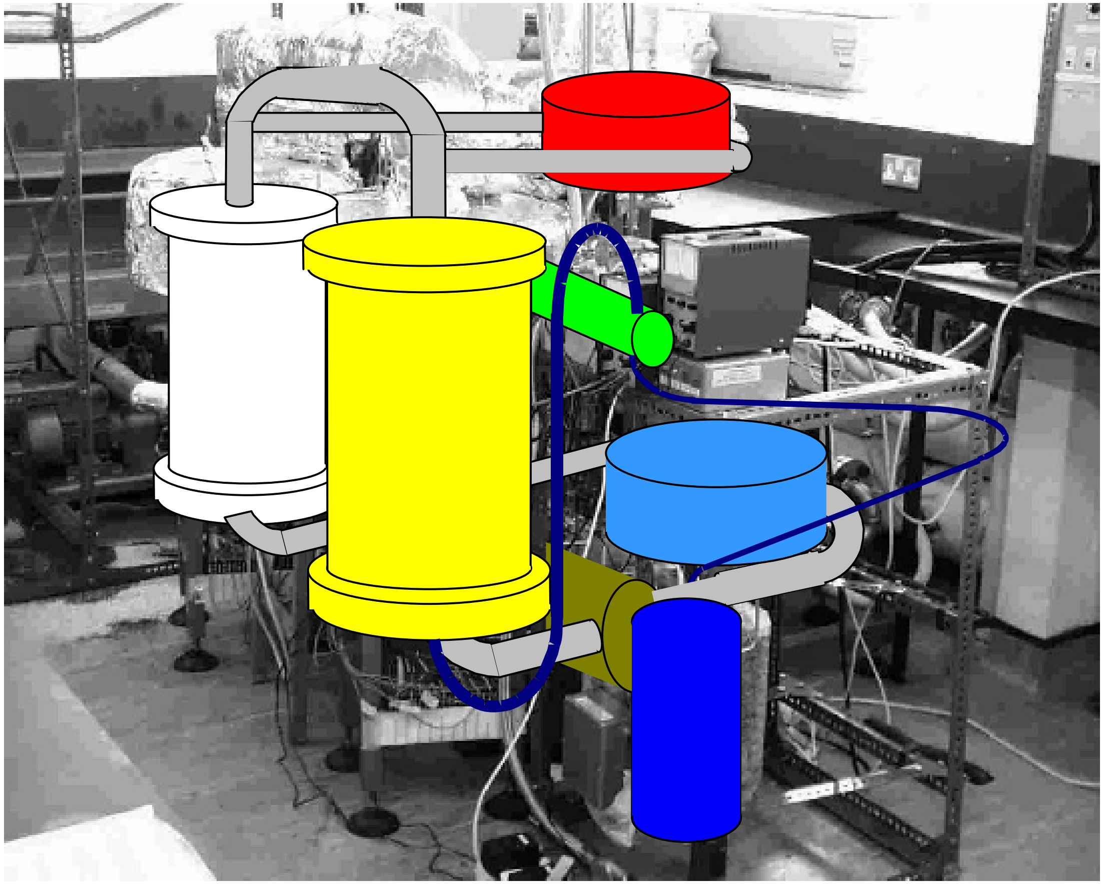


Basket and sample

PROJECTS AT WARWICK :

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

A patented cycle using granular carbon and requiring an ammonia gas circulator. Good heat transfer is obtained by forcing the refrigerant gas through the granular bed.



Active bed

Inert bed

Heater

Cooler

Condenser

Receiver /evaporator

Circulating pump

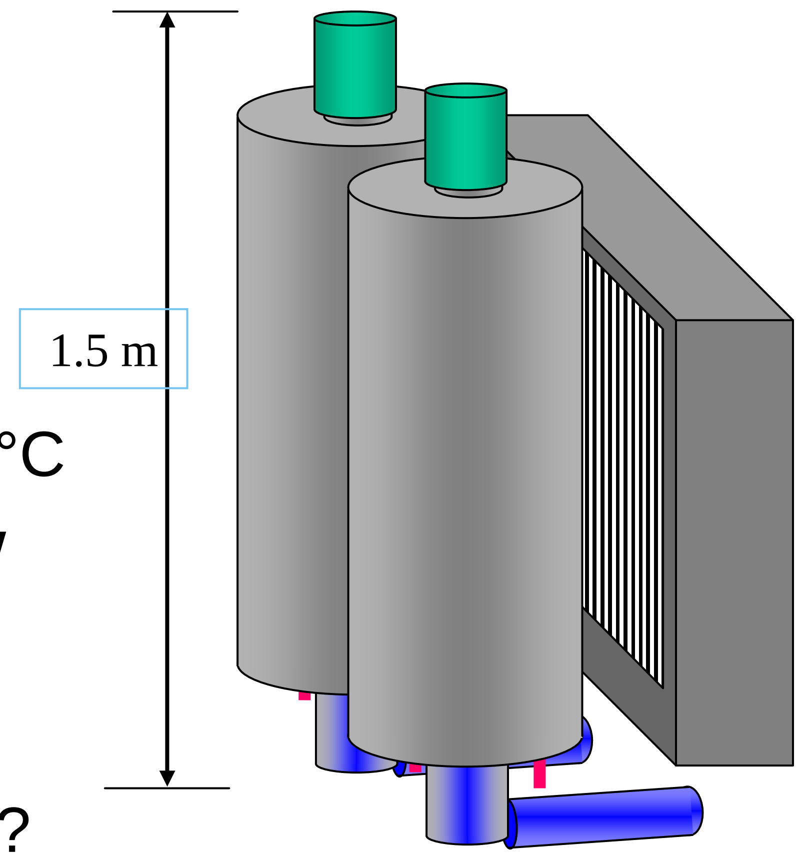
"Proof of concept" machine [prototype #1]

Performance of the proof of concept forced convection adsorption machine [#1]

- **Generating temperature 225° C**
- **Heat rejection temperature 40 ° C**
- **Condensing temperature 35° C**
- **Evaporating temperature -2 ° C**
- **Cooling COP 0.8**

Characteristics of #2 prototype machine

- Cooling power 12 kW
- Heating power 17 kW
- Cooling C.O.P = 0.9
- Heating COP = 1.8
- Driving temperature 175° – 225°C
- Parasitic pumping power 200 W +200 W ancillaries
- Ammonia charge 4 kg
- Projected cost €400-600 / kW ??



Rotor and stator of ammonia circulator

Assembled prototype #2, May 2003

Advantages

- **Already proven in laboratory**
- **High efficiency**

Disadvantages

- **Mechanically complicated**

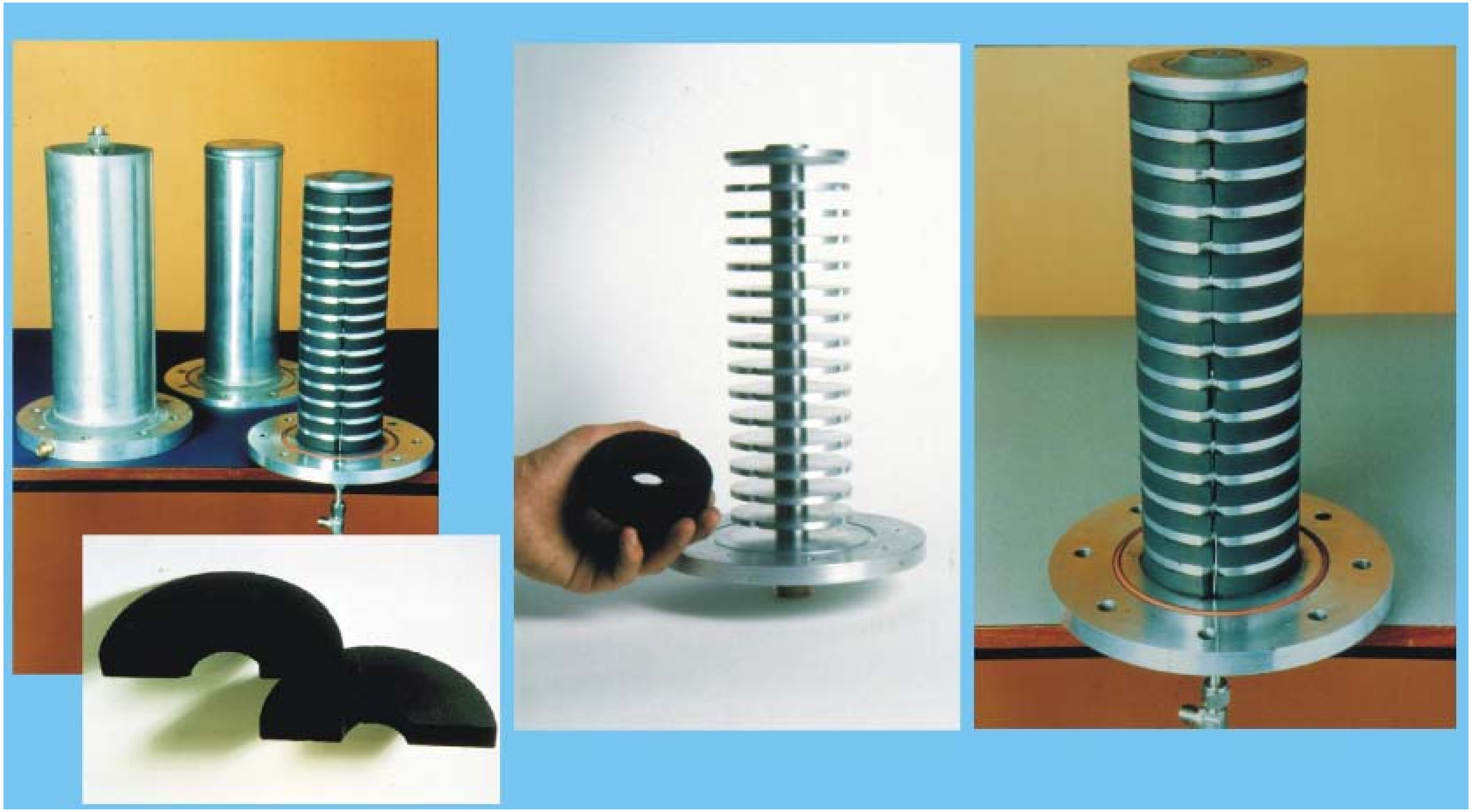
Results of #2 DTER / Industry project

- Gas circulator successful
- Design problems (soluble) lead to poor performance
- There is another prototype [#3] being built in a Carbon Trust project

PROJECTS AT WARWICK :

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

GRANULAR CARBON

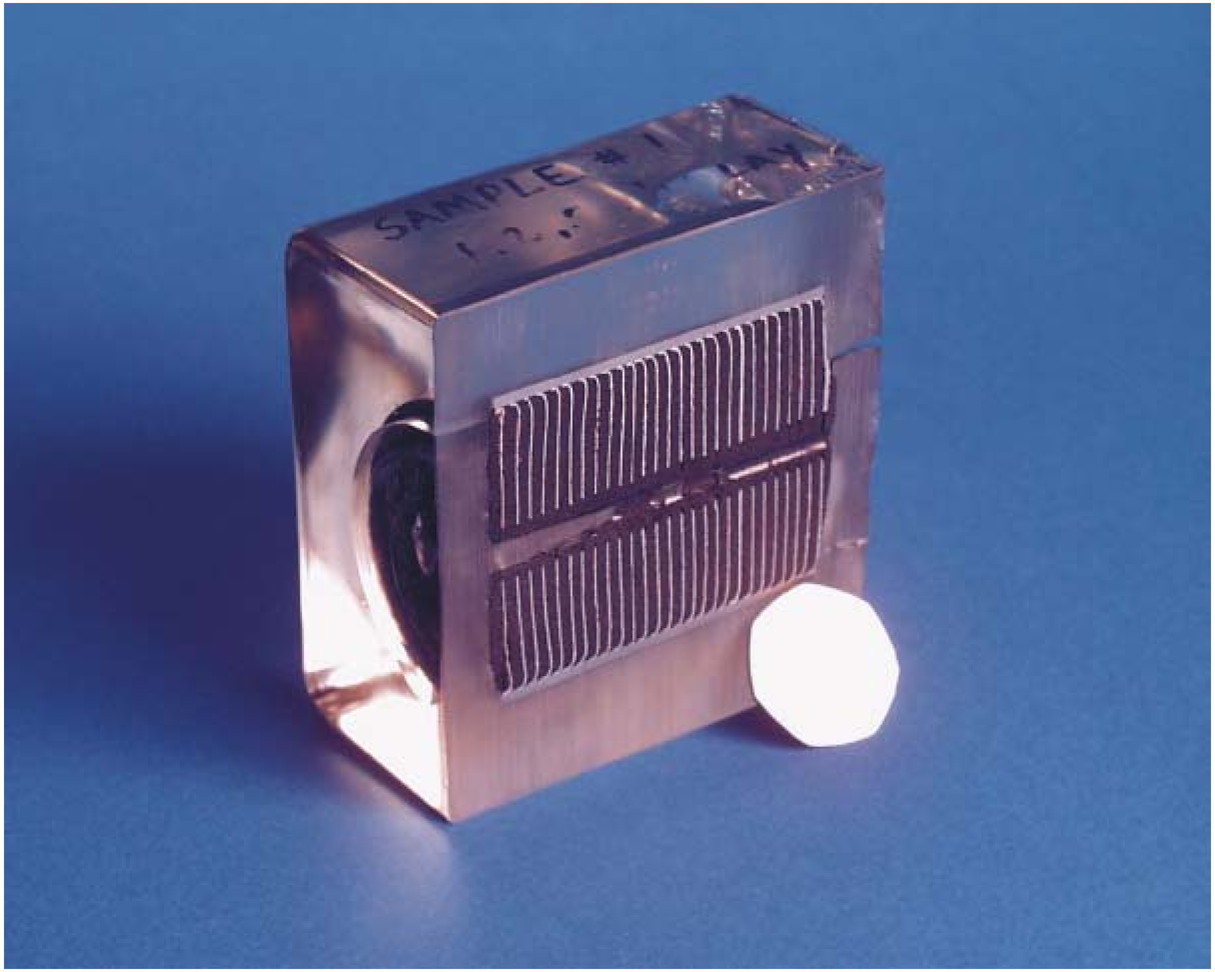


MONOLITHIC CARBON

Monolithic carbon properties

Sample	ρ kg m^{-3}	λ $Wm^{-1}K^{-1}$	h_E Wm^{-2}K^{-1}	X_{max} (kg kg^{-1})	C_{max} J kg^{-1}K^{-1}	K_r m^{2}x 10^{-14}	B_r m^{-1}x 10^8
LM127	750	0.60	350	0.36	8000	36	0.44
LM128	715	0.38	800	0.33	8000	1.3	5.42
Granular	500	0.16	50	0.29	8000	-	-

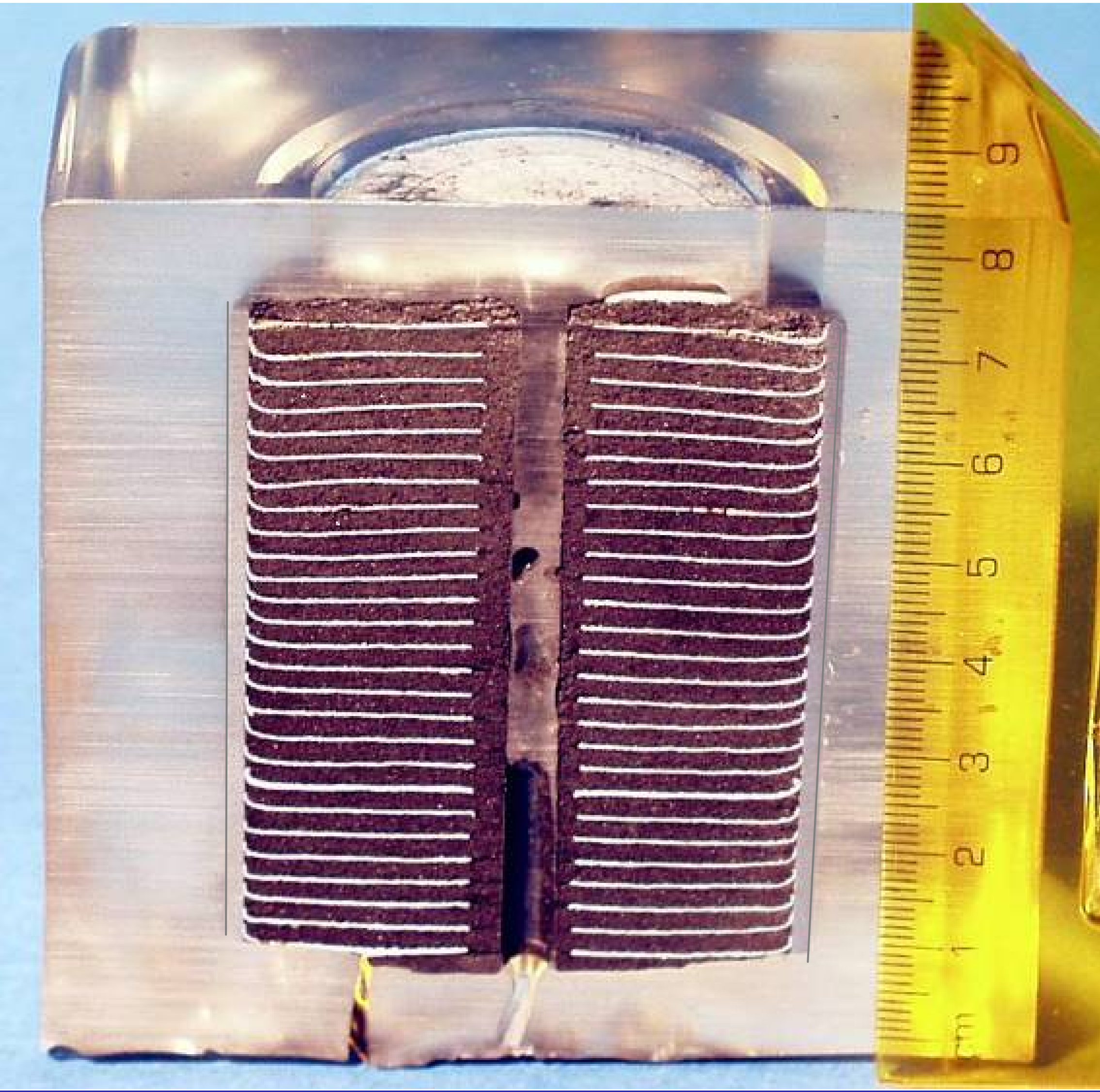
Carbon- Aluminium Laminate



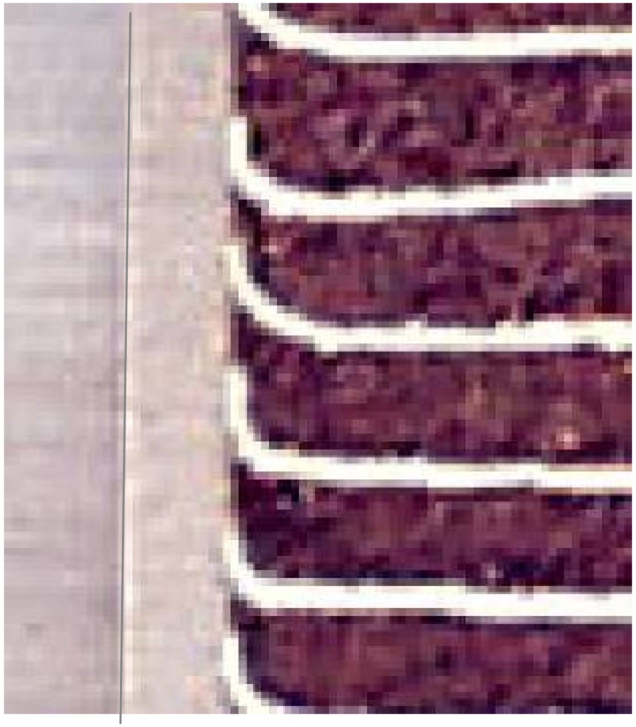
Carbon- Aluminium Laminate

Typical conductivity of monolithic carbon : 0.5 W/mK

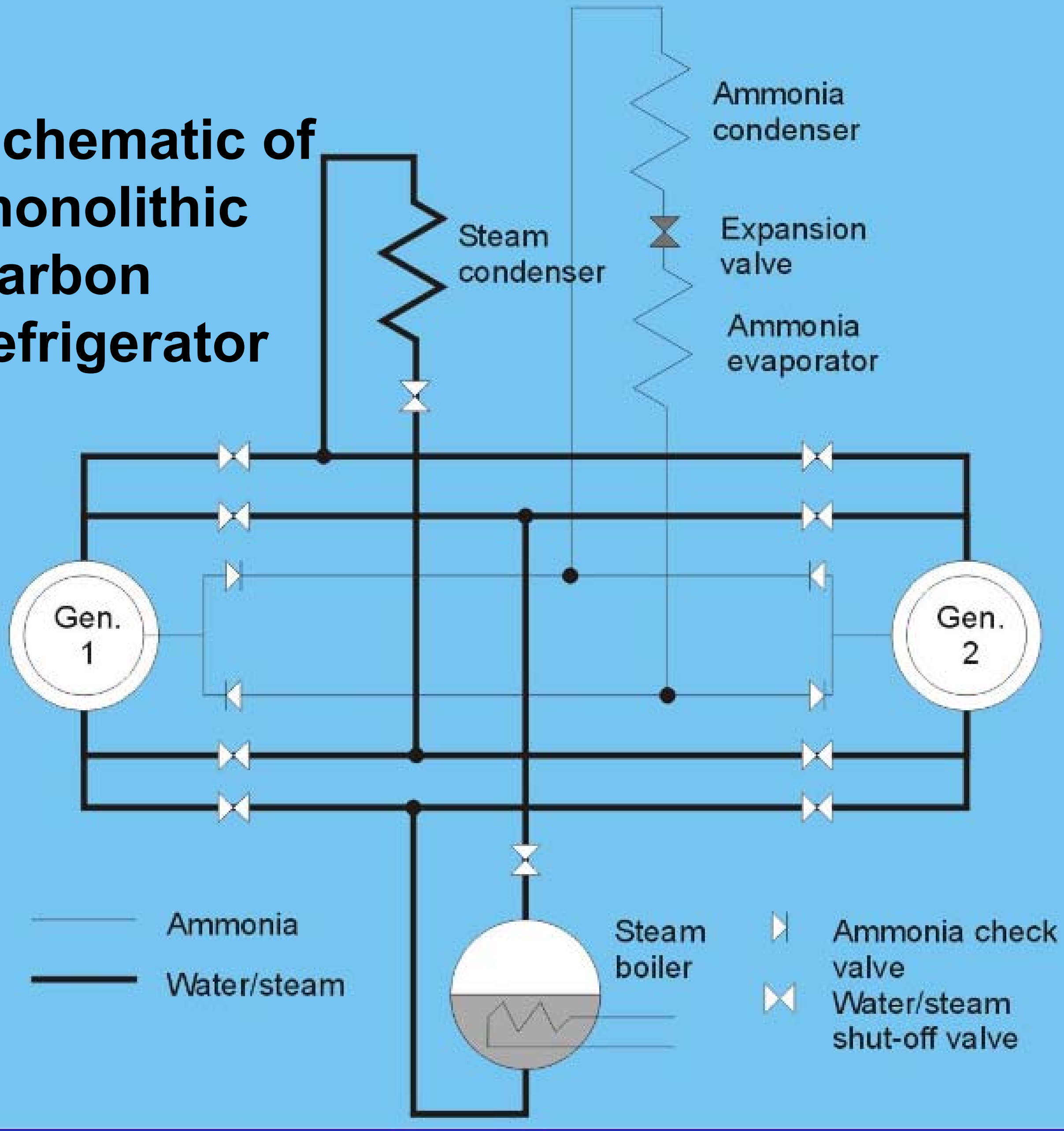
Typical radial conductivity of new carbon - aluminium laminate: 20 W/mK

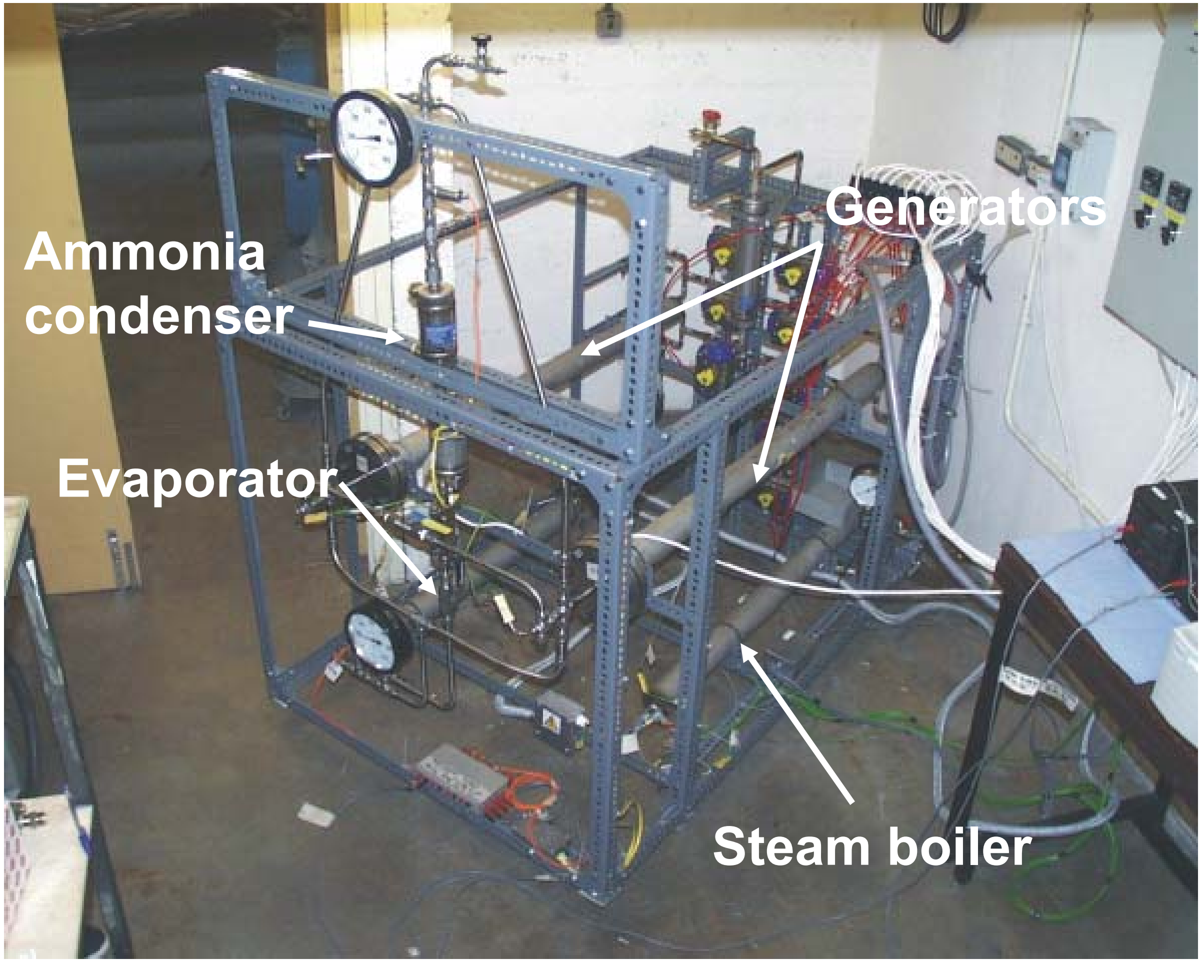


Junction of steel shell and aluminium fin

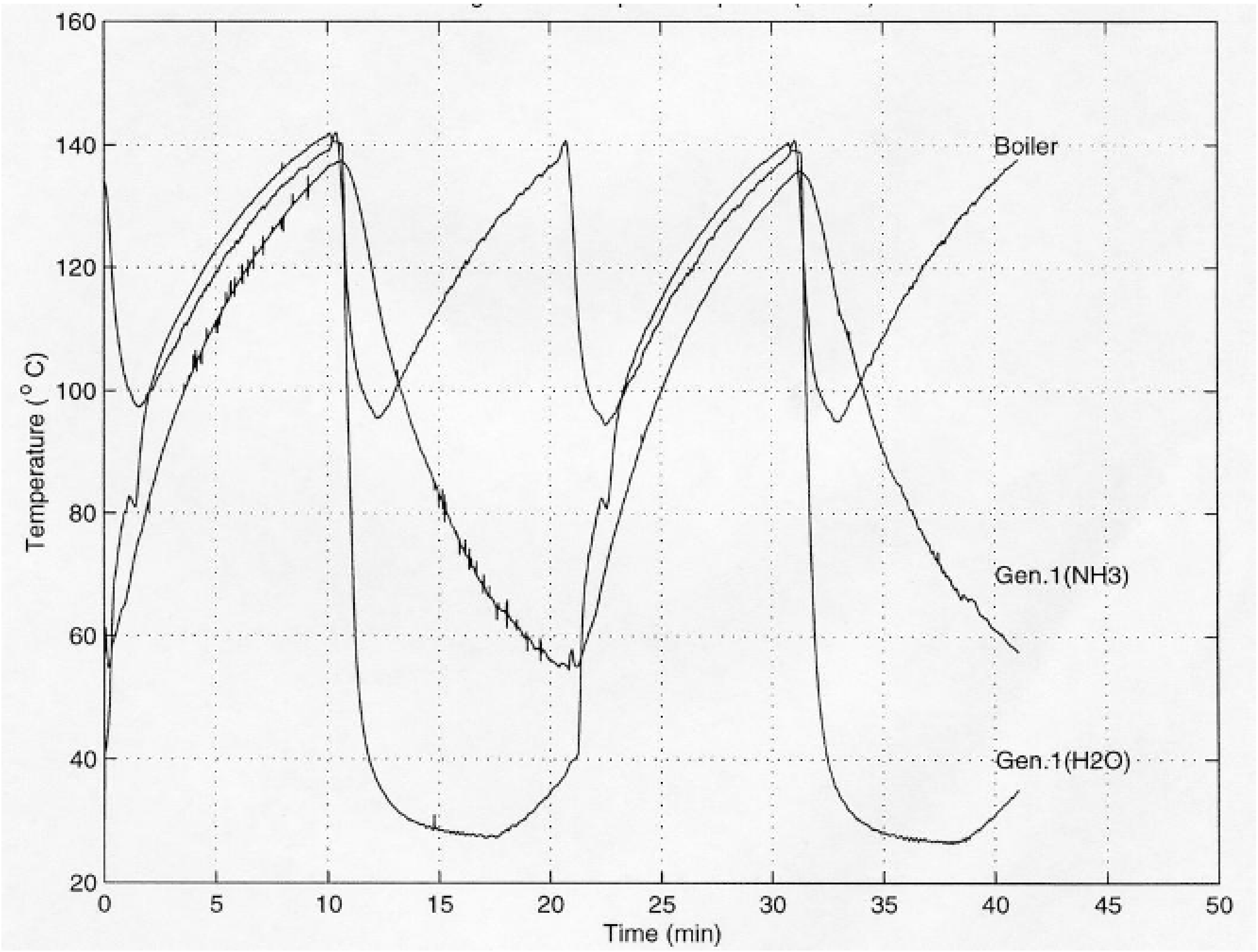


Schematic of monolithic carbon refrigerator





Overall view of first test rig



Typical test results

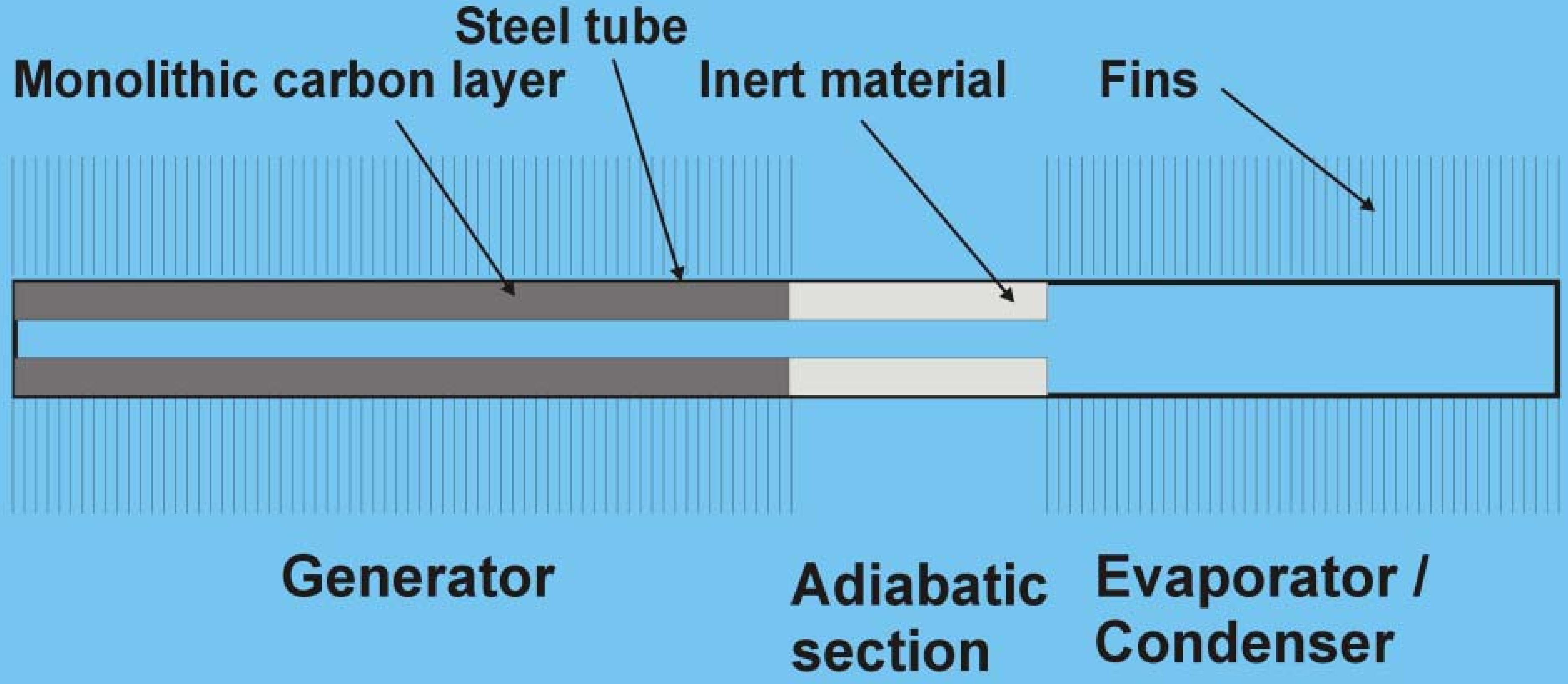
1. **The carbon - aluminium monolith has good heat transfer.**
2. **The design computer model was validated.**
3. **COP obtained = 0.44, Power = 500 Watts**

Unfortunately, the manufacturing process for making this design of laminate is too labour intensive and therefore too costly – we are not continuing with this work at present, but have moved on to lower cost solutions...

PROJECTS AT WARWICK :

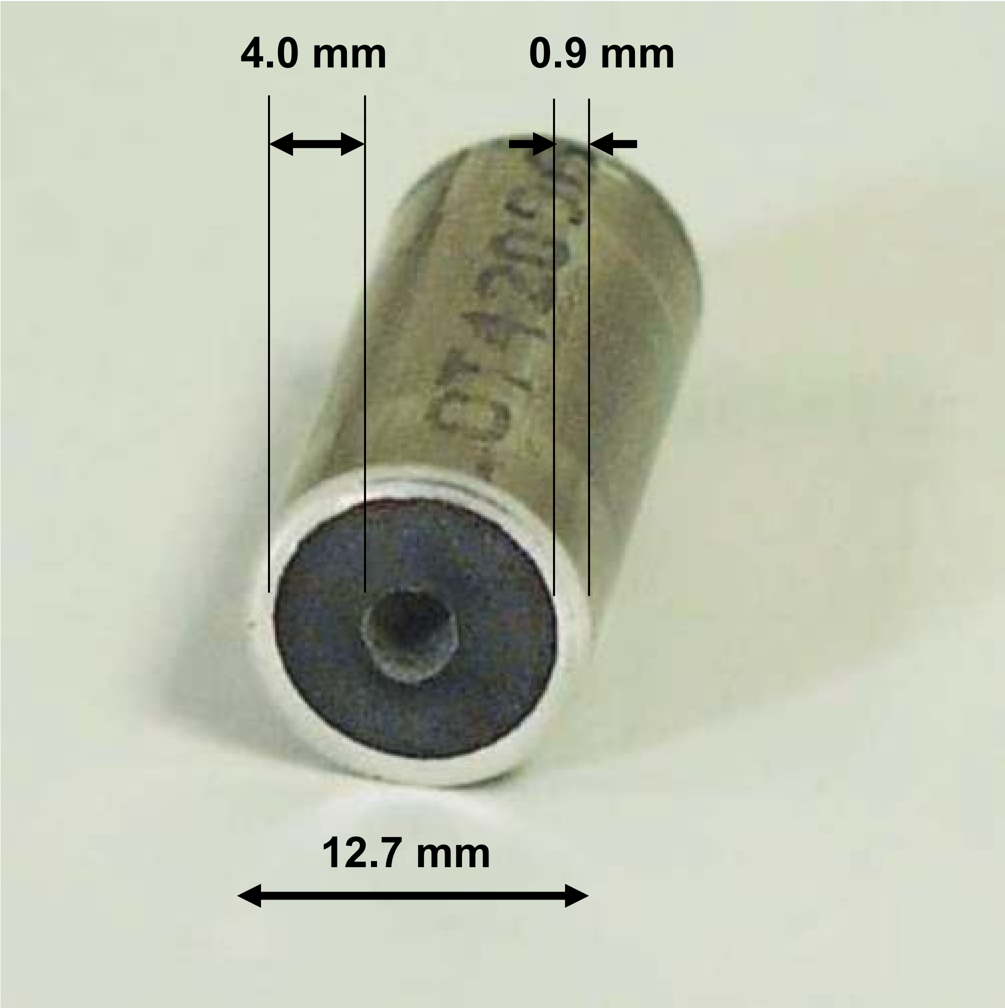
1. Convective Thermal Wave
2. Monolithic carbon plate-type generator
3. **Multiple-Bed regenerative cycle**
4. Plate heat exchanger bonded to thin layers of adsorbent.

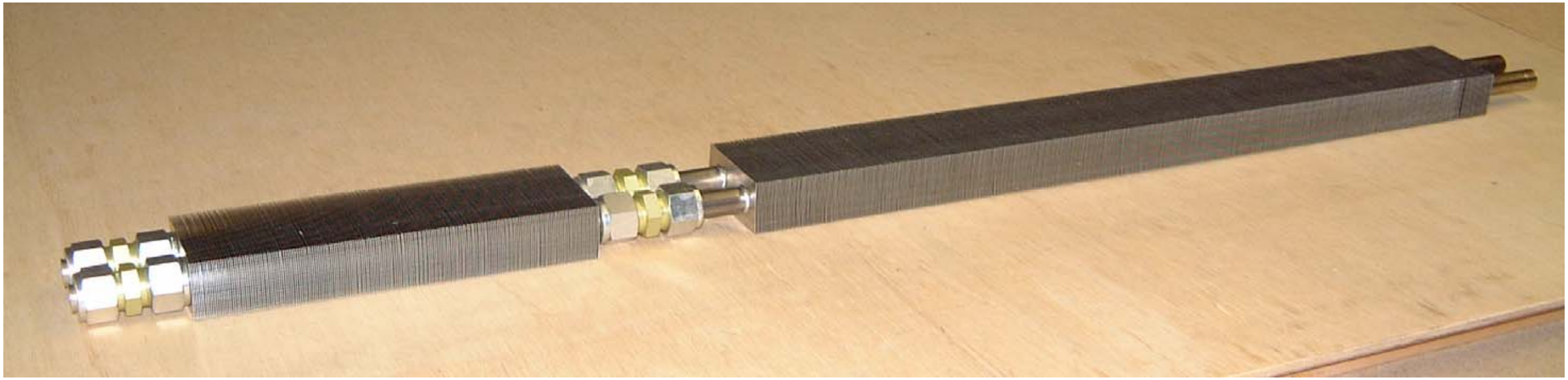
A patented cycle based on modular generators lined with monolithic carbon



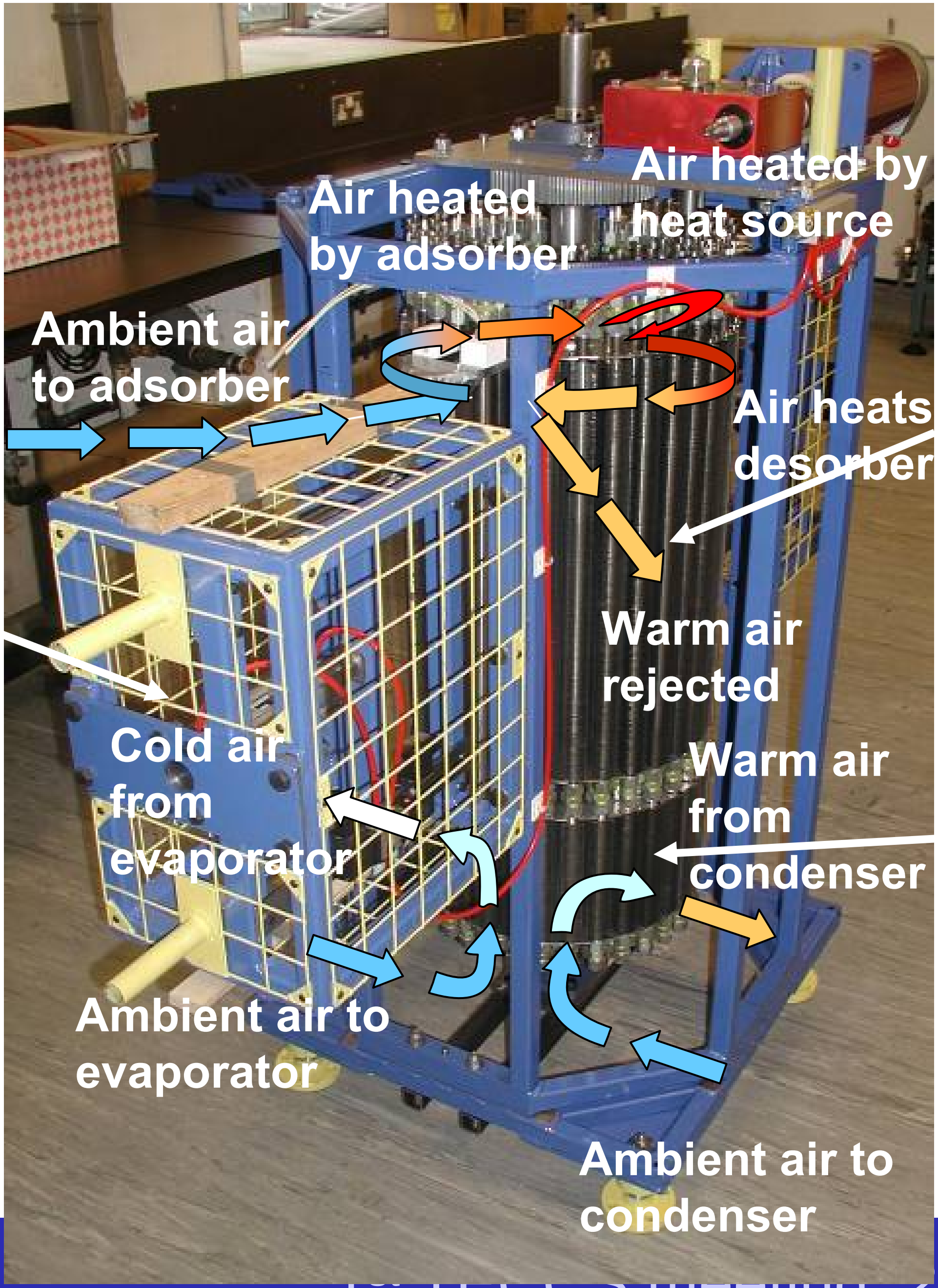
SORPTION MODULE

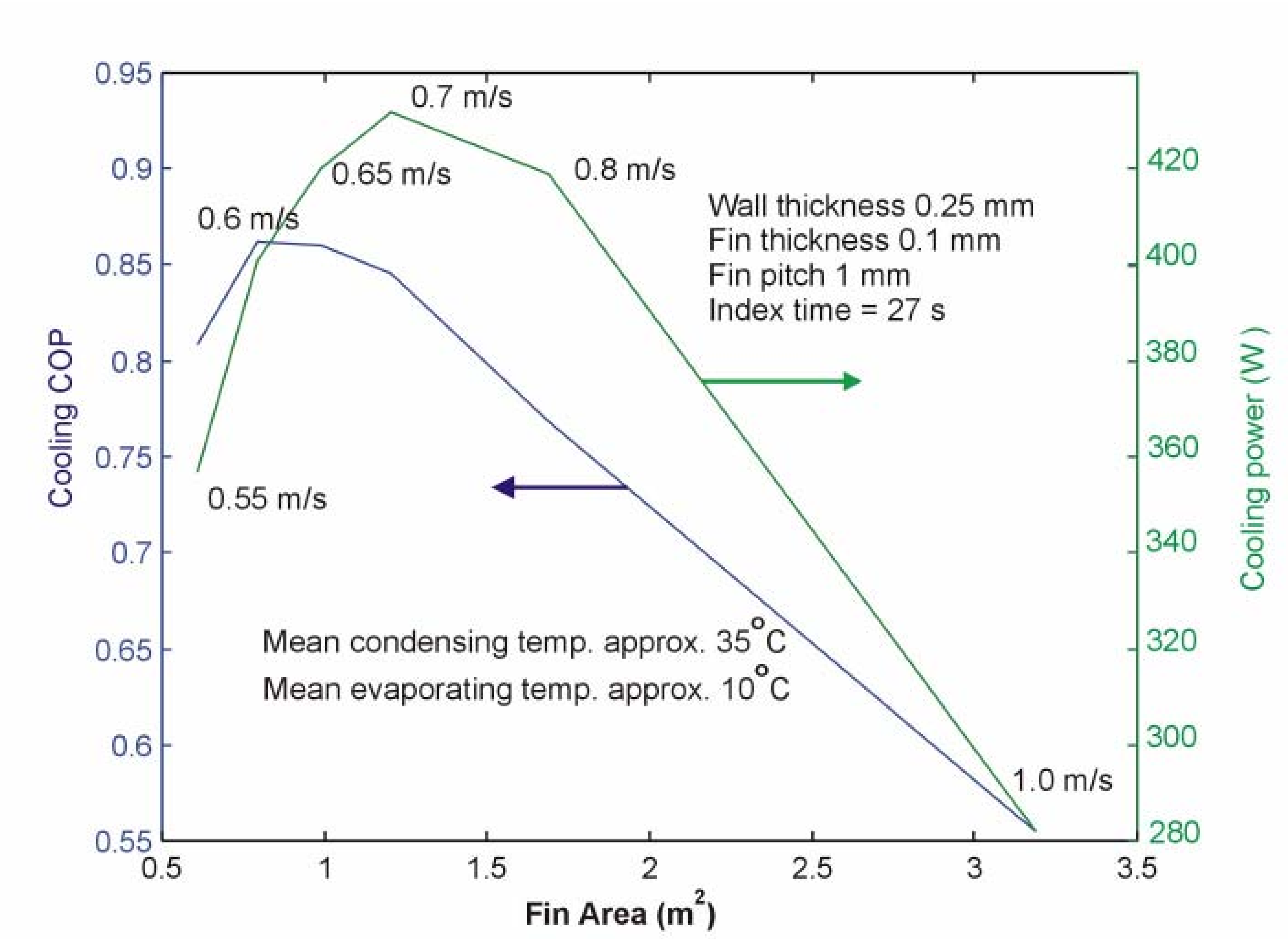
Initial carbon-lined tube



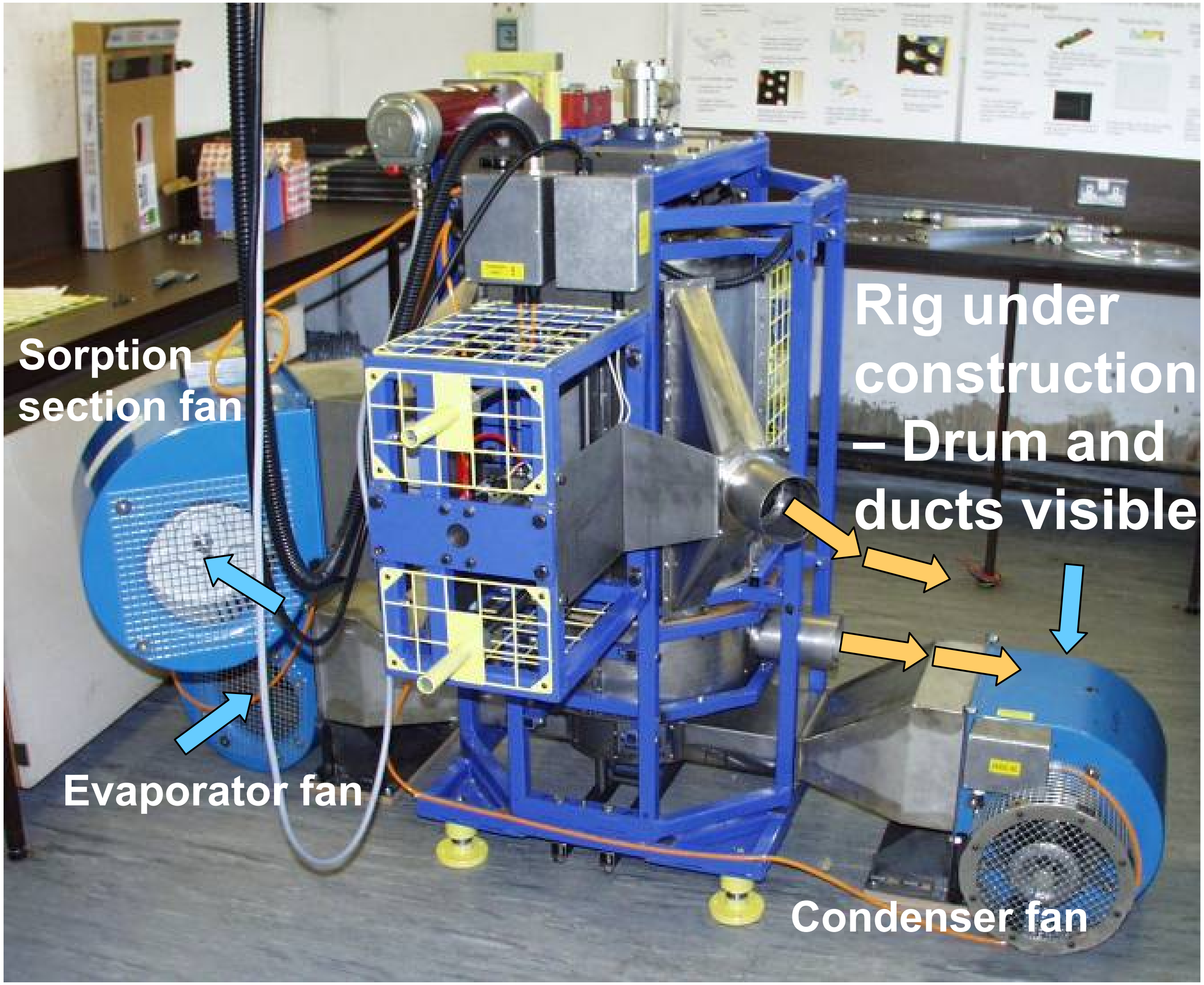


Double sorption module


Air heated by heat source
Air heated by adsorber
Ambient air to adsorber
Air heats desorber
Warm air rejected
Cold air from evaporator
Warm air from condenser
Ambient air to evaporator
Ambient air to condenser



Performance of optimised design


Sorption section fan
Rig under construction – Drum and ducts visible
Evaporator fan
Condenser fan

Complete machine – Outer cladding in place

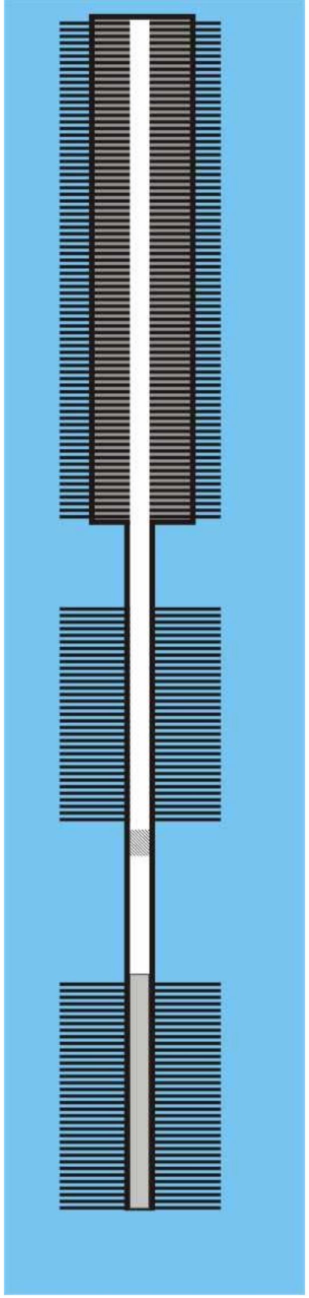
The realisation that the mechanical complexity outweighed the benefits of the 'counterflow' design, lead us to a low-cost 'cross-flow' concept…

VARIATIONS ON MODULE DESIGNS:

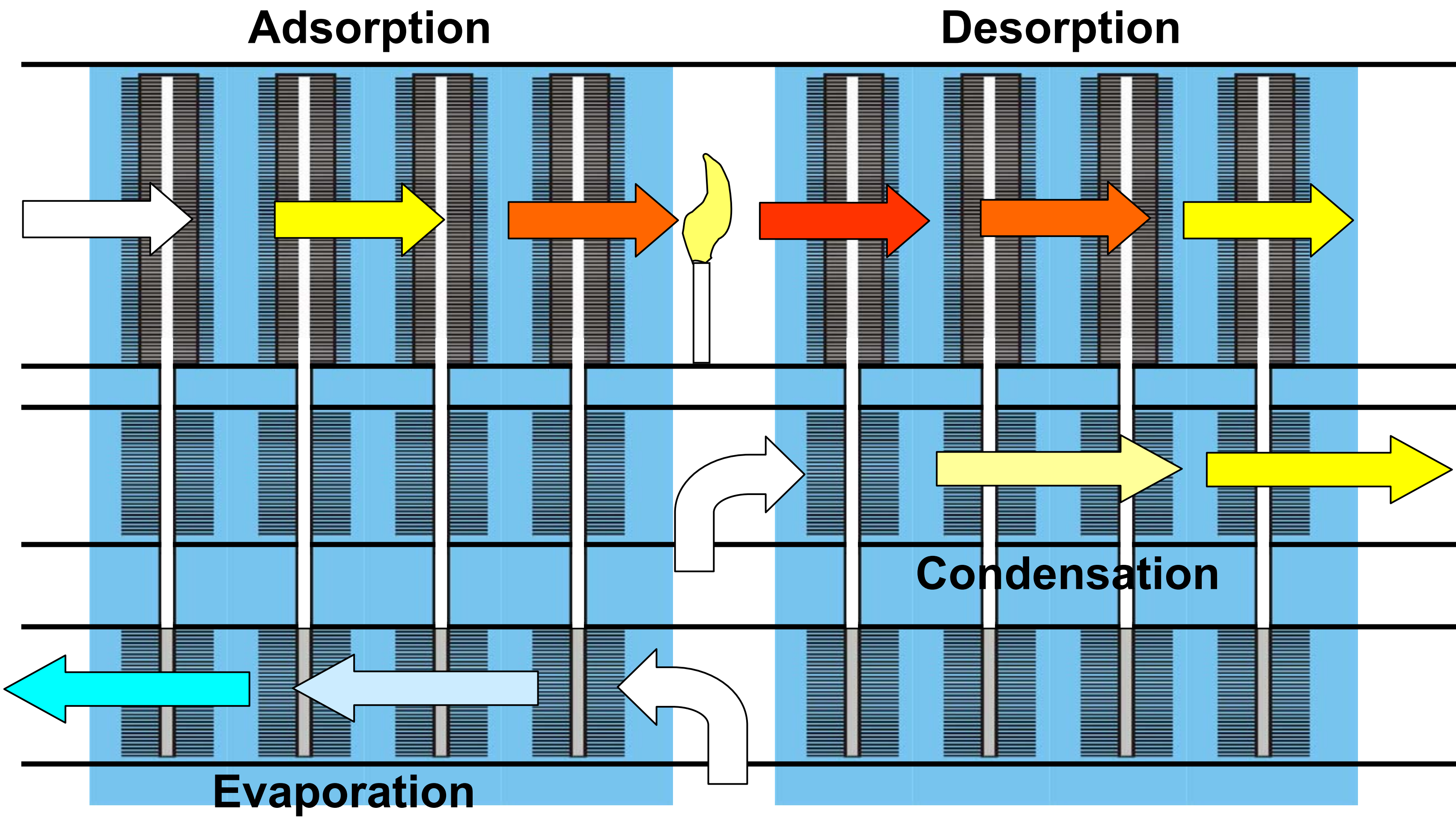
Advanced module (separate condenser and evaporator)

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

Module with separate evaporator, receiver and condenser

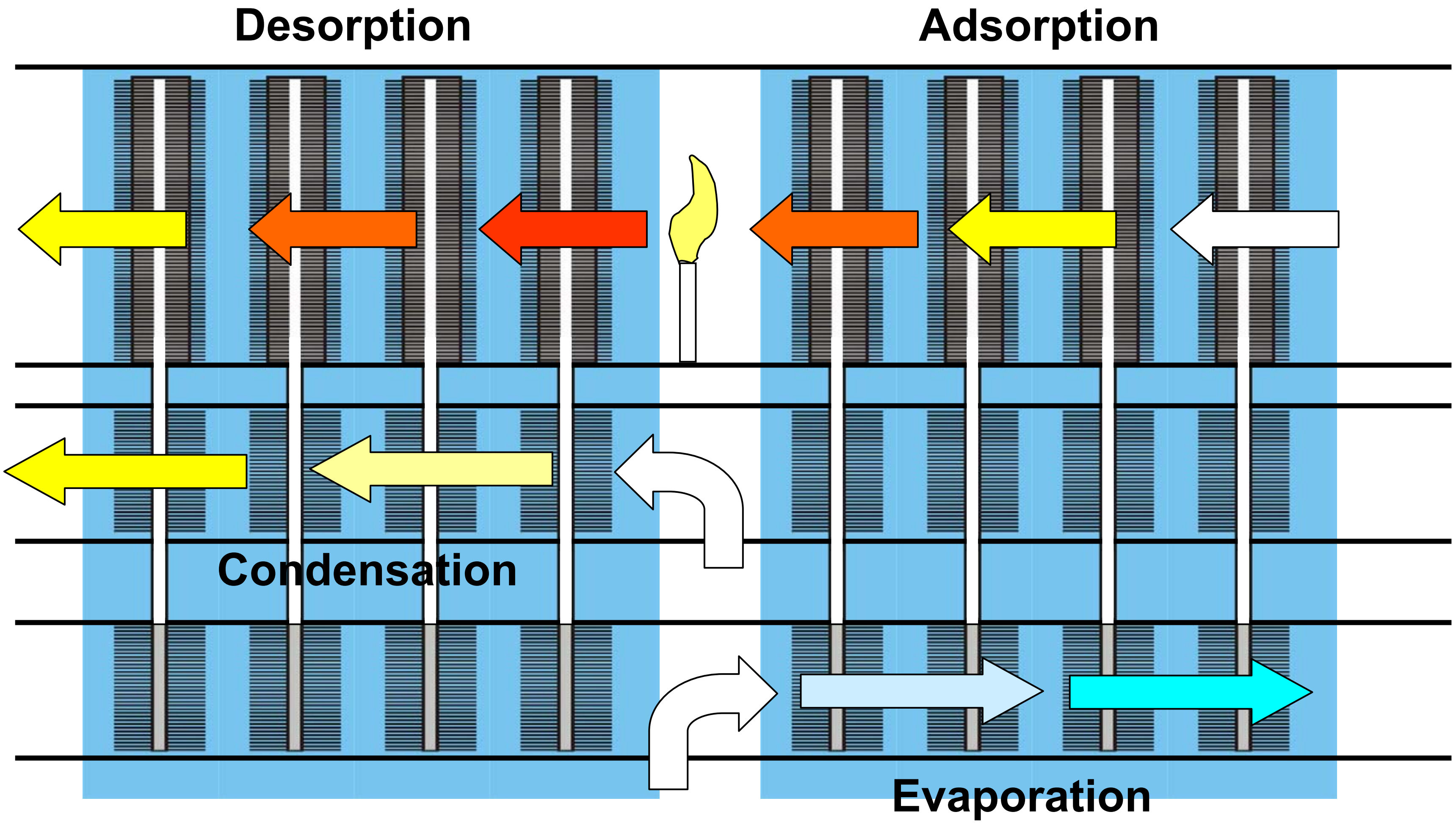


FIXED MODULAR BED CONFIGURATION



Phase 1

FIXED MODULAR BED CONFIGURATION



Phase 2

Advantages :

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

Disavantages :

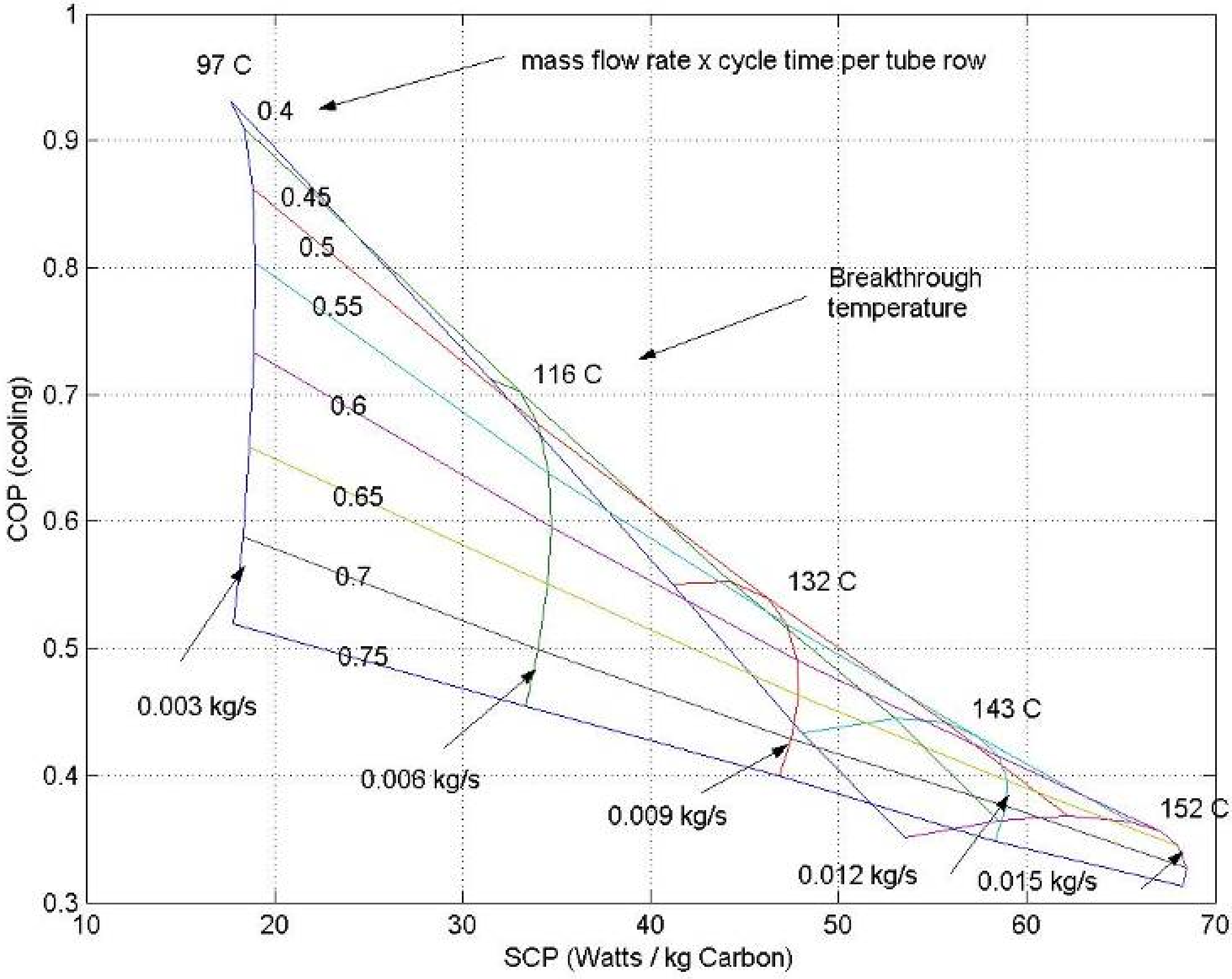
- **More modules needed than for rotating system**

Parameters:

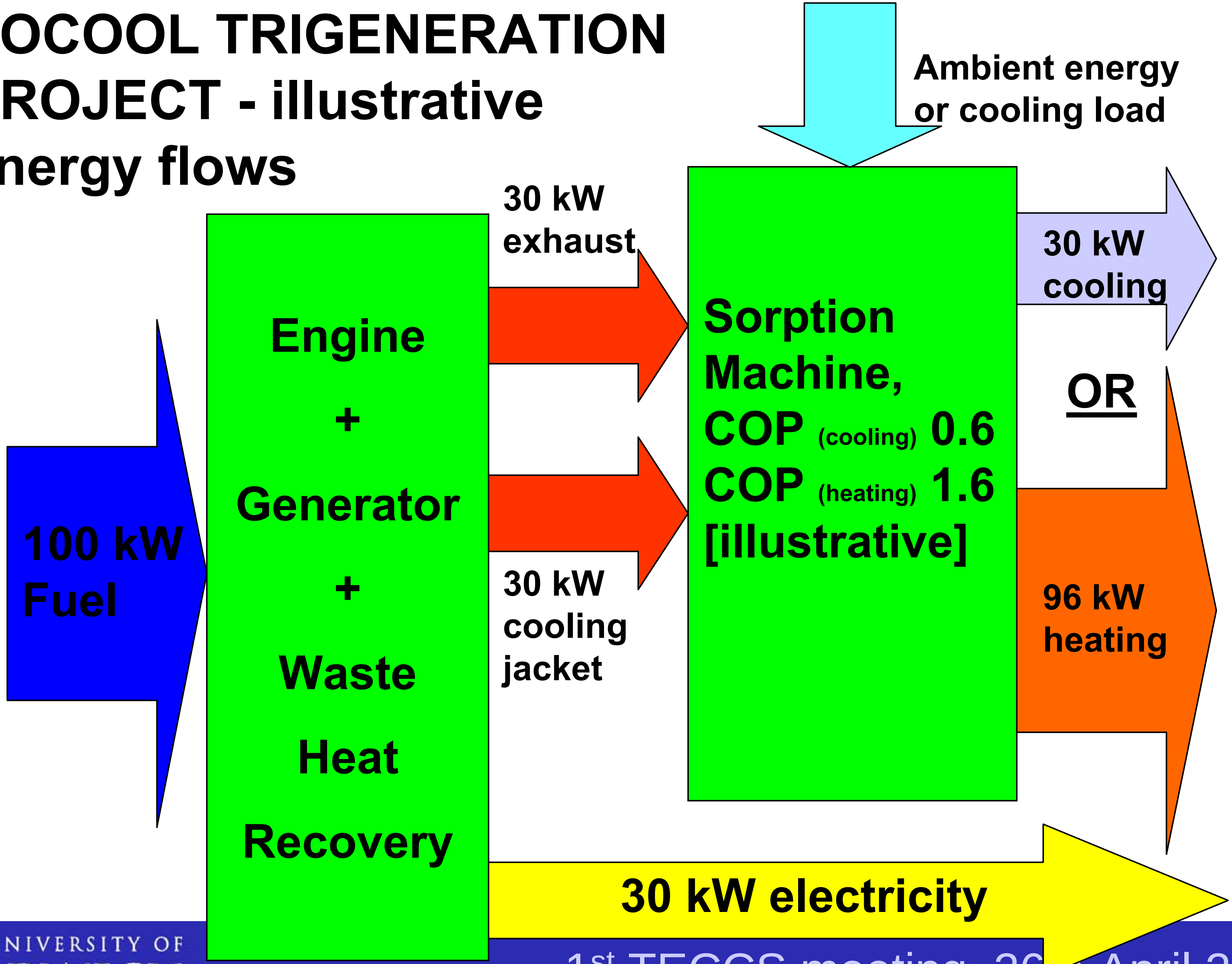
- Number of tubes in row
- Mass flow rate of oil
- Cycle time / row

Performance Indicators:

- COP
- Cooling power / kg carbon


97 C
mass flow rate x cycle time per tube row
0.4
0.45
0.5
0.55
0.6
0.65
0.7
0.75
Breakthrough temperature
116 C
132 C
143 C
152 C
0.003 kg/s
0.006 kg/s
0.009 kg/s
0.012 kg/s
0.015 kg/s
COP (cooling)
SCP (Watts / kg Carbon)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
10
20
30
40
50
60
70

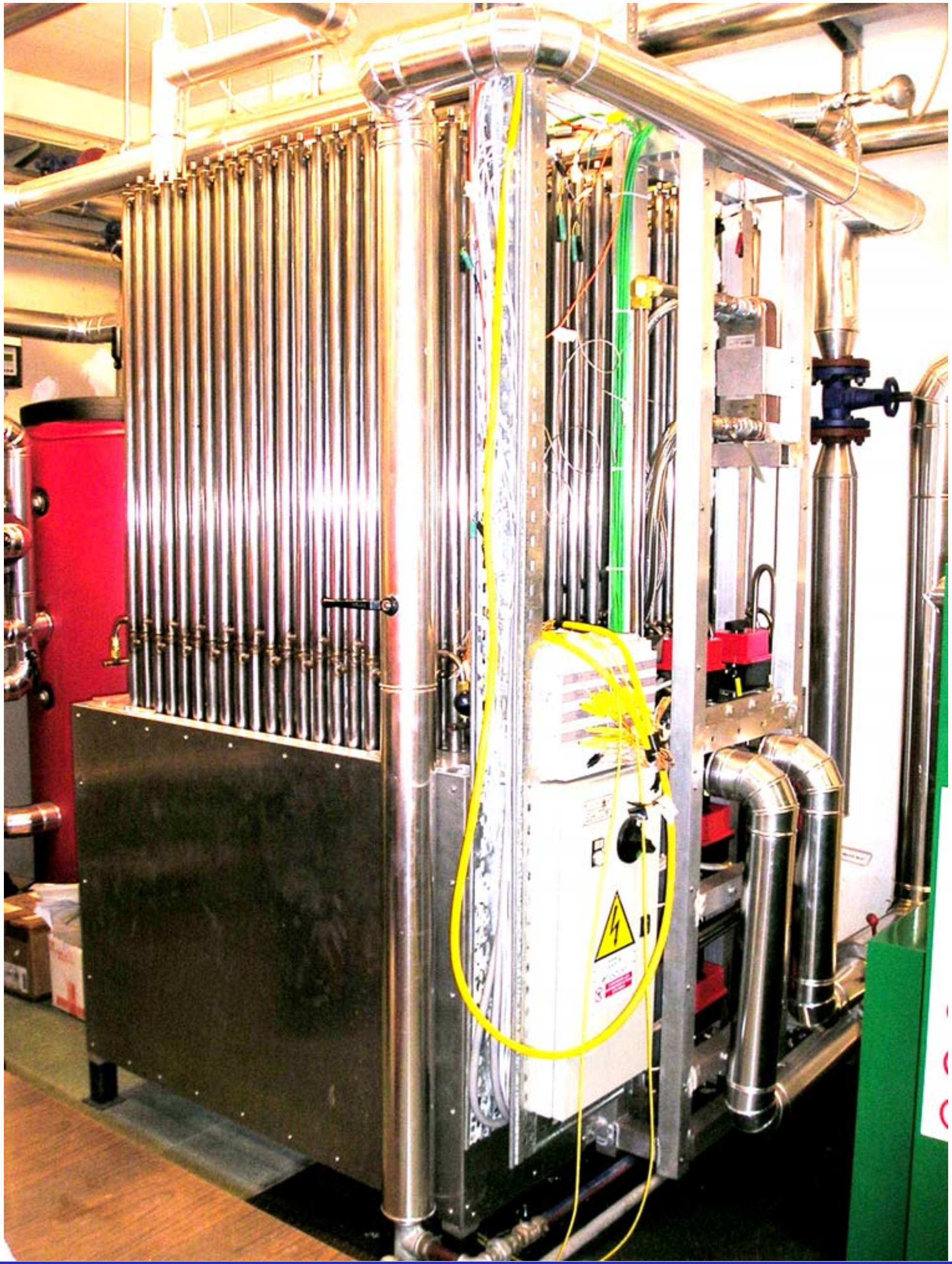
SOCOOL TRIGENERATION PROJECT - illustrative energy flows



Single module under test, January 2005

5 kW SOCOOL prototype before delivery to Italy

THE COMPLETE UW SOCOOL MACHINE INSTALLED AT CRF



‘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 has been built in early 2006 and is being commissioned.

‘Spinner’ project

Generator section

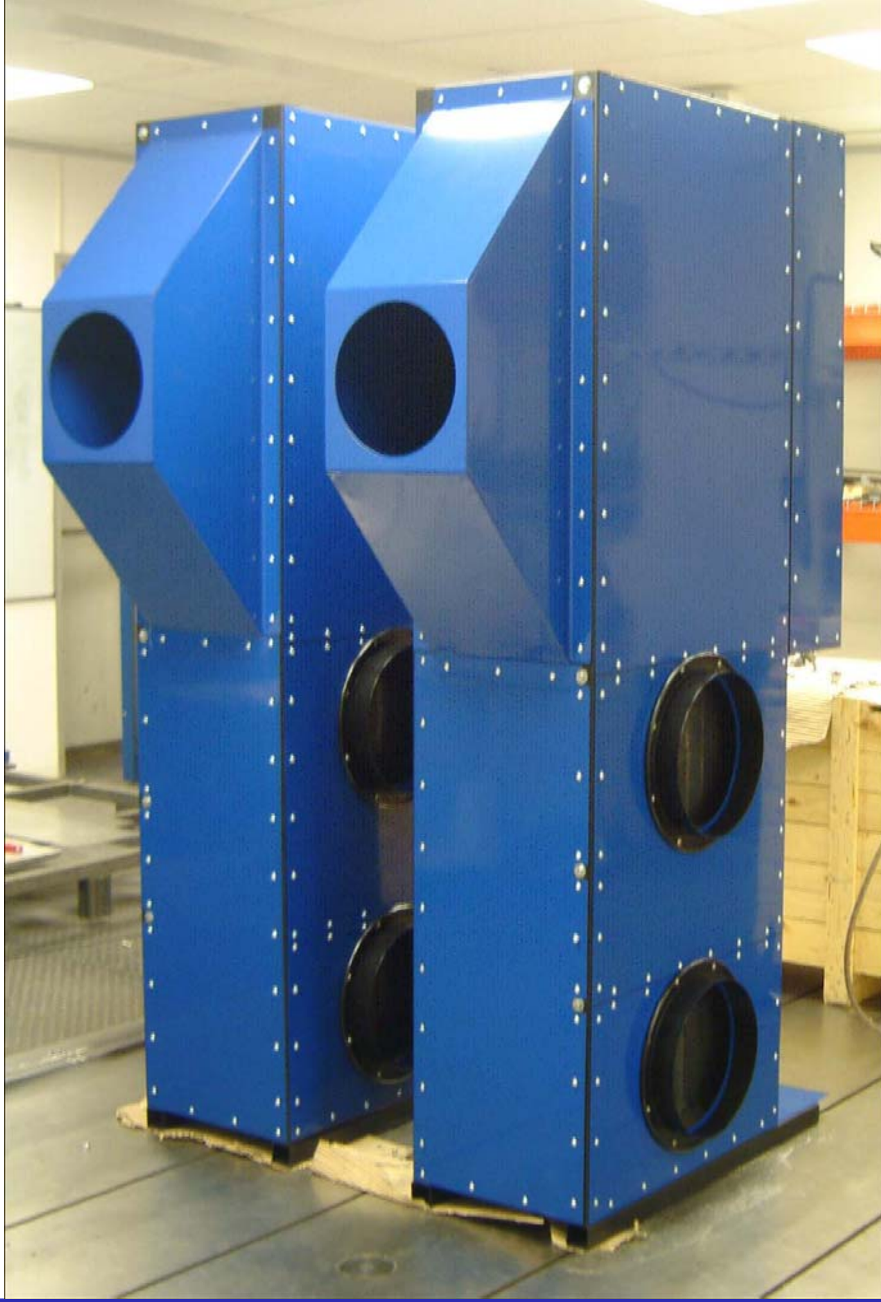
Condenser section

Receiver section

Evaporator section

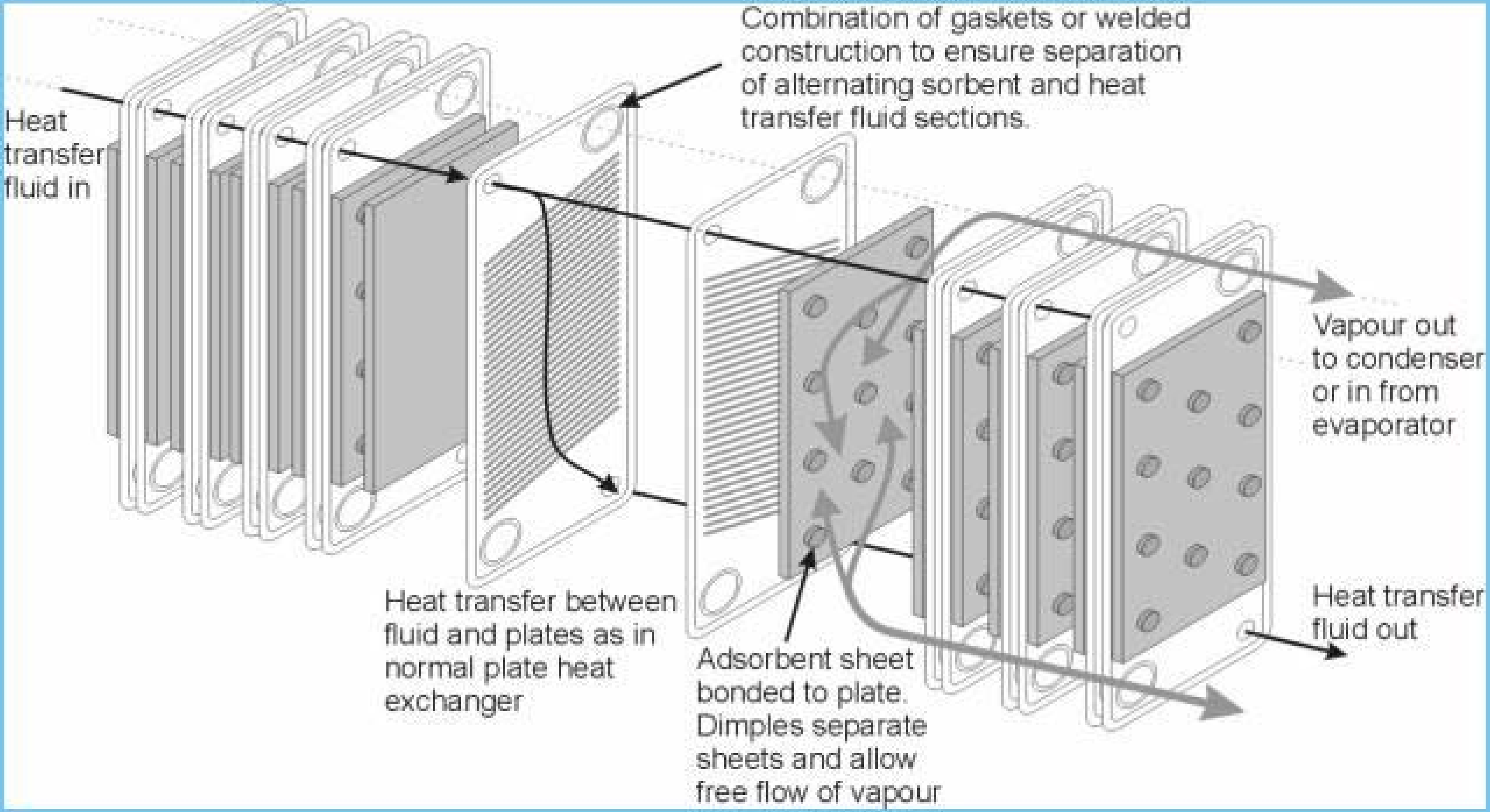
‘Spinner’ project

Assembled prototype without fans

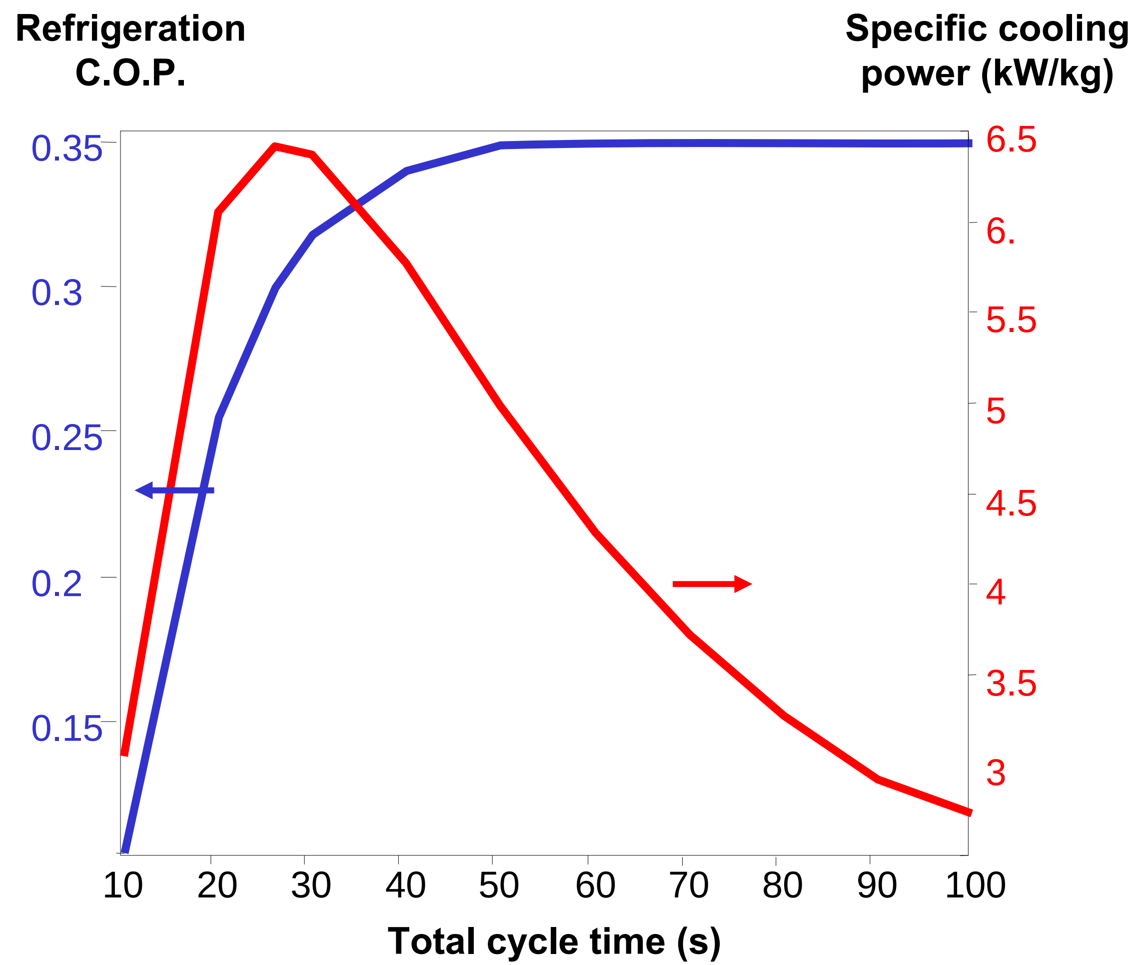


PROJECTS AT WARWICK :

1. Convective Thermal Wave
2. Monolithic carbon generators
3. Multiple-Bed regenerative cycle
4. **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

Advantages

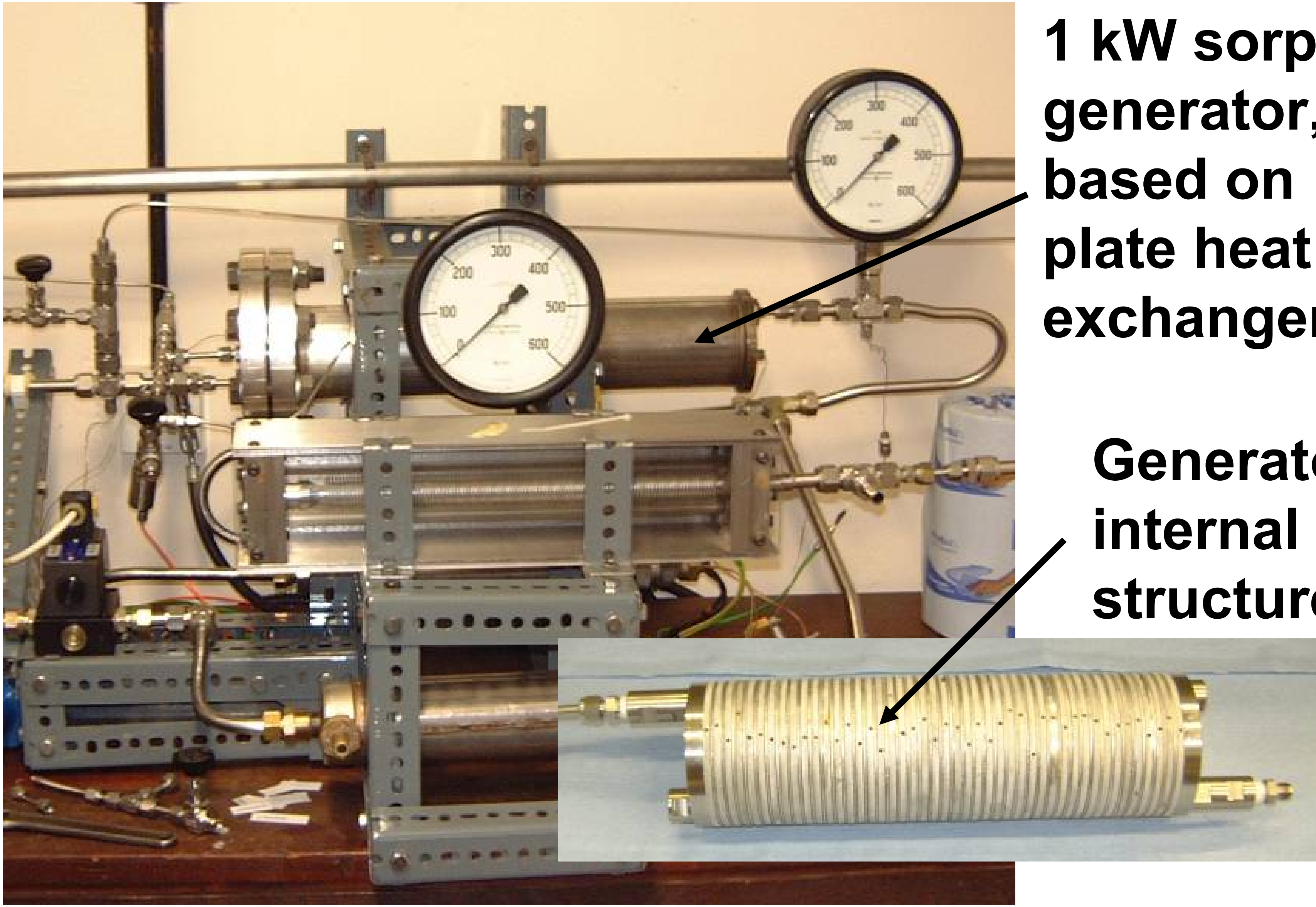
- **VERY compact**
- **Low ammonia mass**

Disadvantages

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

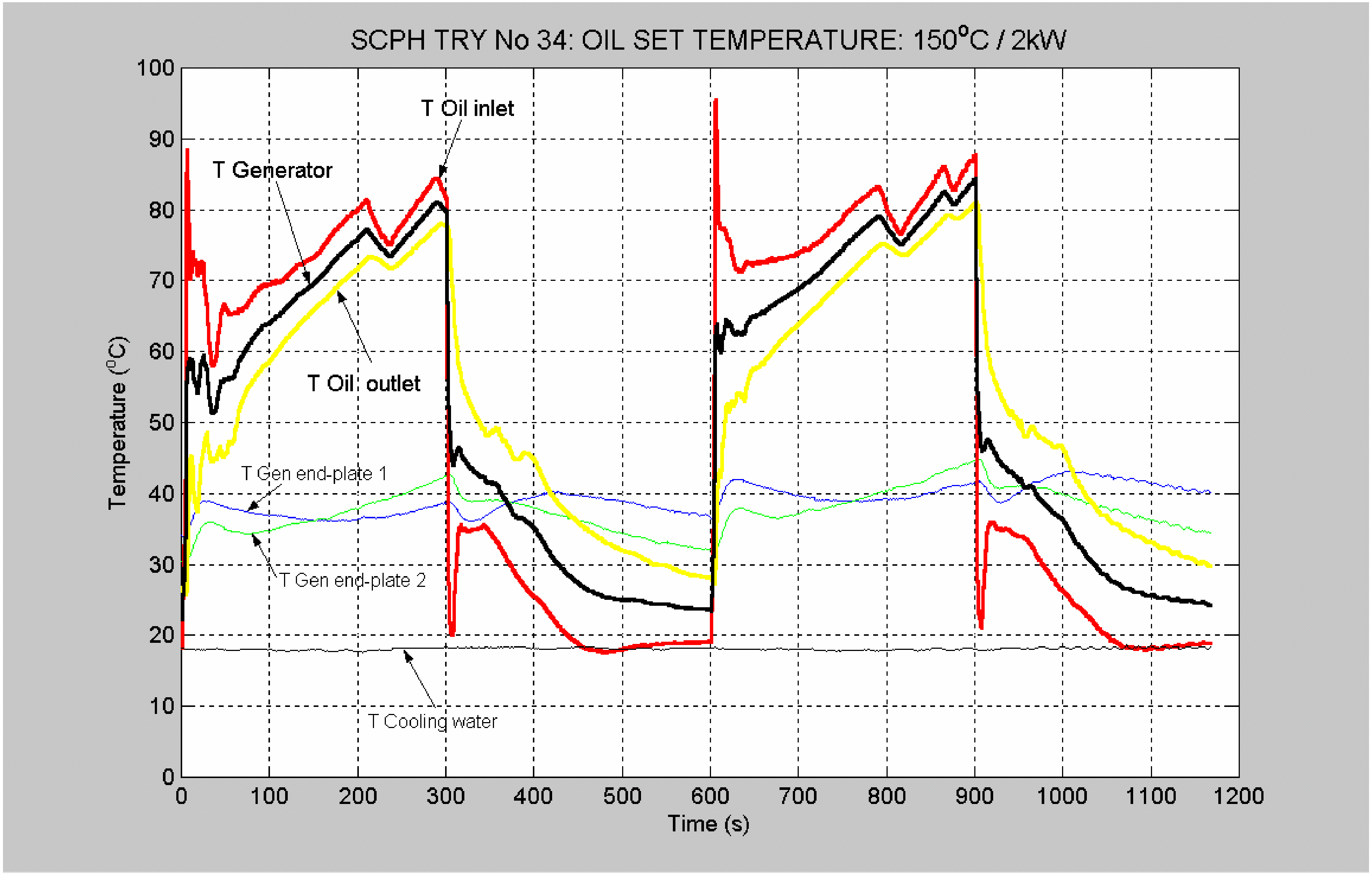
In 2003, a student group project worked on a version of this concept, simply to demonstrate the principle.

Because of cost constraints they had to use O-ring seals rather than nickel-brazed plates, but still managed to achieve useful results.



1 kW sorption generator, based on plate heat exchanger

Generator internal structure



SCPH TRY No 34: OIL SET TEMPERATURE: 150°C / 2kW
T Oil inlet
T Generator
T Oil: outlet
T Gen end-plate 1
T Gen end-plate 2
T Cooling water
Temperature (°C)
Time (s)
100
90
80
70
60
50
40
30
20
10
0
0
100
200
300
400
500
600
700
800
900
1000
1100
1200

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

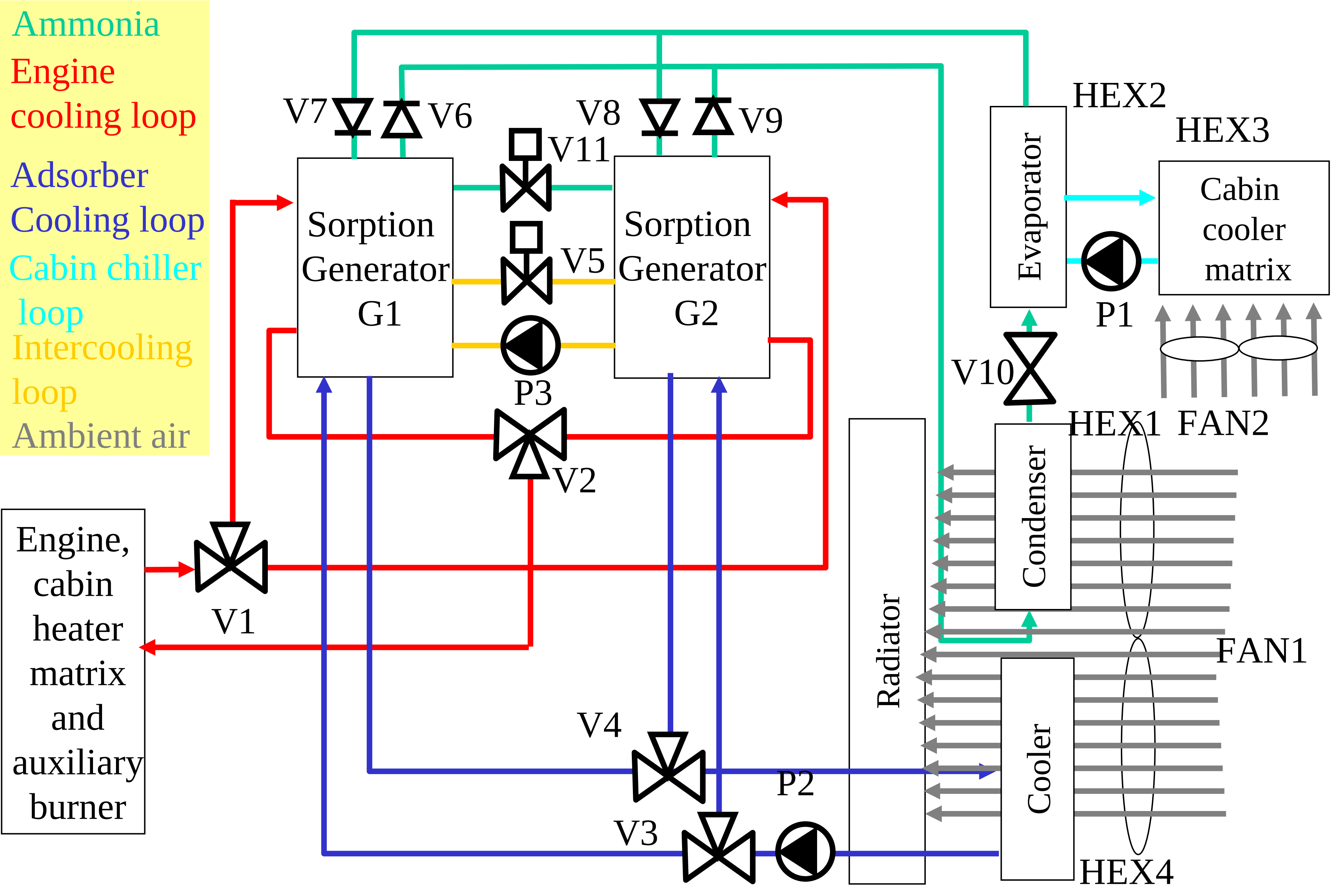
It is coordinated by CRF and started in March 2005.

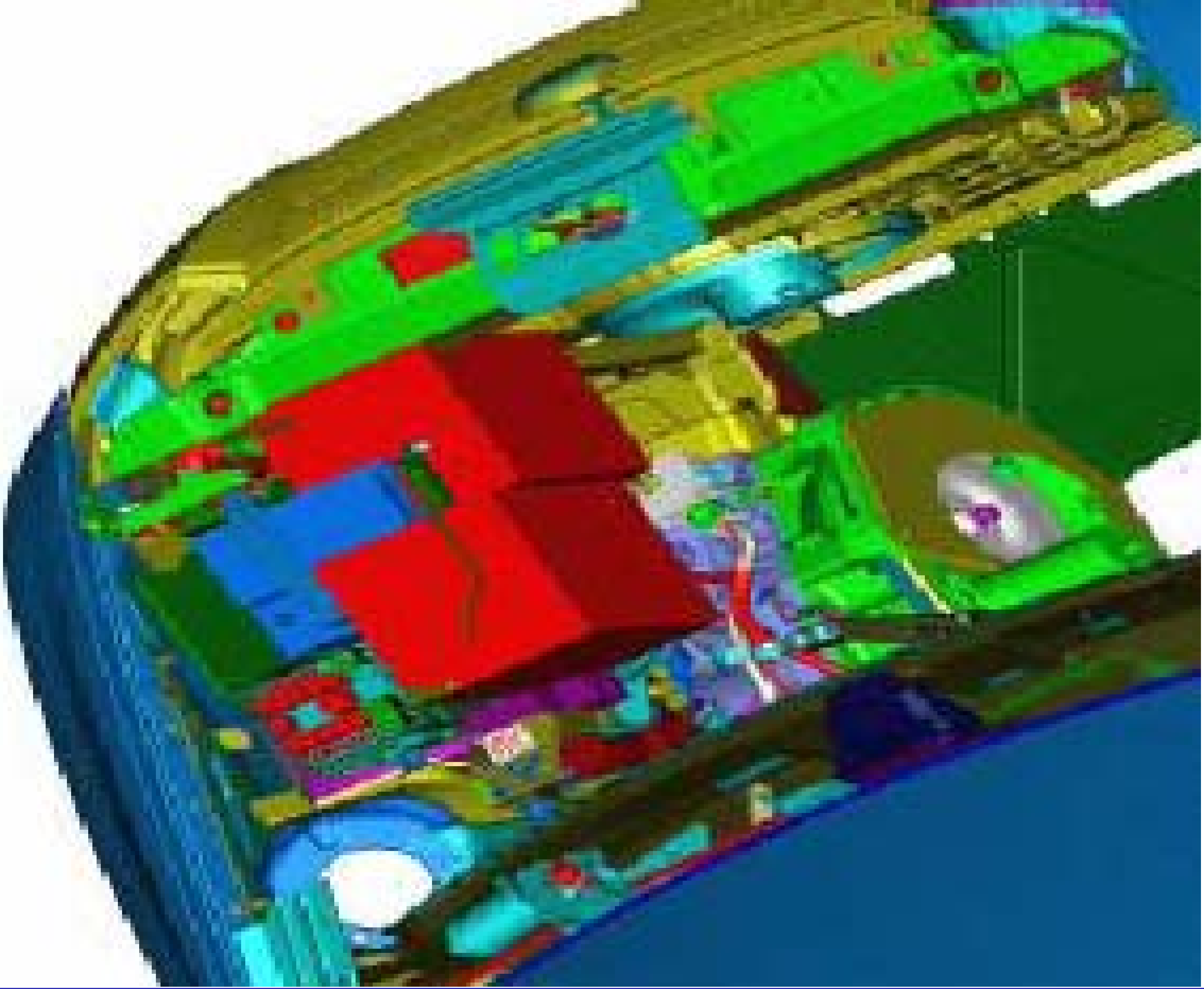
We are collaborating with Chemviron Carbon and Bodycote to work on a novel brazed plate generator design.

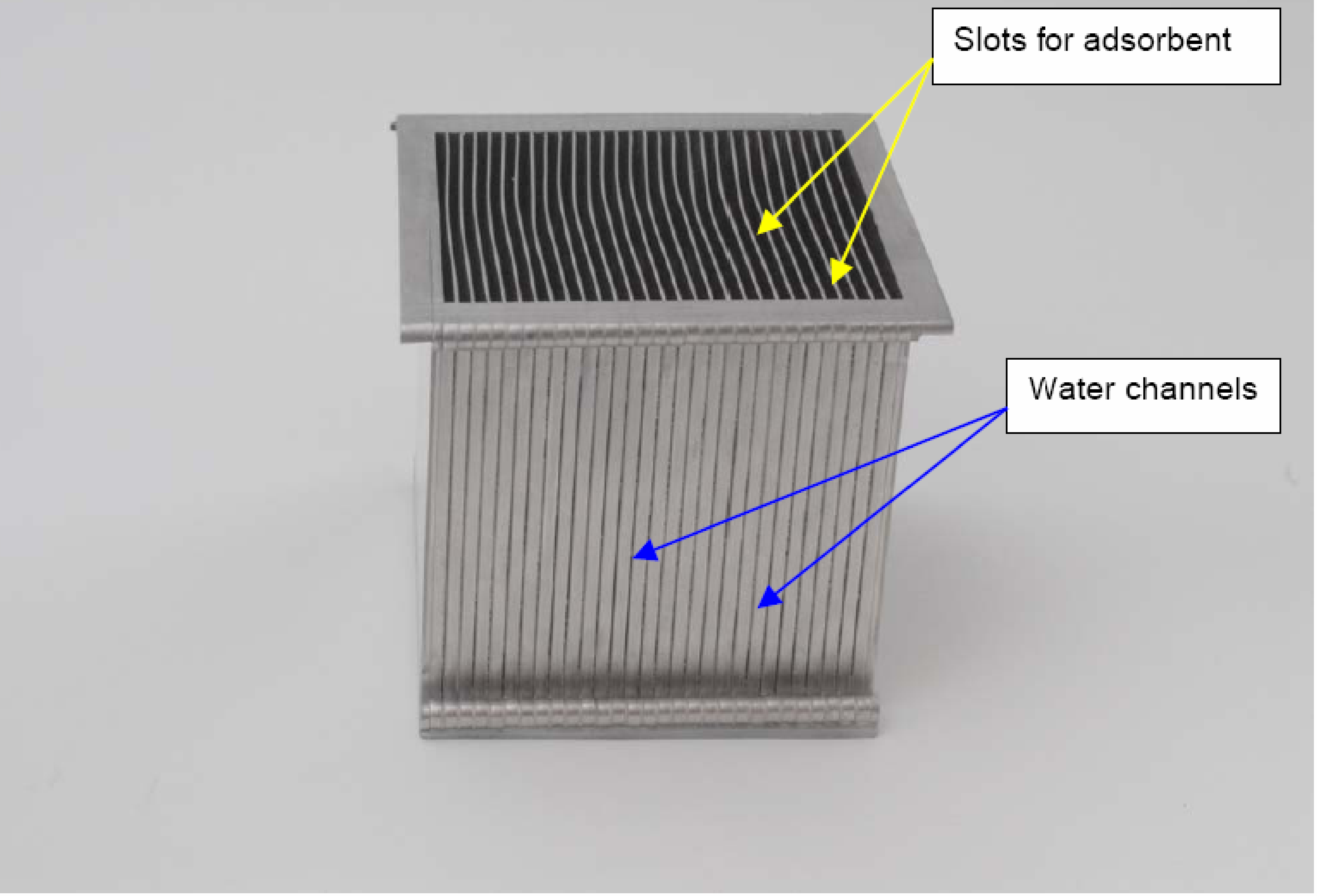
Two applications:

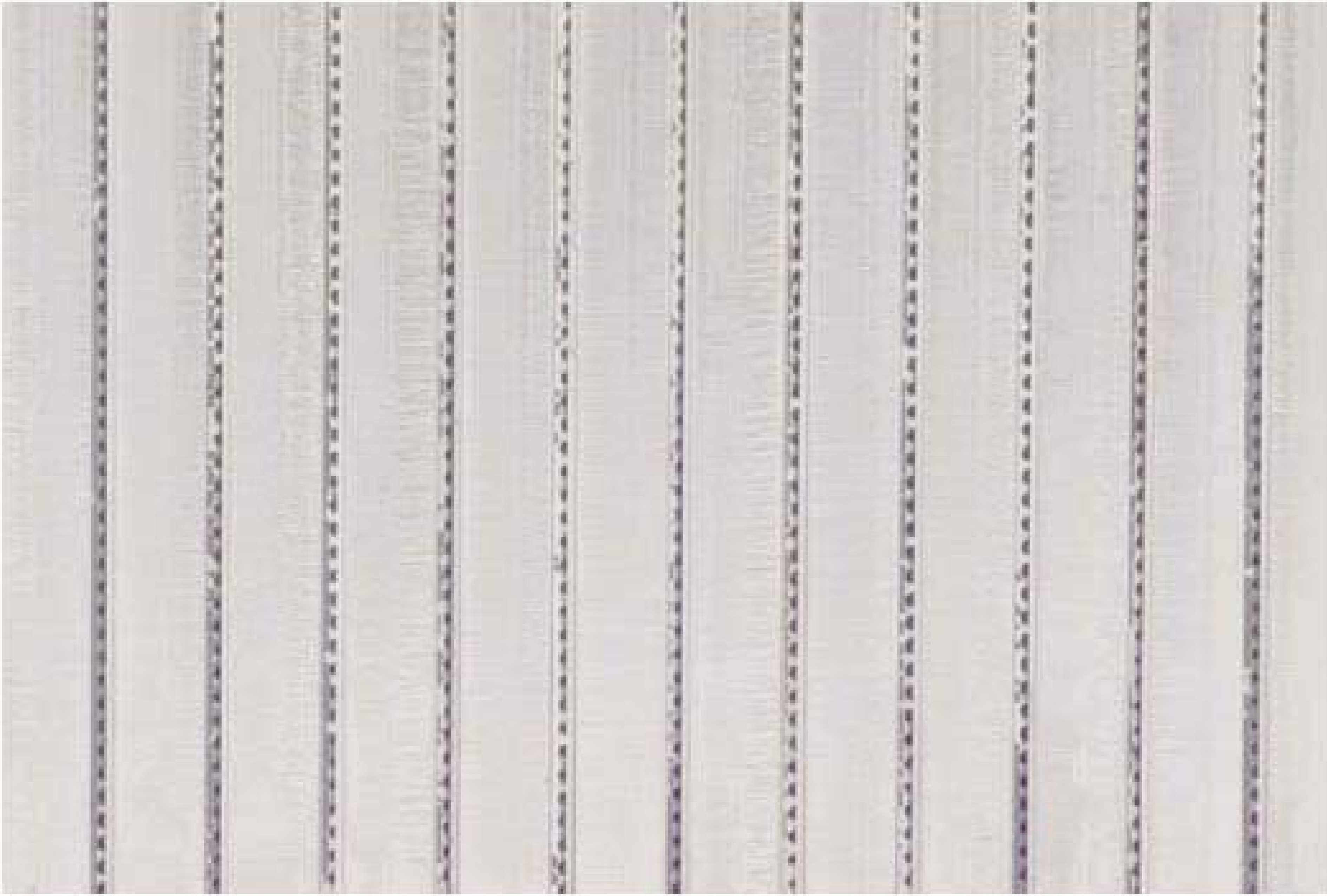
- **C-Class car (2 -3 kW)**
- **Long distance truck**

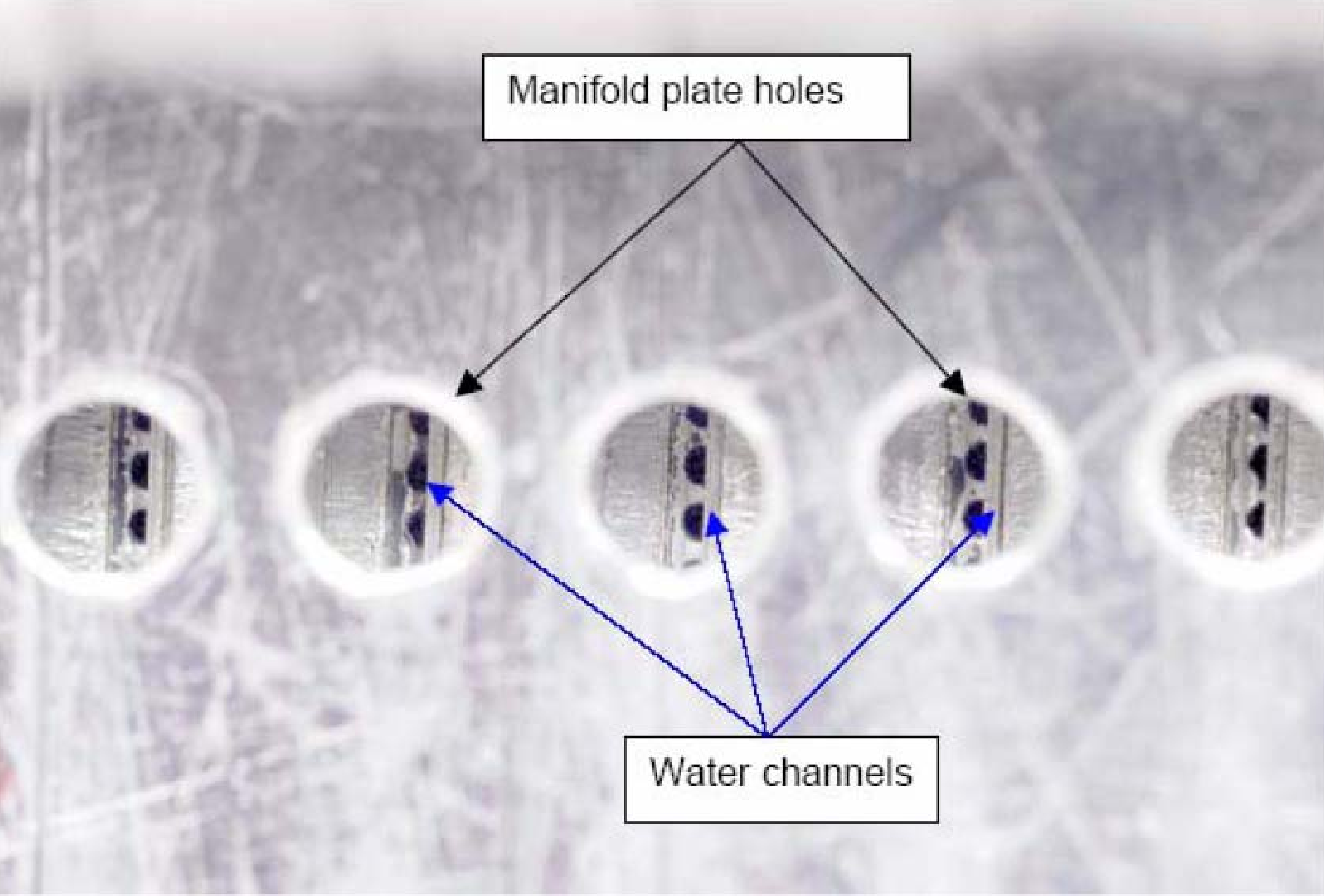
The initial generator design was manufactured in January 2007. Two such generators are needed per system.

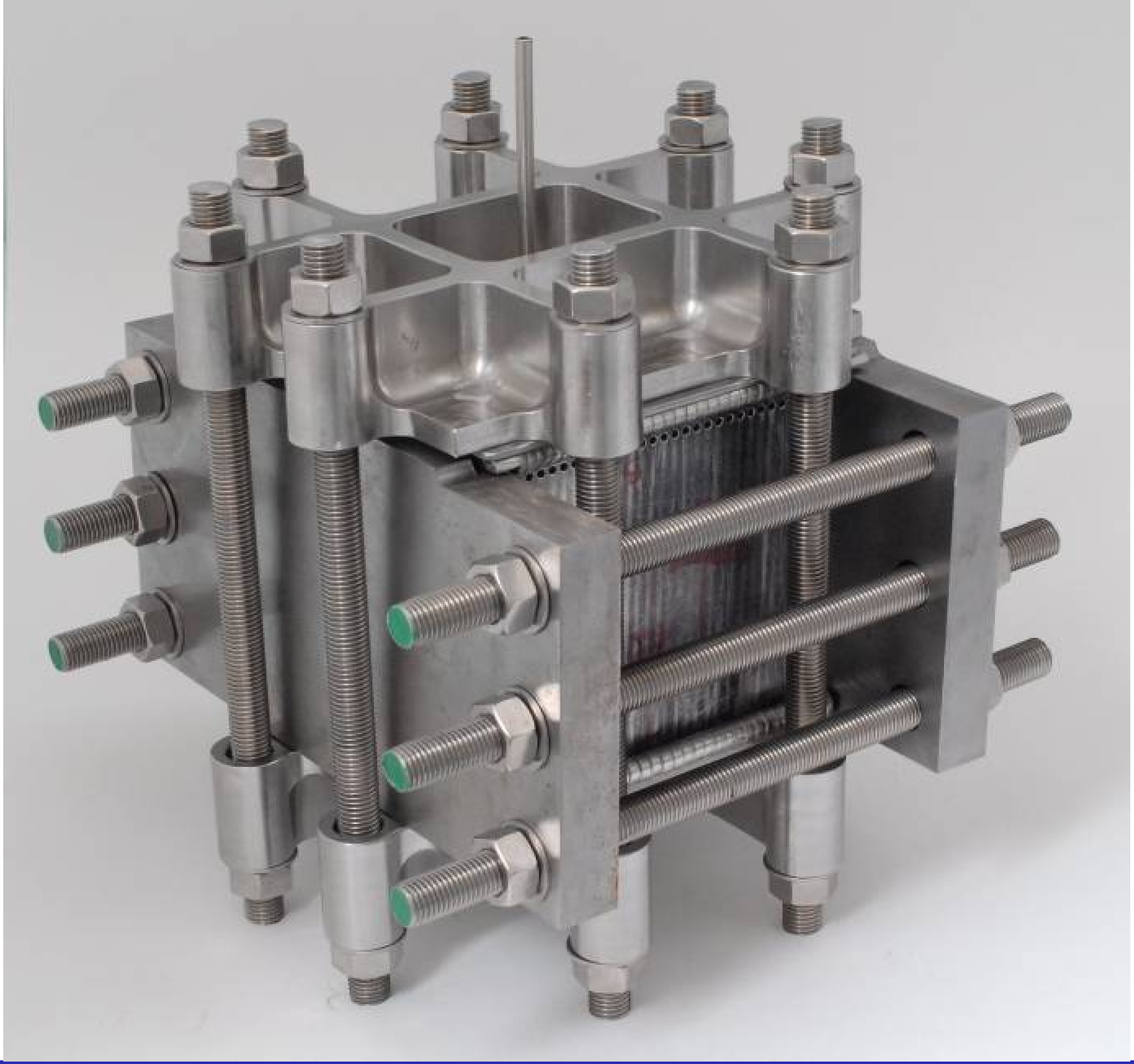

Ammonia
Engine cooling loop
Adsorber Cooling loop
Cabin chiller loop
Intercooling loop
Ambient air
V7
V6
V8
V9
V11
V5
Sorption Generator G1
Sorption Generator G2
P3
V2
HEX2
HEX3
Evaporator
Cabin cooler matrix
P1
V10
HEX1
FAN2
Condenser
Radiator
FAN1
Engine, cabin heater matrix and auxiliary burner
V1
V4
P2
V3
Cooler
HEX4

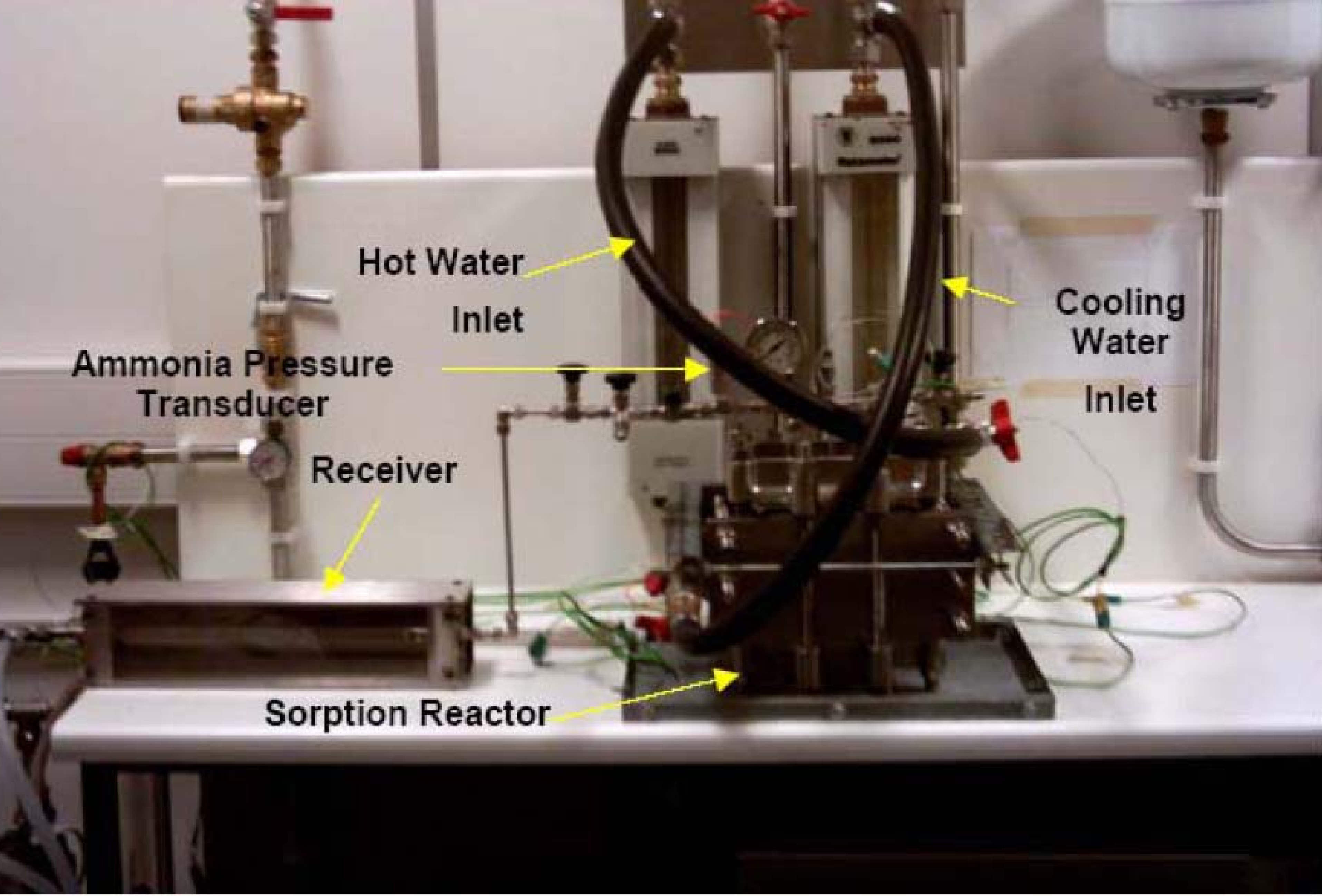


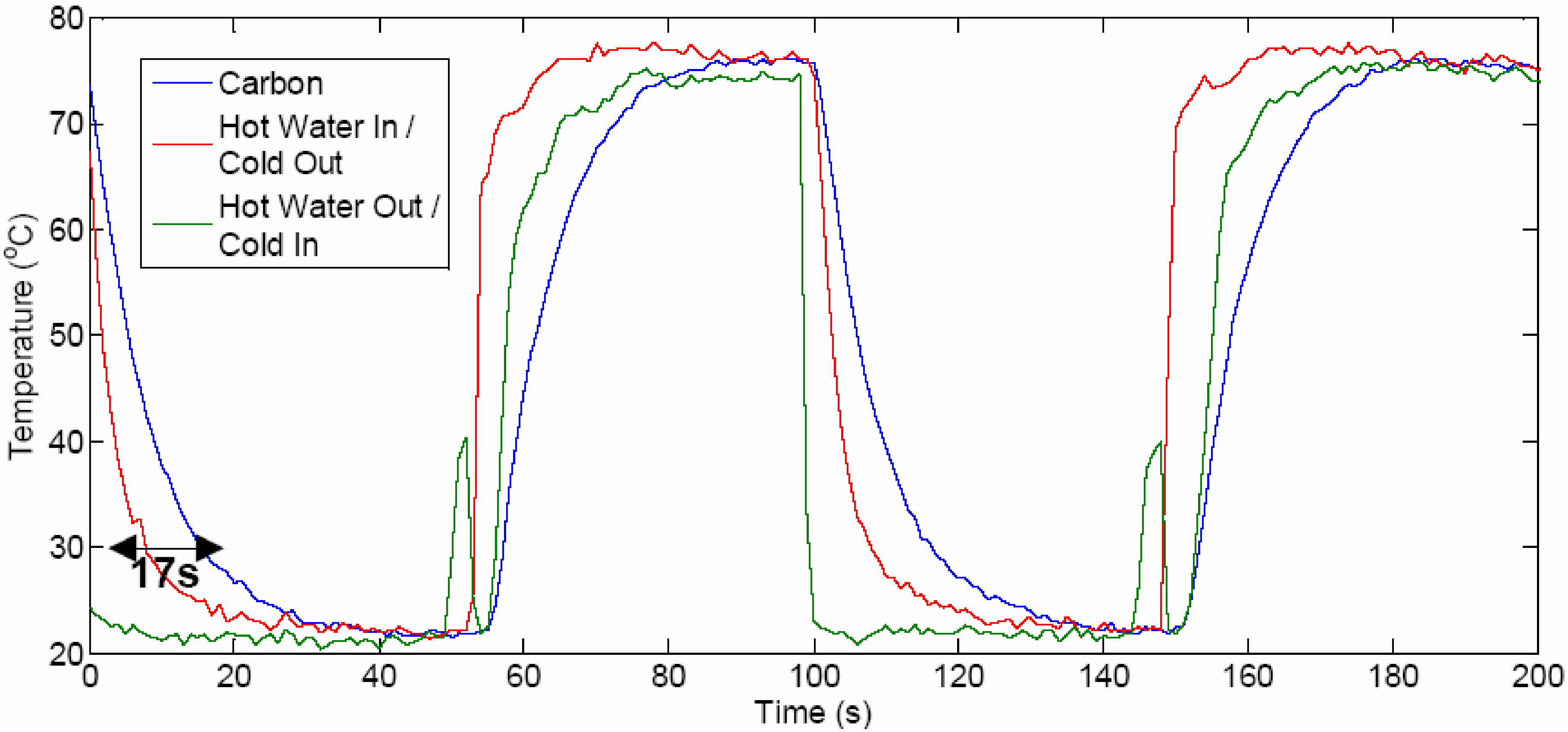

Slots for adsorbent
Water channels



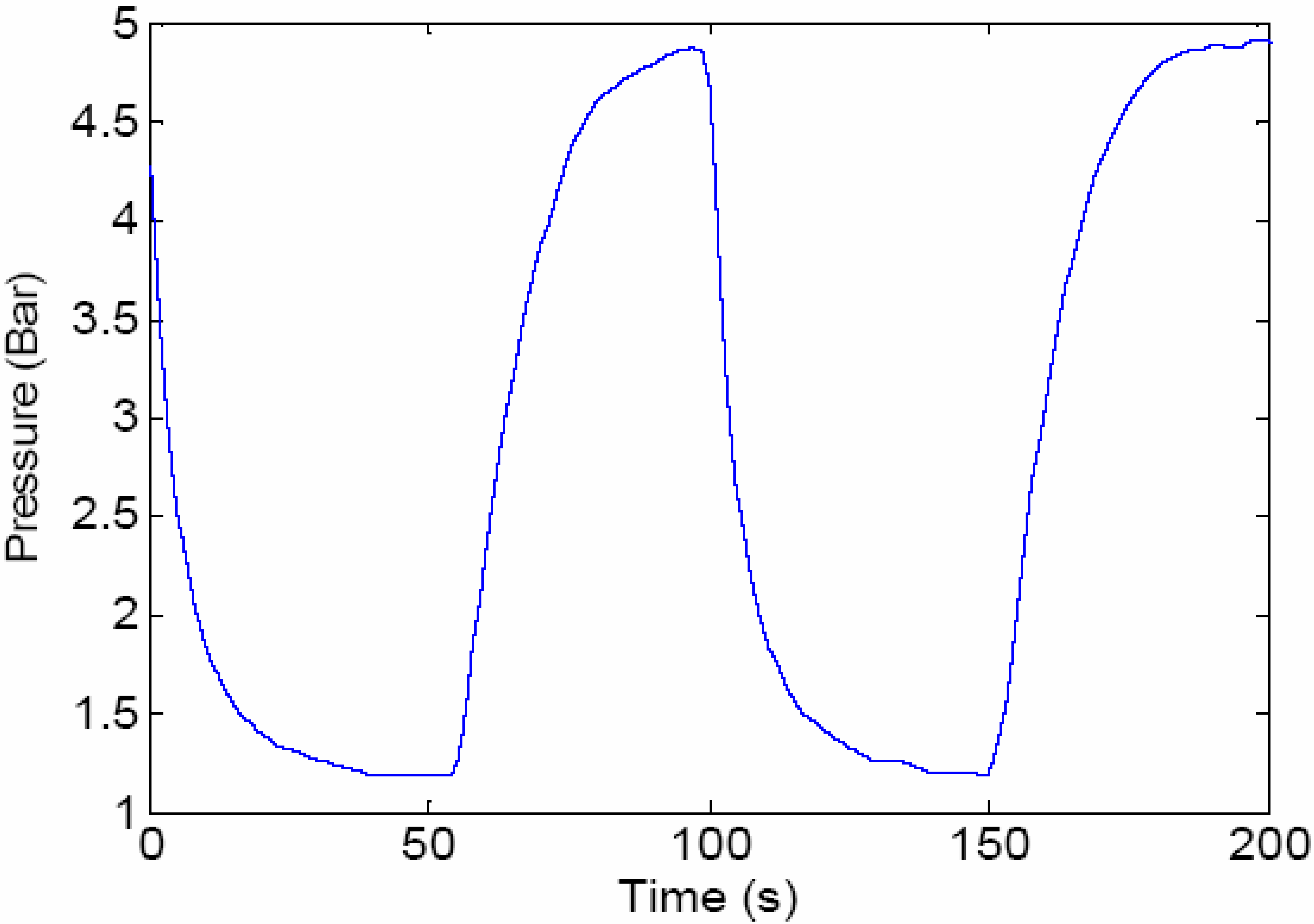

Manifold plate holes
Water channels




Hot Water
Inlet
Cooling
Water
Inlet
Ammonia Pressure
Transducer
Receiver
Sorption Reactor



Preliminary test: carbon and heating/cooling water temperatures



Preliminary test pressure swing

We hope to have a 2-bed system working in the laboratory within three months.

If successful a test-bed system will be installed in a car in 2008.

EPSRC Domestic Gas-Fired Heat Pump Project

EPSRC Domestic Gas-Fired Heat Pump Project - Background

In the UK, Space Heating and Hot Water Represents:

82% of Domestic Energy Consumption

64% of Industrial Energy Consumption

- 39% of UK Energy Consumption Used For Space Heating and Hot Water

Improvements in the efficiency of space heating and hot water production could dramatically reduce carbon emissions and energy usage

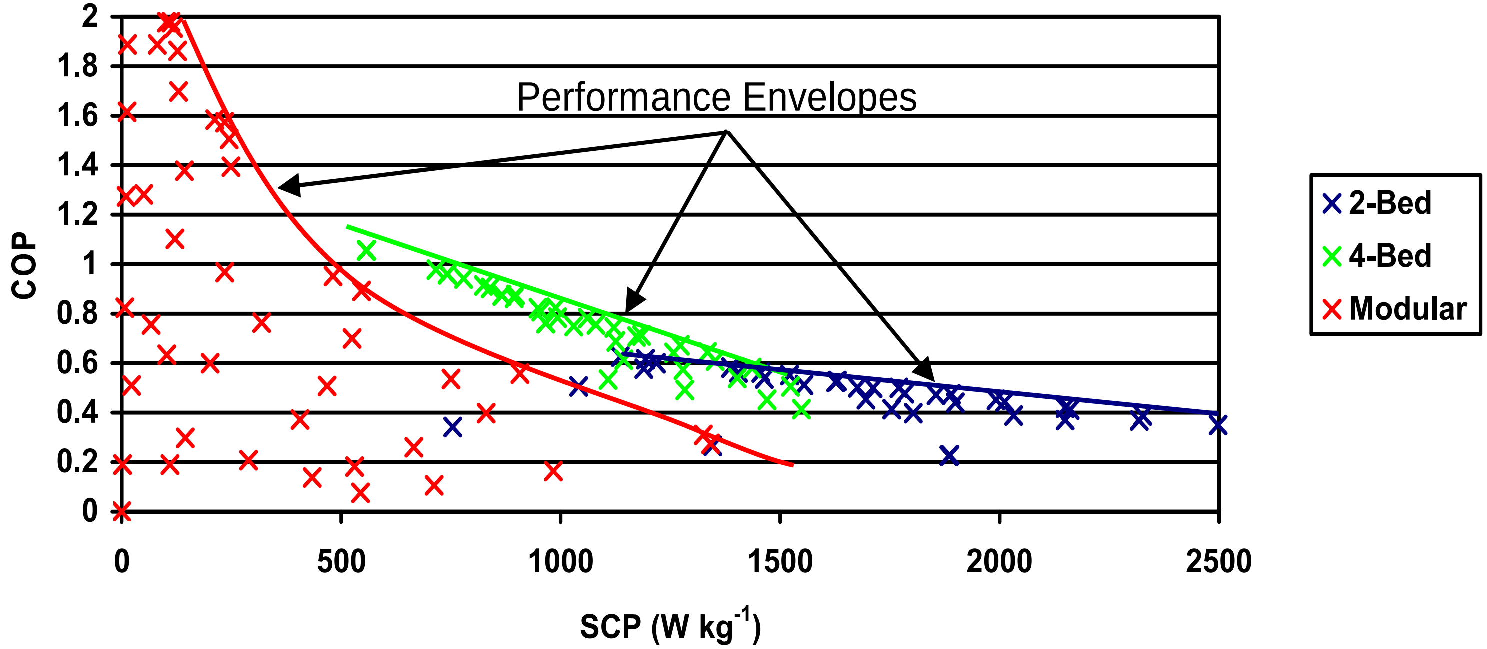
EPSRC Domestic Gas-Fired Heat Pump Project - Specification

- **Replacement for a Domestic Gas Combination Boiler**
- **Air Source (Ease of Installation)**
- **Heating Output of 7kW**
- **Hot Water Output of 10 l min^{-1} @ 30°C Temperature Rise (~21 kW)**
- **Eventual Packaged System Volume ≤2×Volume Conventional Gas Boiler**

EPSRC Domestic Gas-Fired Heat Pump Project – Cycle selection

Two Main Heat Recovery Methods for Adsorption Cycles:

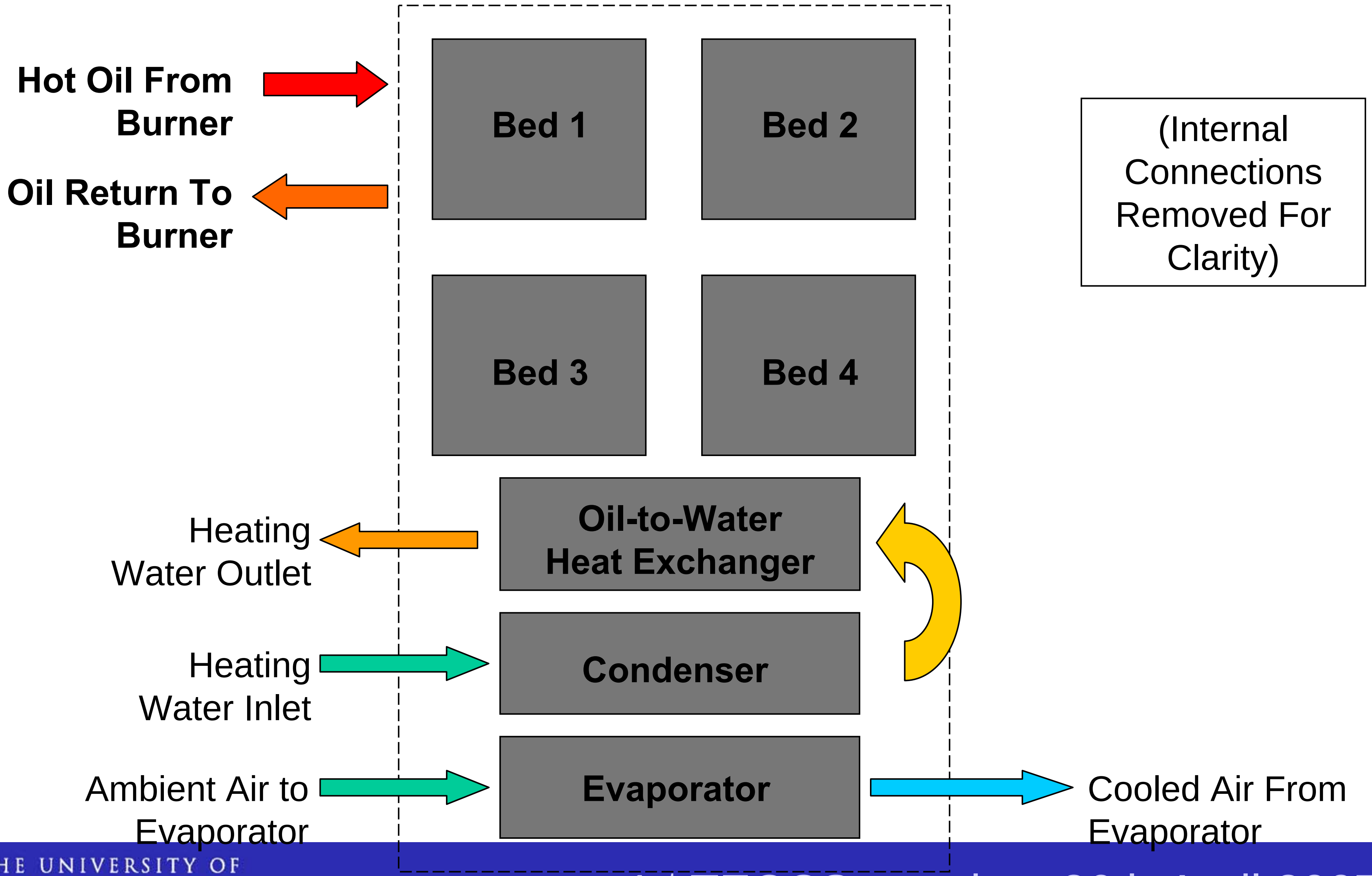
- Thermal Wave (Performance envelope in Red Below)
- Multiple-Bed (Four-Bed In Green, Two-Bed In Blue)



EPSRC Domestic Gas-Fired Heat Pump Project - System

- Adsorption Cycle Carbon-Ammonia Heat Pump
- Four-Bed Heat Recovery With Mass Recovery
- Gas Fired by a Regenerative Gas Burner

System Schematic – Heat Pump

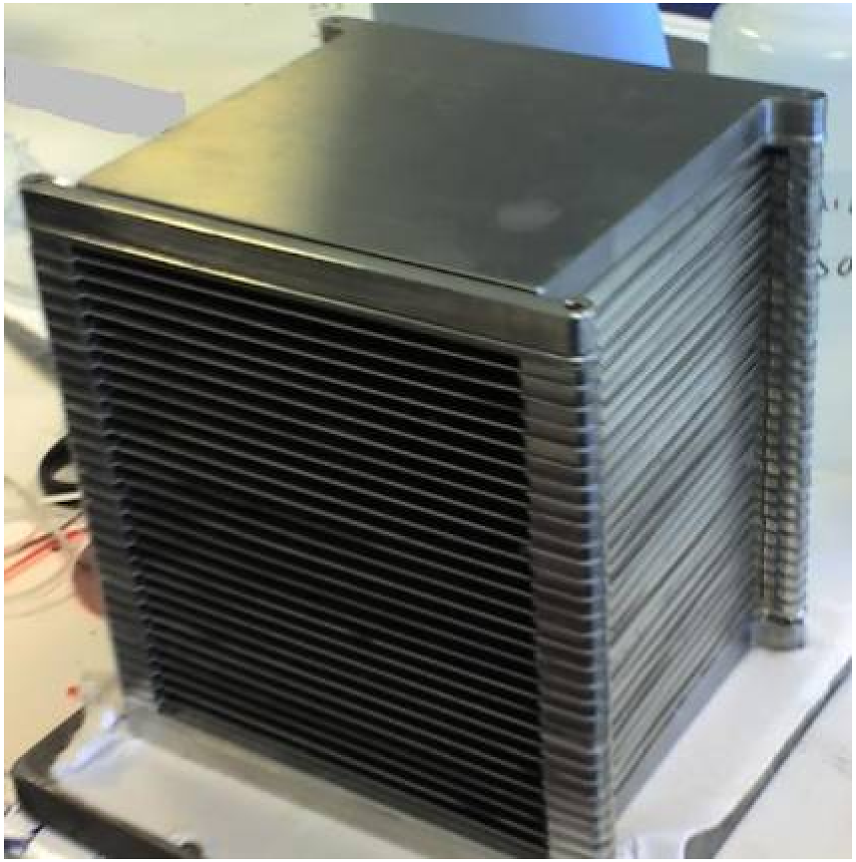


Sorption Generator Design

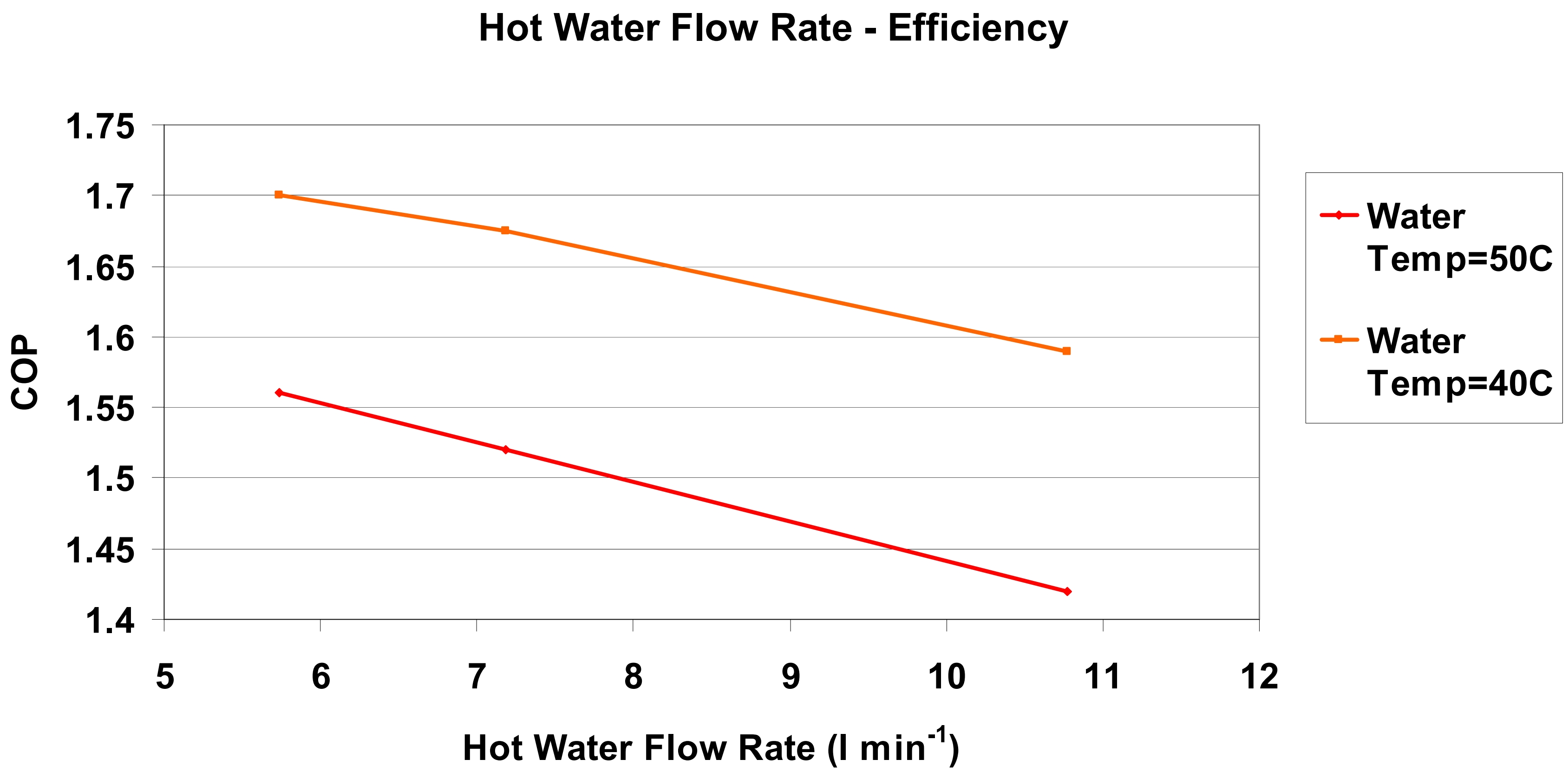
Plate Heat Exchanger Sorption Generator

Designed for the EU TOPMACS Mobile Air Conditioning Project

Gives a High Power Density



EPSRC Domestic Gas-Fired Heat Pump Project - System Performance – Water Heating



- Air Source Temperature: 10°C
- Hot Water Inlet Temperature: 20°C

EPSRC Domestic Gas-Fired Heat Pump Project - System Performance – Water Heating

System Can Match a Combination Boiler:

- 10 l min-1 flow rate @ 30°C Temperature Rise
- 21 kW Output

Including an Assumed Burner Efficiency of 0.8:

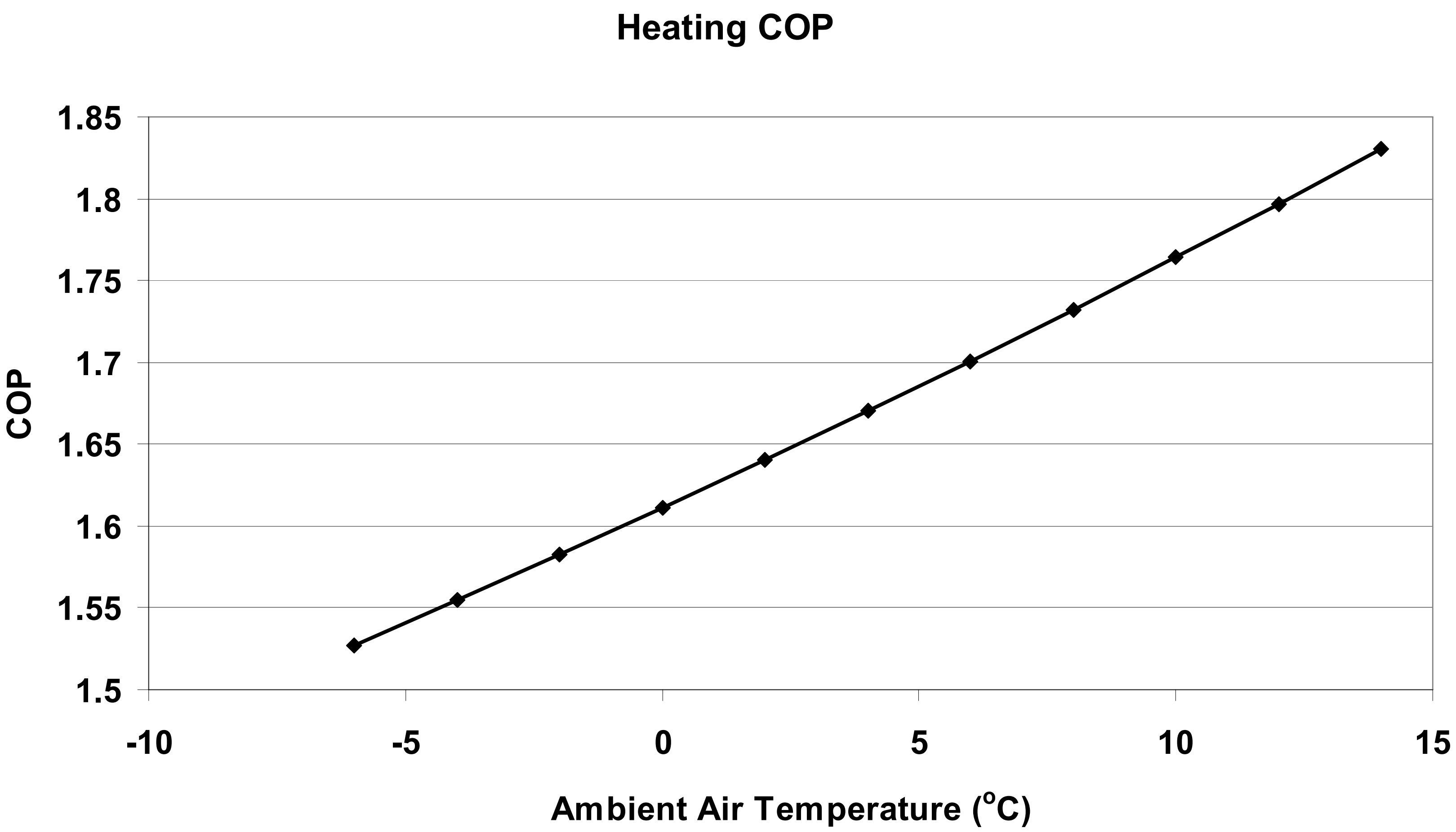
- @ 50°C Hot Water Temperature: Overall COP ≅1.2
- @ 40°C Hot Water Temperature: Overall COP ≅1.32

Typical Condensing Combination Boiler Efficiency 0.88

Gas Fired Heat Pump:

- 33% More Efficient
- 1.5 Times Lower Gas Consumption

EPSRC Domestic Gas-Fired Heat Pump Project - System Performance – Space Heating

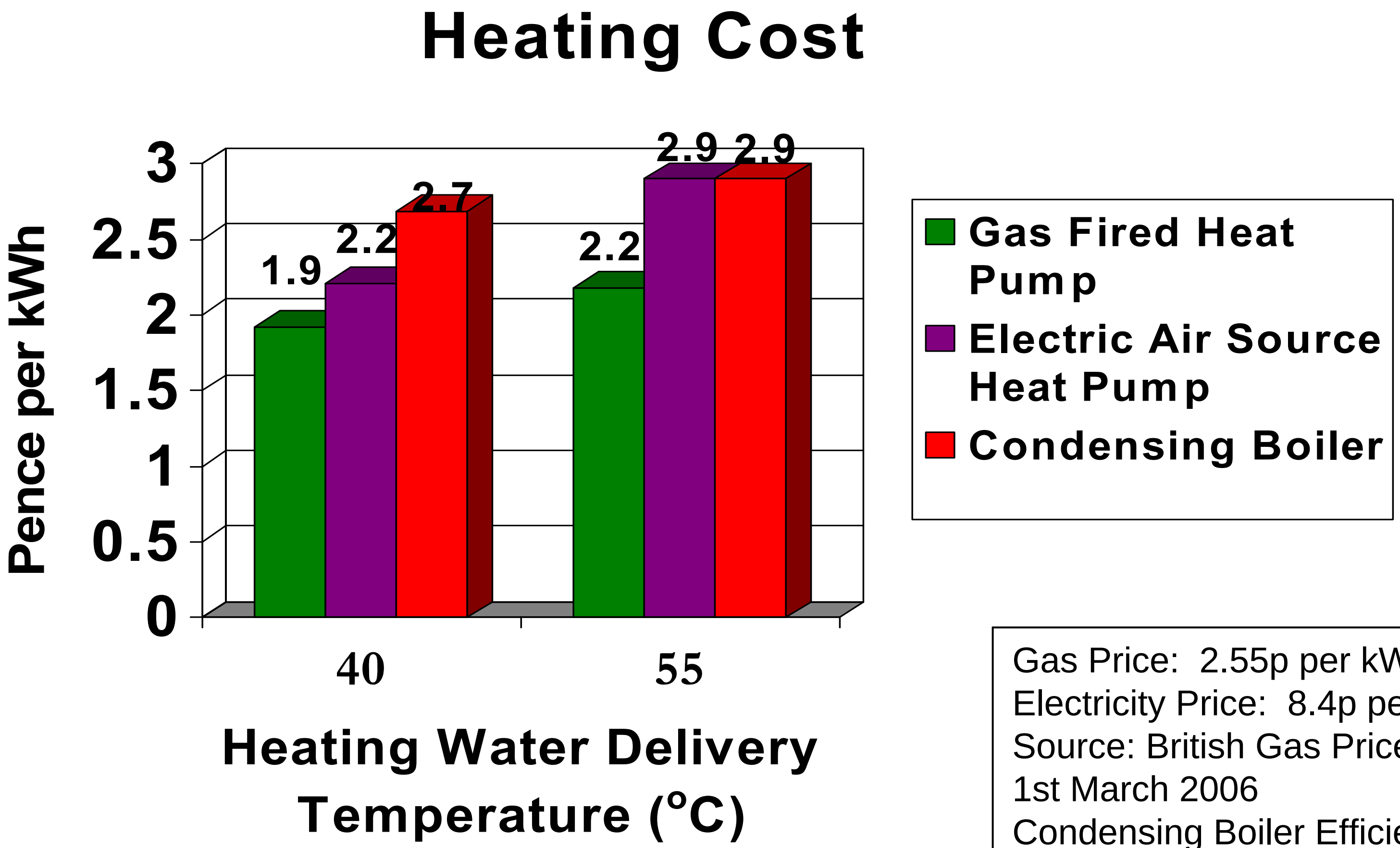


Heating Water Supply Temperature: 35°C
(i.e. Underfloor Heating)

EPSRC Domestic Gas-Fired Heat Pump Project - System Performance – Space Heating

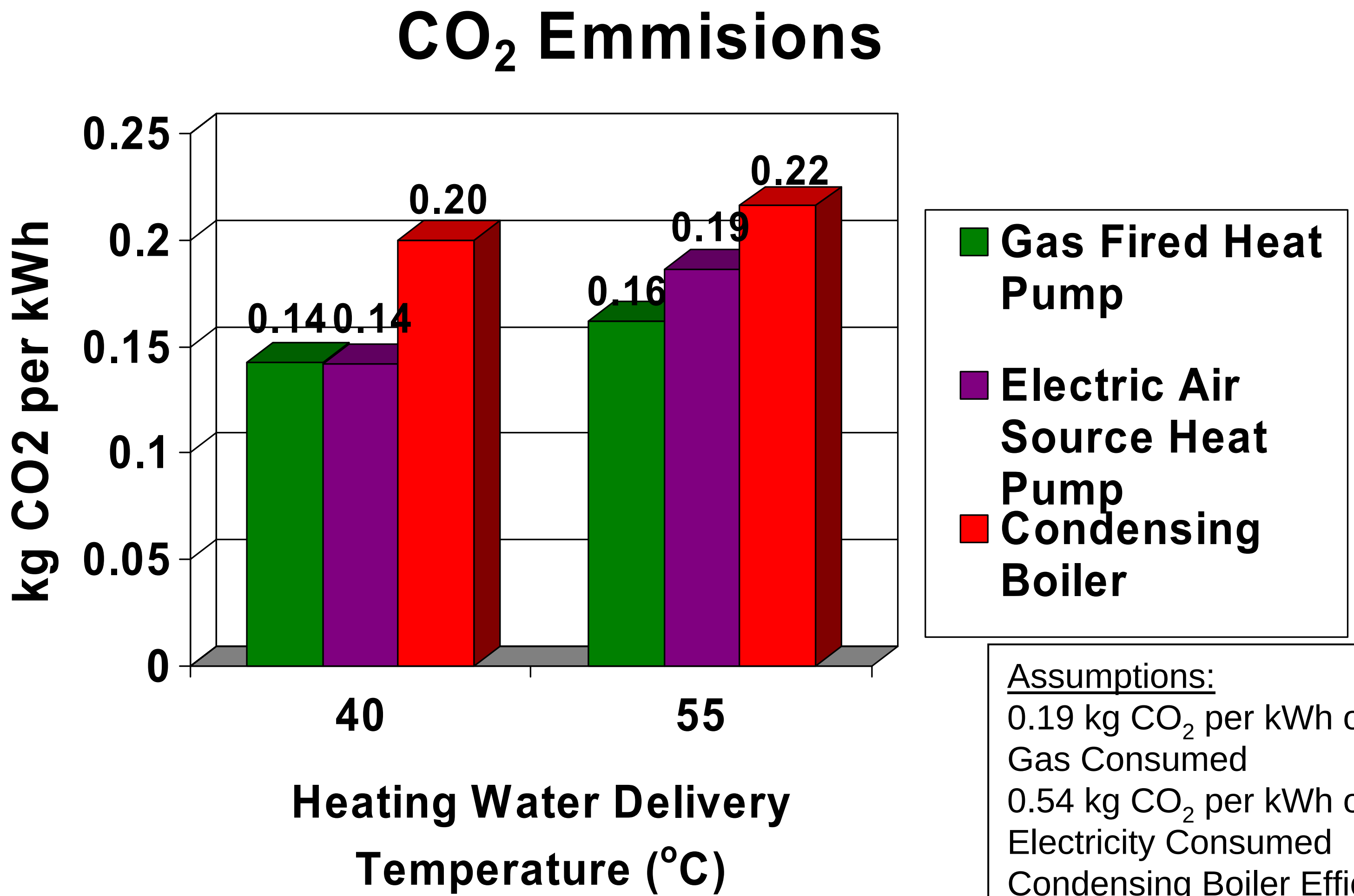
- Seasonal Heating COP: 1.69 (Typical UK Midlands Heating Season)
- Seasonal Heating COP Including Burner Efficiency: 1.35
- Condensing Boiler Efficiency: 0.88 (source: SEDBUK)
- 1.5 Times Reduction in Gas Usage

EPSRC Domestic Gas-Fired Heat Pump Project - System Performance – Space Heating



Gas Price: 2.55p per kWh
Electricity Price: 8.4p per kWh
Source: British Gas Prices From 1st March 2006
Condensing Boiler Efficiency: 95% and 88%

EPSRC Domestic Gas-Fired Heat Pump Project - System Performance – Space Heating



<u>Assumptions:</u>
0.19 kg CO_2 per kWh of Natural Gas Consumed
0.54 kg CO_2 per kWh of UK Grid Electricity Consumed
Condensing Boiler Efficiency 95% and 88%

EPSRC Domestic Gas-Fired Heat Pump Project – Current Status

- Design for a Gas Fired Adsorption Heat Pump Completed
- Shown to Compare Favourably to Alternative Technologies
- Significant Fuel Cost and Carbon Emissions Reductions
- Prototype Undergoing Manufacture Prior to Testing

Future Projects

1. **EU FP7 – Solar Powered Air Conditioning, 5 – 10 kW cooling**
2. Solar powered cold store, 2 kW cooling
3. Ice-maker for use in Indian villages in conjunction with a biomass fuelled engine.
4. Further development of the gas-fired heat pump – seeking venture capital or manufacturing investment.

Solar Air Conditioning

- **Feasibility studies carried out on the use of solar collectors to drive adsorption cycle air conditioners.**

- **Evacuated tube collectors proved more cost effective than flat plate collectors.**
  - **Evacuated Tube Collector Cost: €785/m^2.**
  - **Flat Plate Collector Cost: €500/m^2.**

Solar Air Conditioning

Performance Calculations

Conditions:

Evacuated tube collector driving a four bed adsorption cycle with mass recovery and plate type generators.

High porosity ‘Maxsorb’ carbon.

Hottest day of the year in Seville, Spain: Peak ambient temperature 40°C.

Results:

Optimum of 2.5 m^2 of collector per kg of carbon adsorbent.

9.8 MJ of cooling per m^2 collector per day.

Equivalent to 0.34 kW m^{-2} of collector over an 8 hour cooling period.

Solar Air Conditioning

Typical room air conditioner: ~3 kW

Would require approximately:

- **9 m^2 of collector at a cost of €7000.**
- **3.6 kg of carbon (total generator volume ~7 litres).**

Cost will be dominated by the collector:

- **Important to achieve maximum efficiency from the adsorption air conditioner.**

Future Projects

1. EU FP7 – Solar Powered Air Conditioning, 5 – 10 kW cooling
2. **Solar powered cold store, 2 kW cooling**
3. Ice-maker for use in Indian villages in conjunction with a biomass fuelled engine.
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Future Projects

Solar powered cold store, 2 kW cooling

A 1-year project, expected to start in May 2007 is to build a walk-in container for food preservation, which will be field tested. It will use evacuated tube solar collectors with ammonia-carbon plate heat exchangers.

Future Projects

1. EU FP7 – Solar Powered Air Conditioning, 5 – 10 kW cooling
2. Solar powered cold store, 2 kW cooling
3. **Ice-maker for use in Indian villages in conjunction with a biomass fuelled engine.**
4. Further development of the gas-fired heat pump – seeking venture capital or manufacturing investment.

Future Projects

Ice-maker for use in Indian villages in conjunction with a biomass fuelled engine.

A three year project funded by EPSRC, with partners in Aston, Bristol, Leeds and IIT Delhi seeks to establish a complete village energy infrastructure based on biofuels.

We have the task of building an ice-maker driven by the waste heat of an engine.

Future Projects

1. EU FP7 – Solar Powered Air Conditioning, 5 – 10 kW cooling
2. Solar powered cold store, 2 kW cooling
3. Ice-maker for use in Indian villages in conjunction with a biomass fuelled engine.
4. **Further development of the gas-fired heat pump – seeking venture capital or manufacturing investment.**