SOLAR COOLING

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Why Solar Cooling

- Dramatic increase of air conditioning since the early 80ies
- Cost of energy
- Issues related to environmental pollution
  - Due to energy production
  - Due to the use of CFC's and HCFC's
- Matches demand with source availability
- Crucial for improving life standards in developing countries

Thermal Comfort

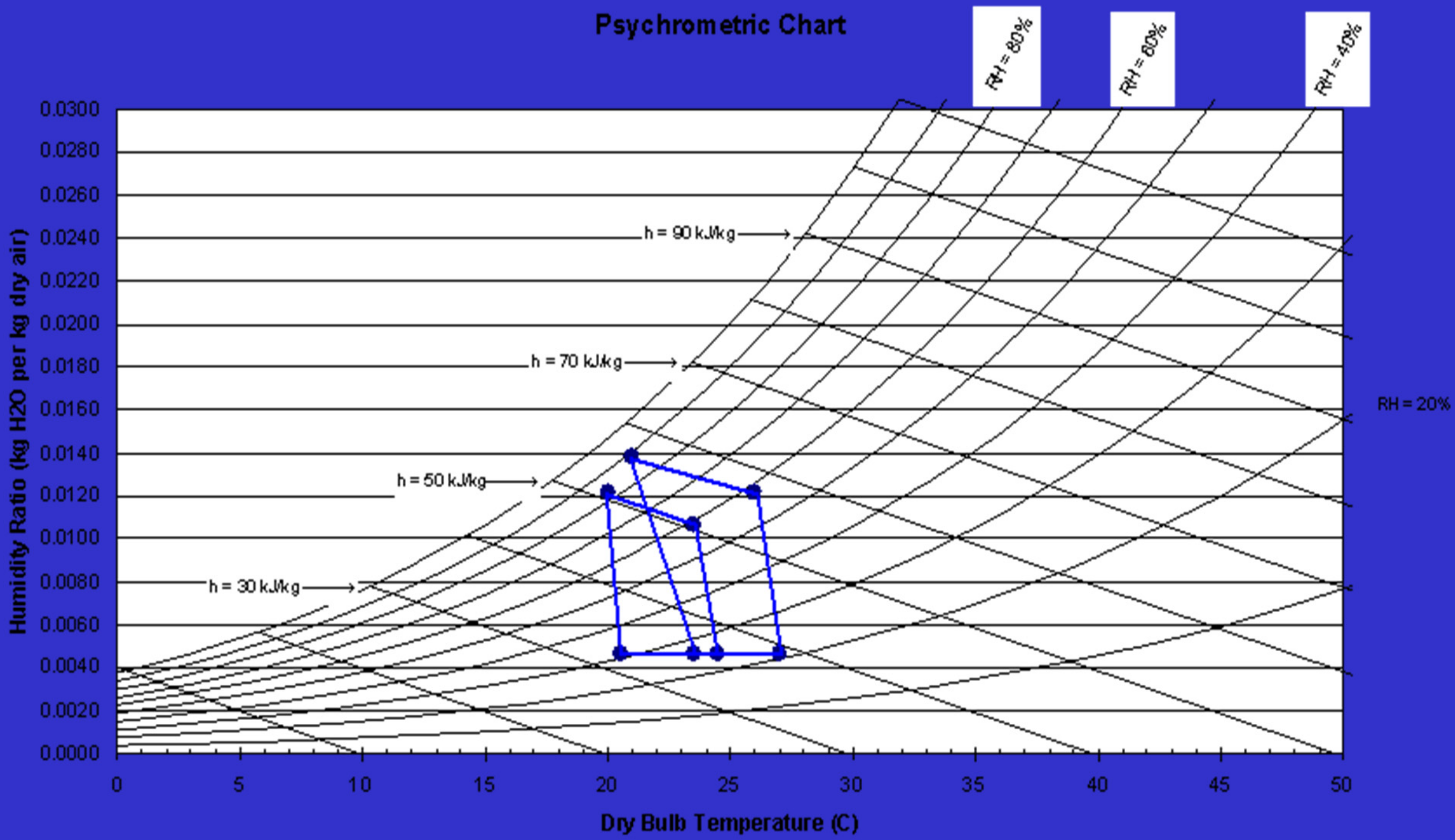
"Is that condition of mind that expresses satisfaction with the thermal environment"

Depends on may parameters:

- Meteorological
- Physiological / psychological
- Clothing
- etc

Conclusion: Concept **not easily** quantifiable!

Thermal Comfort – ASHRAE Approach



Underlying Physics

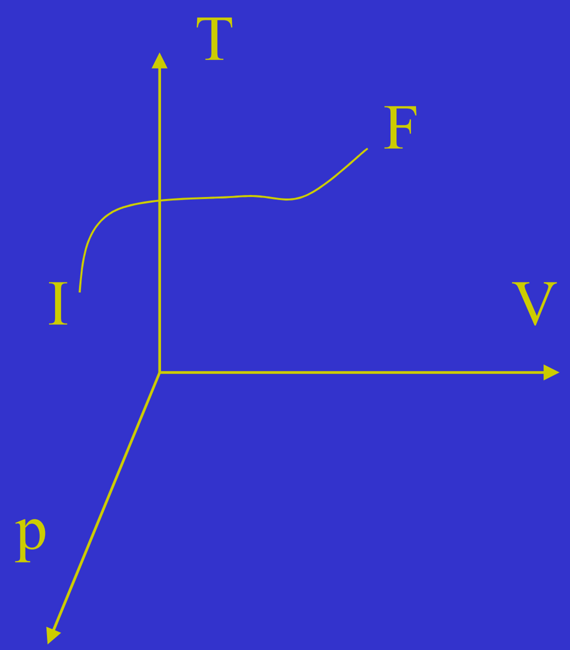
Thermodynamics

1[st] Law: The change of internal energy (ΔU) of a system is equal to the heat absorbed (Q), plus the external work (W) done on the system

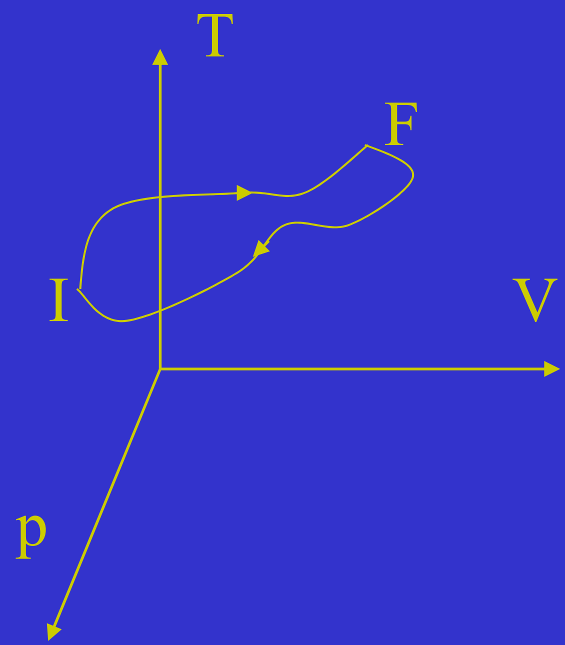
W, Q related to the changes the system experiences when going from an initial to a final state

Thermodynamic Cycle

Simple Transformation



Cyclical Transformation or Cycle



Entropy

The concept of entropy was originally introduced in 1865 by Rudolf Clausius. He defined the *change in entropy* of a thermodynamic system, during a reversible process in which an amount of heat ΔQ_r is applied at constant absolute temperature T, as

$$\Delta S = \Delta Qr \,/\, T$$

Clausius gave the quantity S the name "entropy", from the Greek word *τροπή*, "transformation". Since this definition involves only differences in entropy, the entropy itself is only defined up to an arbitrary additive constant

Thermodynamics - 2nd Law

The most probable processes that can occur in an isolated system are those in which entropy increases or remains constant

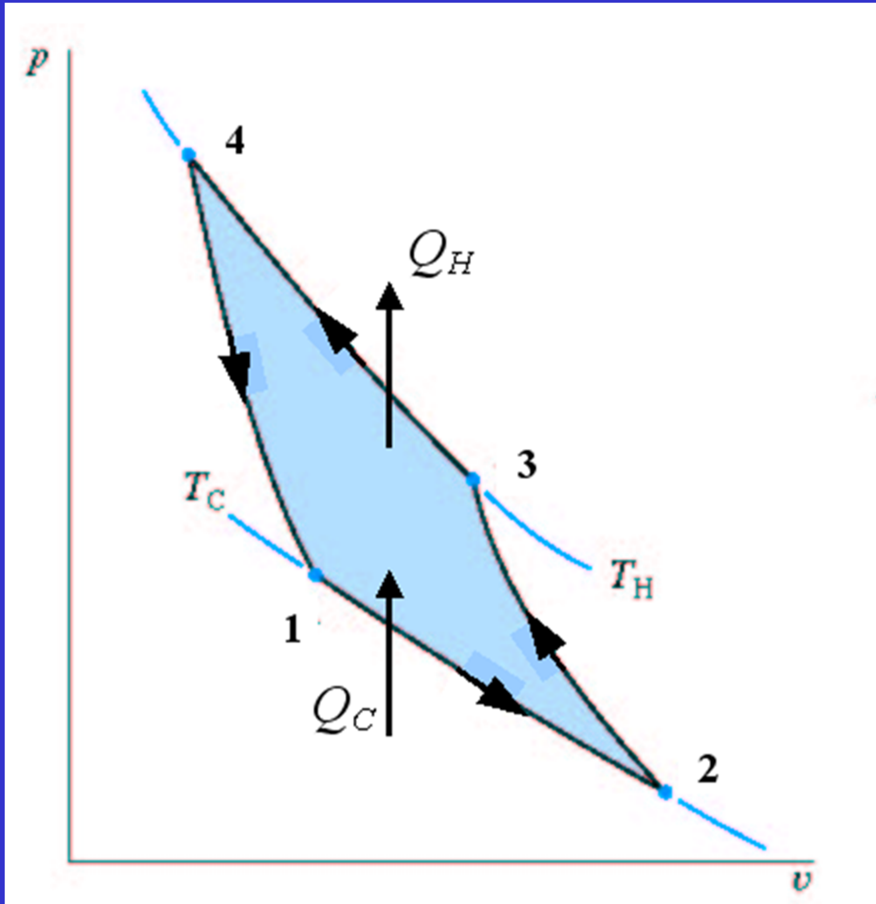
In other words:

> In an isolated system there is a well-defined trend of occurrence of process and this is determined by the direction in which entropy increases.

In other words:

> Heat flows naturally from a system of higher temperature to a system of lower temperature.

Ideal Carnot Refrigeration Cycle



1→2 Isothermal expansion
2→3 Adiabatic compression
3→4 Isothermal compression
4→1 Adiabatic expansion

$$W_{cycle} = \int_1^2 Pdv + \int_2^3 Pdv + \int_3^4 Pdv + \int_4^1 Pdv$$

$$= \text{shaded area (net work } in\text{)}$$

Coefficient of Performance (COP)

$$COP = \frac{\text{Useful cooling energy}}{\text{Net energy supplied by external sources}}$$

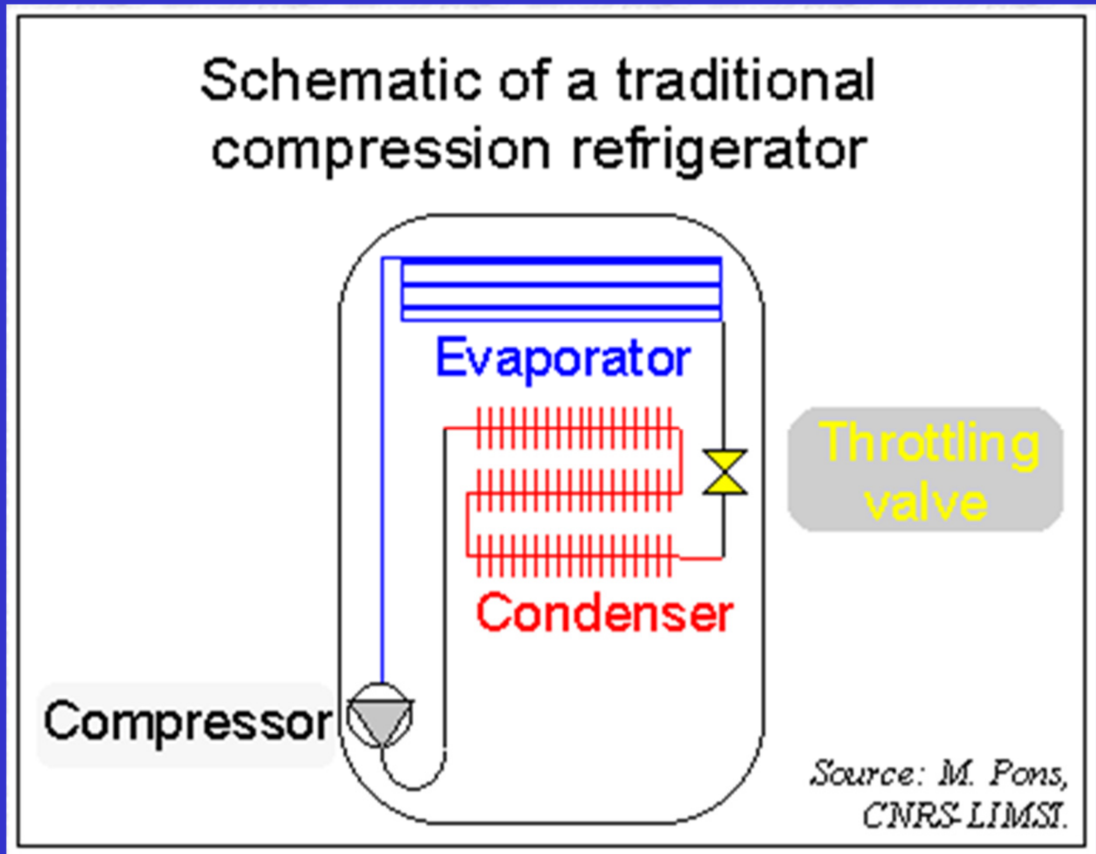
Latent Heat

Is the amount of energy in the form of heat released or absorbed by a substance during a change of phase (i.e. solid, liquid, or gas), – also called a phase transition.[

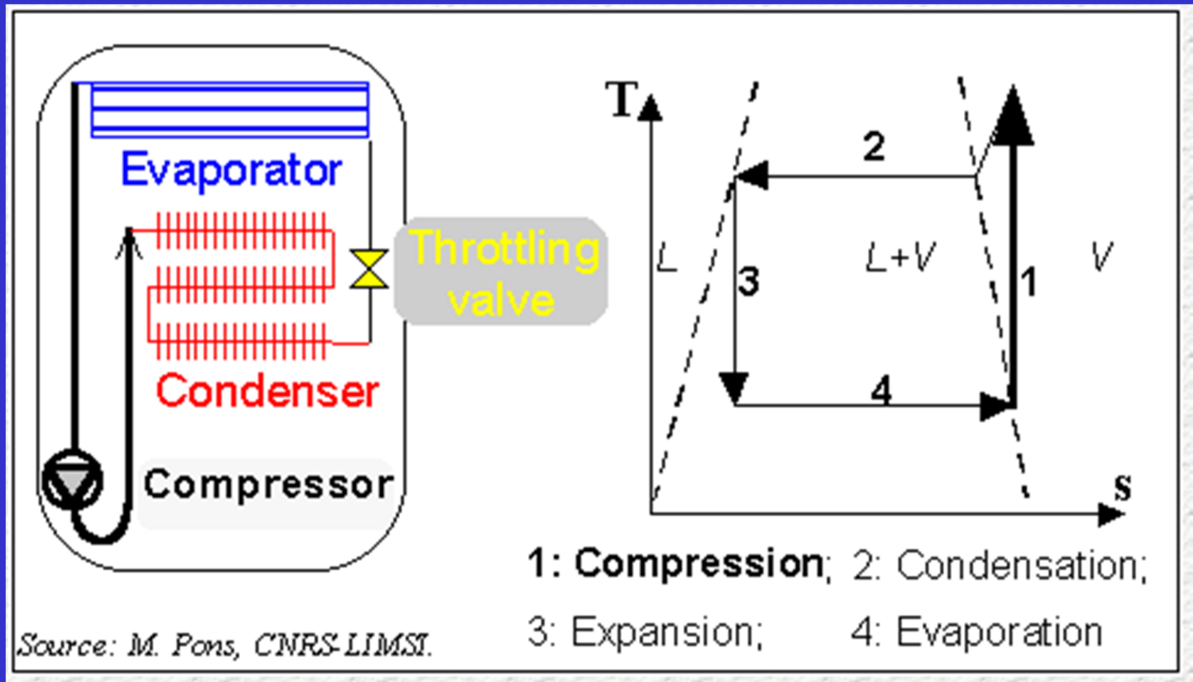
Two latent heats are typically described: latent heat of fusion (melting), and latent heat of vaporization (boiling). The names describe the direction of heat flow from one phase to the next: solid → liquid → gas. The change is endothermic, i.e. the system absorbs energy, when the change is from solid to liquid to gas. It is exothermic (the process releases energy) when it is in the opposite direction.

Because energy is needed to overcome the molecular forces of attraction between water particles, the process of transition from a parcel of water to a parcel of vapor requires the input of energy causing a drop in temperature in its surroundings. If the water vapor condenses back to a liquid or solid phase onto a surface, the latent energy absorbed during evaporation is released as sensible heat onto the surface. The large value of the latent heat of condensation of water vapor is the reason that steam is a far more effective heating medium than boiling water, and is more hazardous.

Conventional cooling cycle

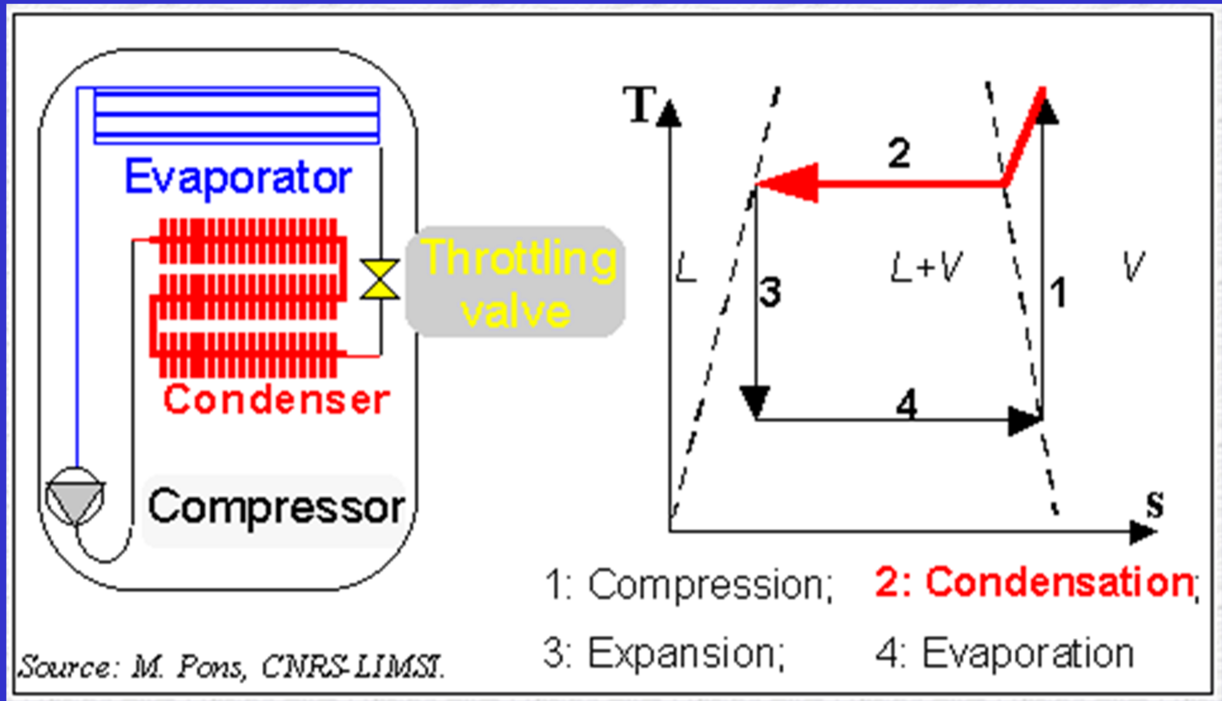


Compression



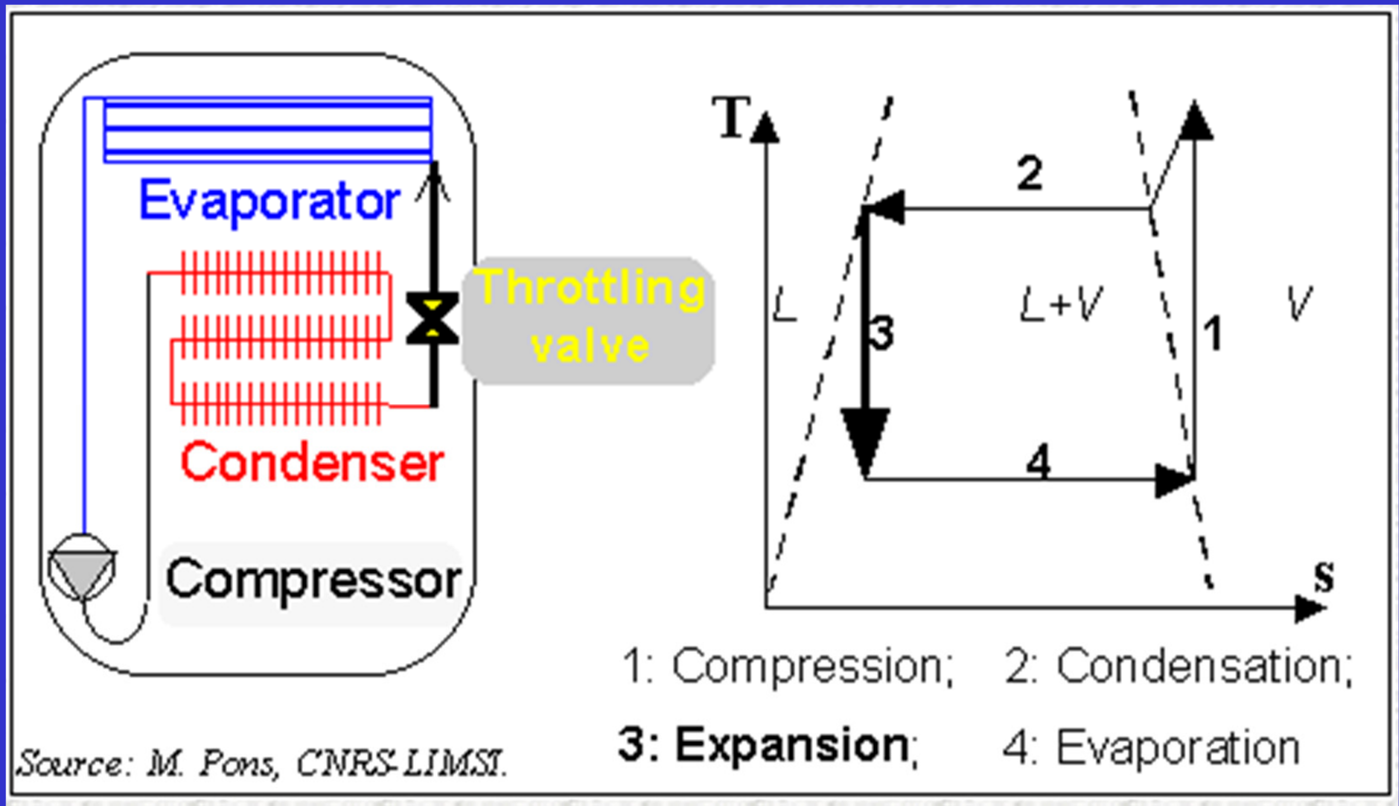
Vapor is compressed and its temperature increases
($p V = n R T$)

Condensation



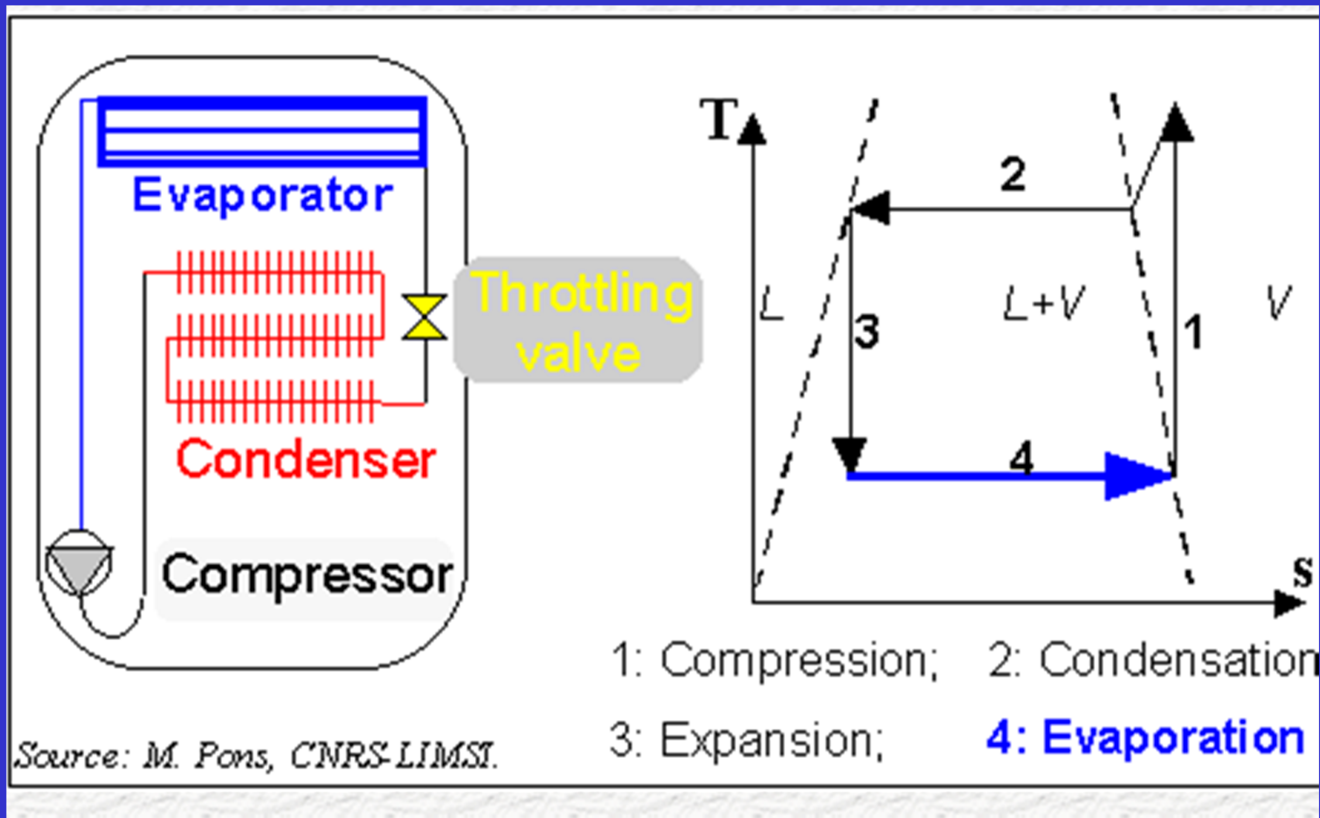
The fluid at "high pressure" is cooled by ambient air and therefore condensed

Expansion



The liquid refrigerant is depressurized and its temperature decreases ($p\ V = n\ R\ T$)

Evaporation



The liquid refrigerant at "low pressure" receives heat at low temperature and evaporates

Thermal Solar Cooling Techniques

Absorption Cooling

Energy is transferred through phase-change processes

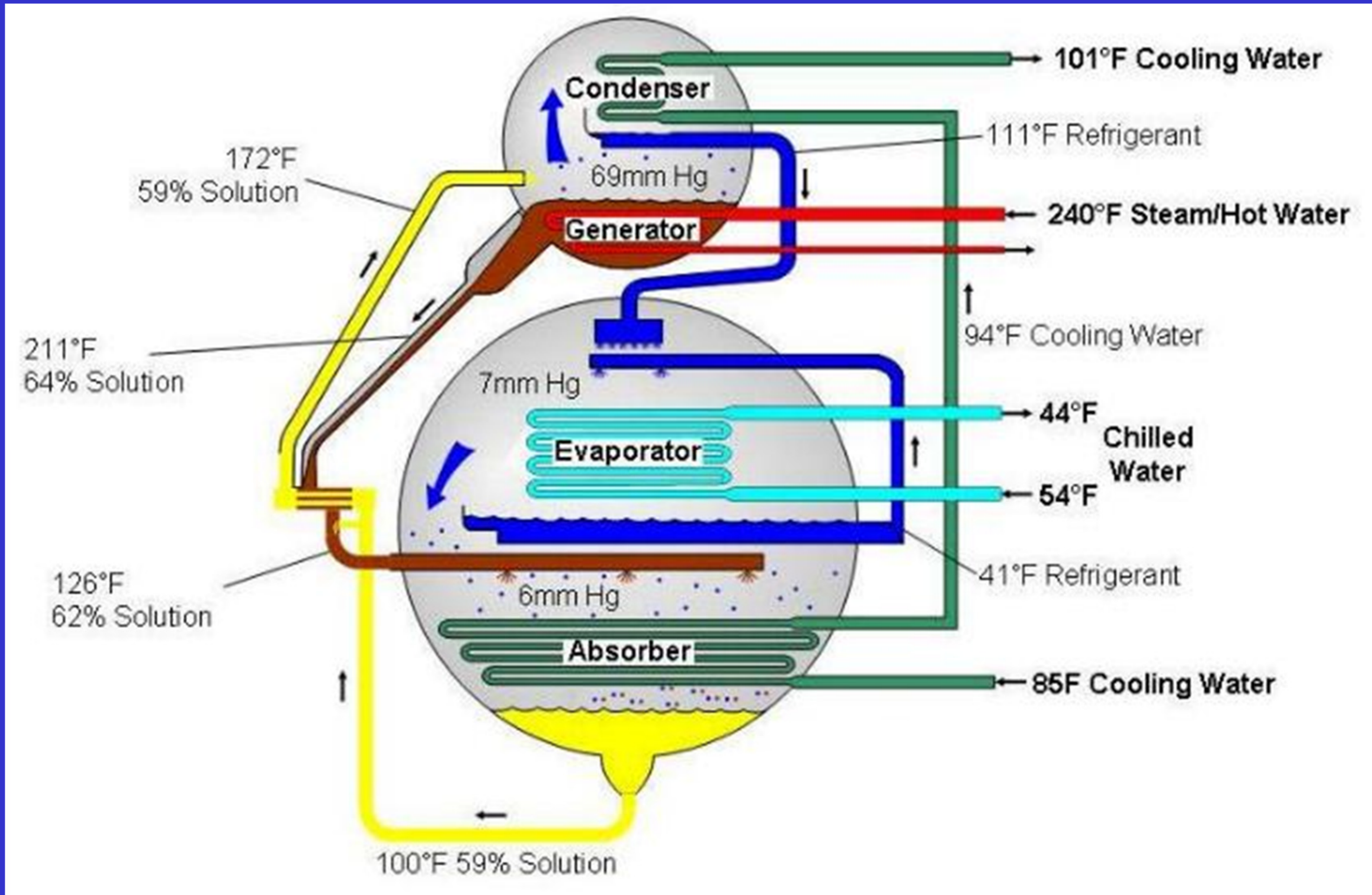
Adsorption Cooling

Energy is transferred through phase-change processes

Desiccant Cooling

Energy is transferred through latent heat processes

Absorption Cooling (1)

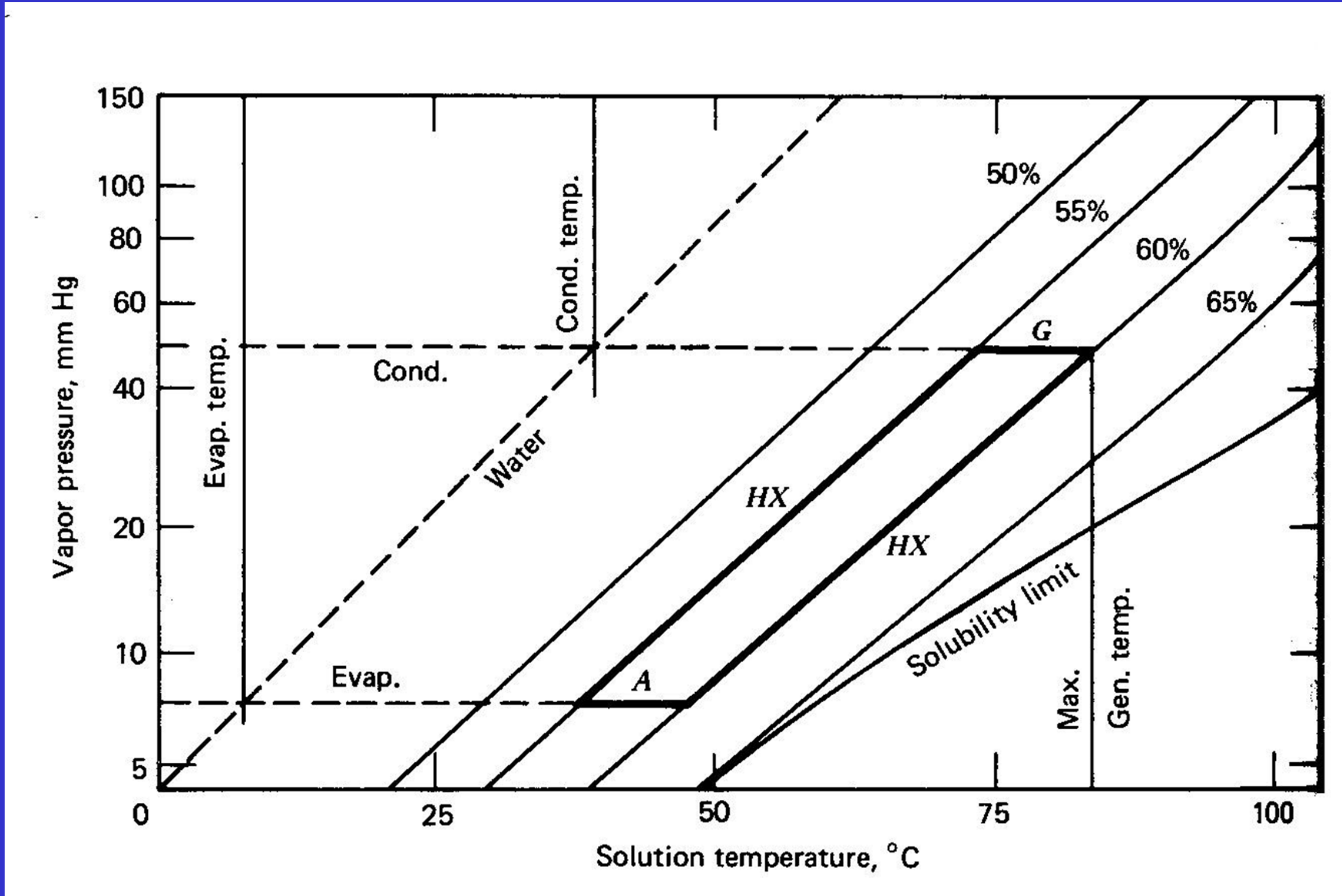


Absorption Cooling (2)

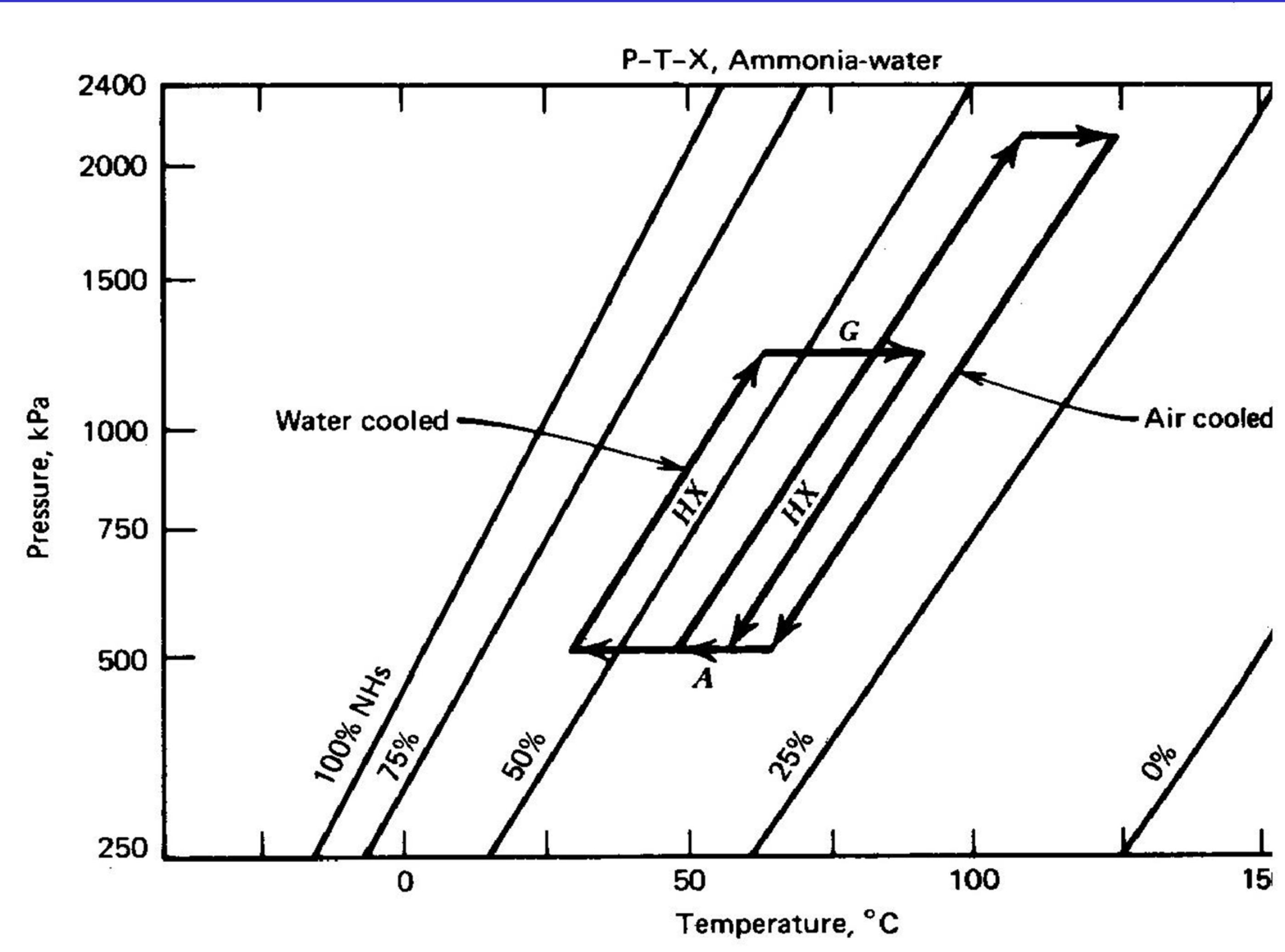
Substances used

Absorbent	Refrigerant
LiBr	H_2O
H_2O	NH_3

Properties of LiBr – H_2O



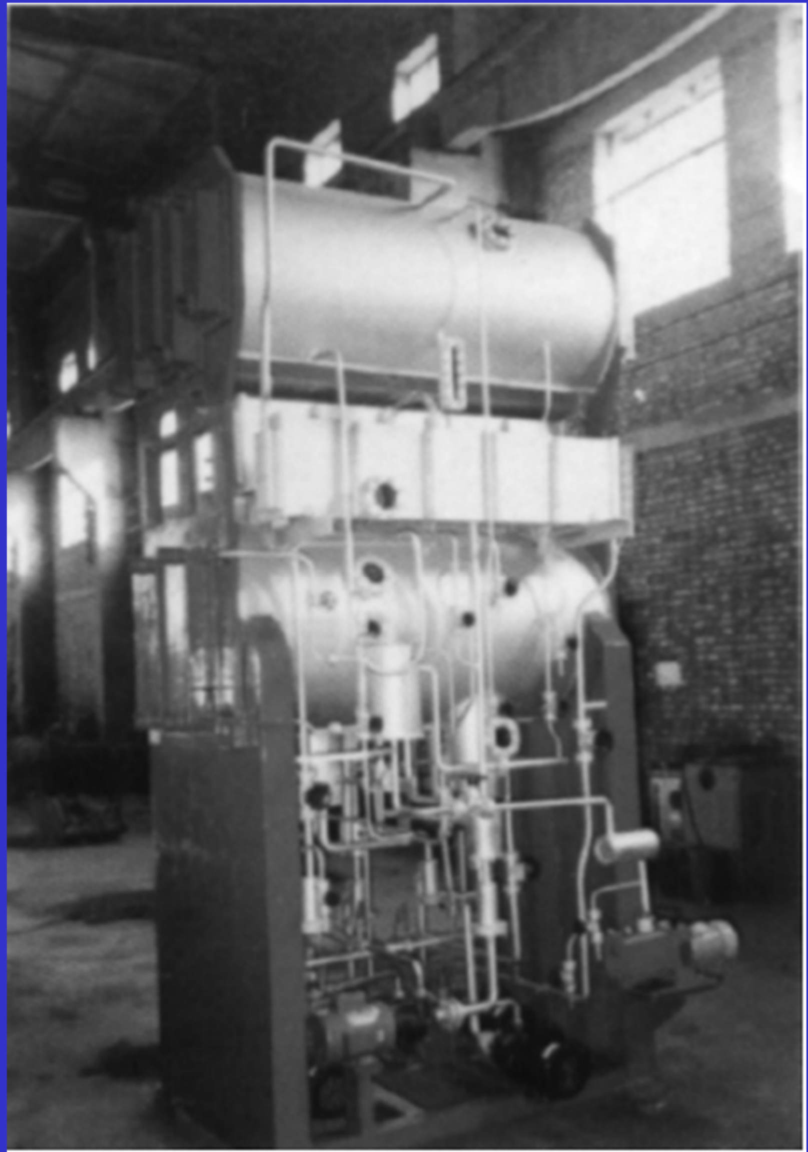
Properties of $H_2O - NH_3$



Real application – Solar collectors

Source: K. Sumathy, Z. C. Huang and Z. F. Li, Solar Energy, 2002, 72(2), 155-165

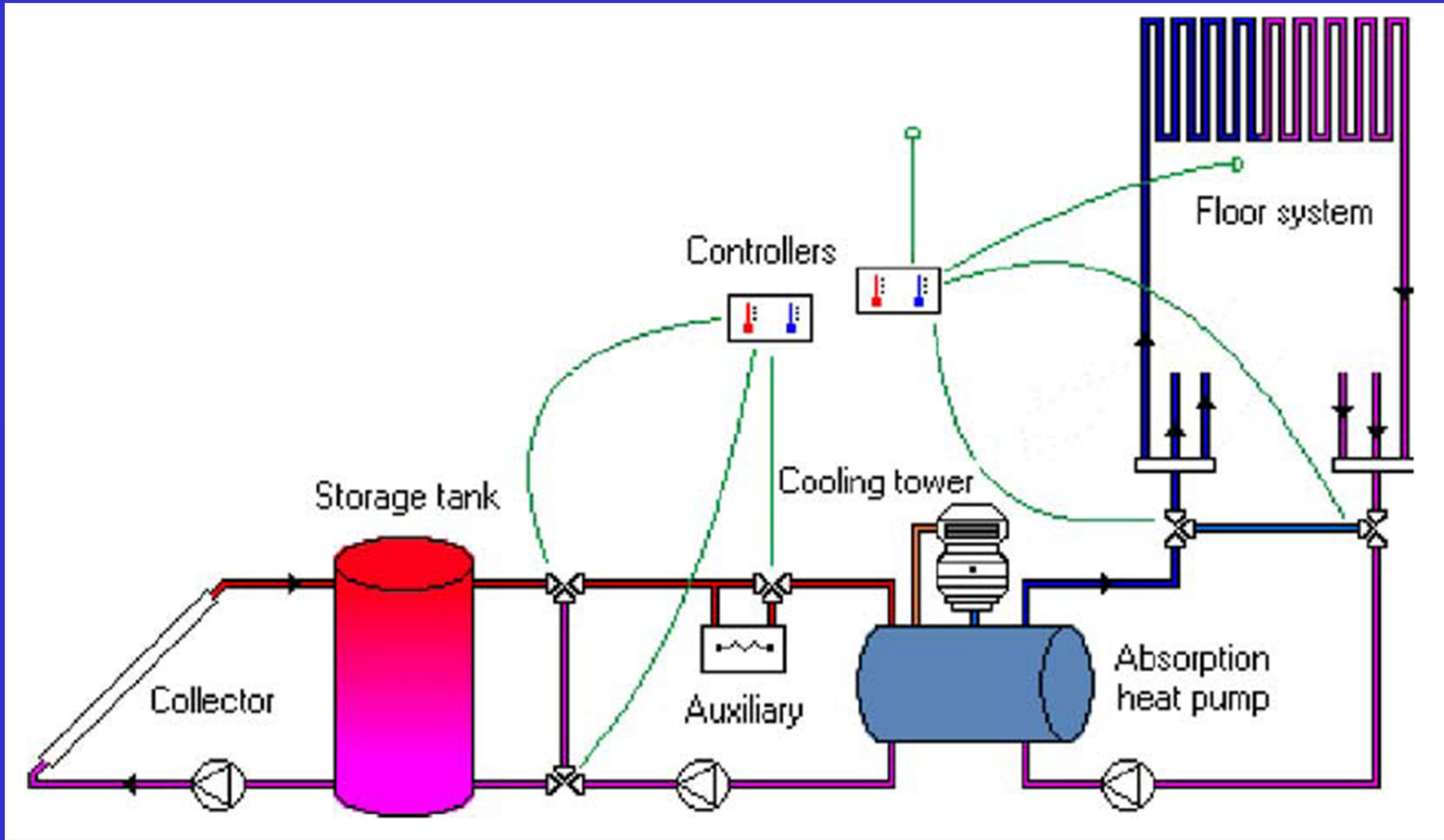
Absorption machine



Source: K. Sumathy, Z. C. Huang and Z. F. Li, Solar Energy, 2002, 72(2), 155-165

Single effect Yazaki machine (10 ton LiBr)

System combined to sub-floor exchanger



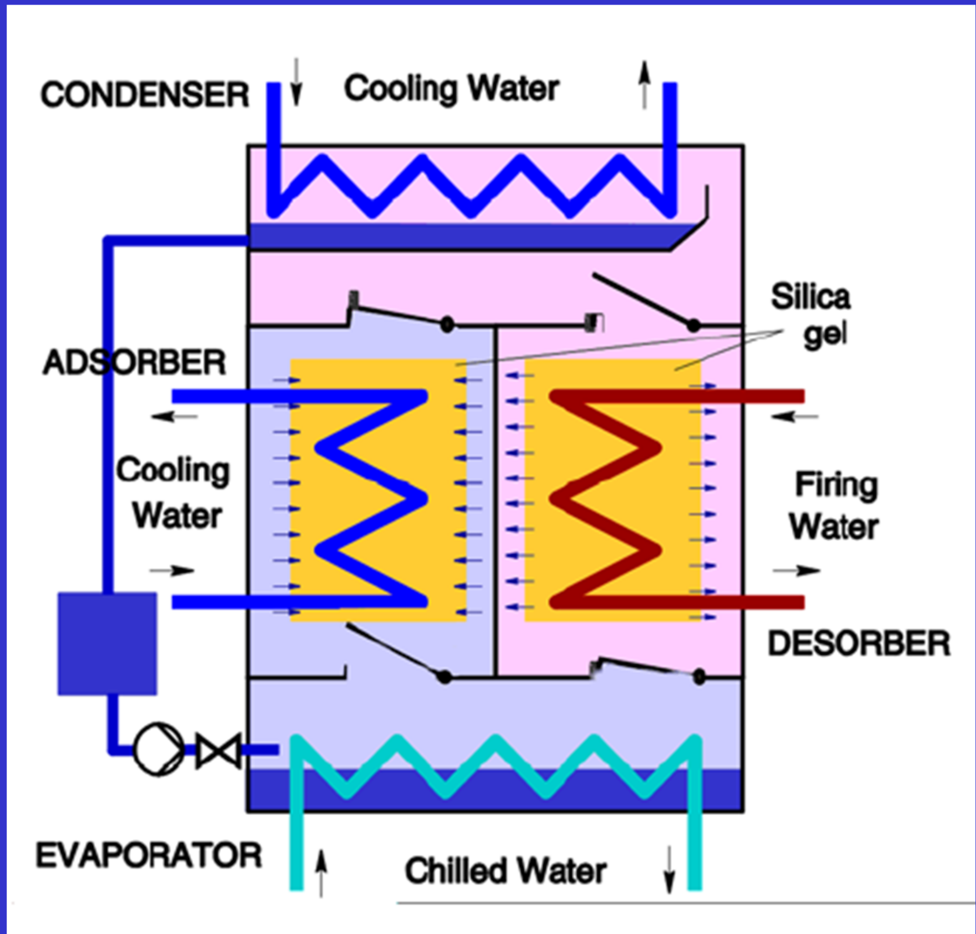
Adsorption cooling

Adsorption is the use of solids for removing substances from gases and liquids

The phenomenon is based on the preferential partitioning of substances from the gaseous or liquid phase onto the surface of a solid substrate.

The process is ***reversible***

Adsorption Cooling



Adsorption Cooling - Summary

The cycle is intermittent because production of cooling energy is not continuous: it occurs only during part of the cycle
When there are two adsorbers in the unit, they can be operated separately and production of cooling energy can be quasi-continuous.

When all the energy required for heating the adsorber(s) is supplied by the heat source, the cycle is termed *single effect*.

Typically, for domestic refrigeration conditions, the COP of single effect adsorption cycles is of about 0.3-0.4.

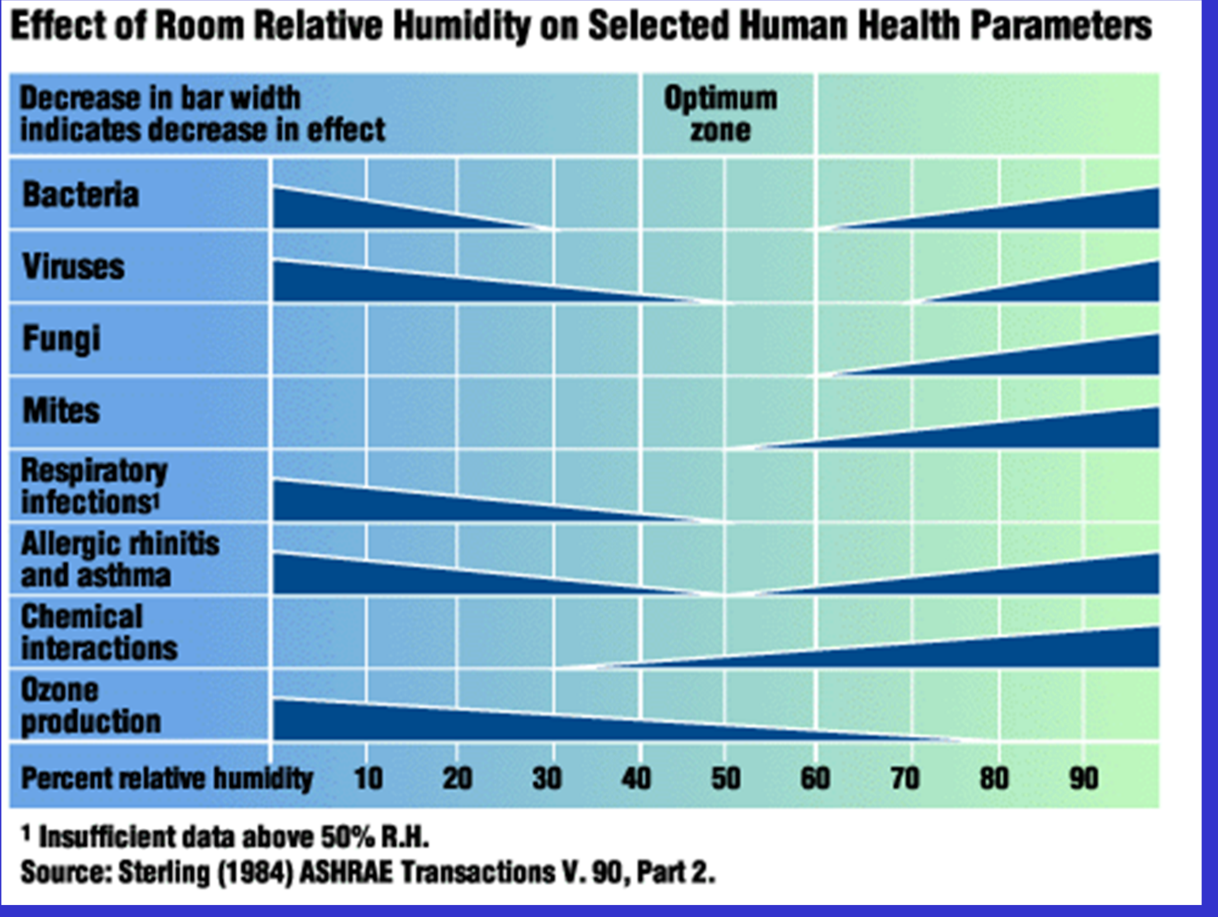
When there are two adsorbers or more, other types of cycles can be designed.

In *double effect cycles* or in *cycles with heat regeneration*, some heat is internally recovered between the adsorbers, and that improves the COP.

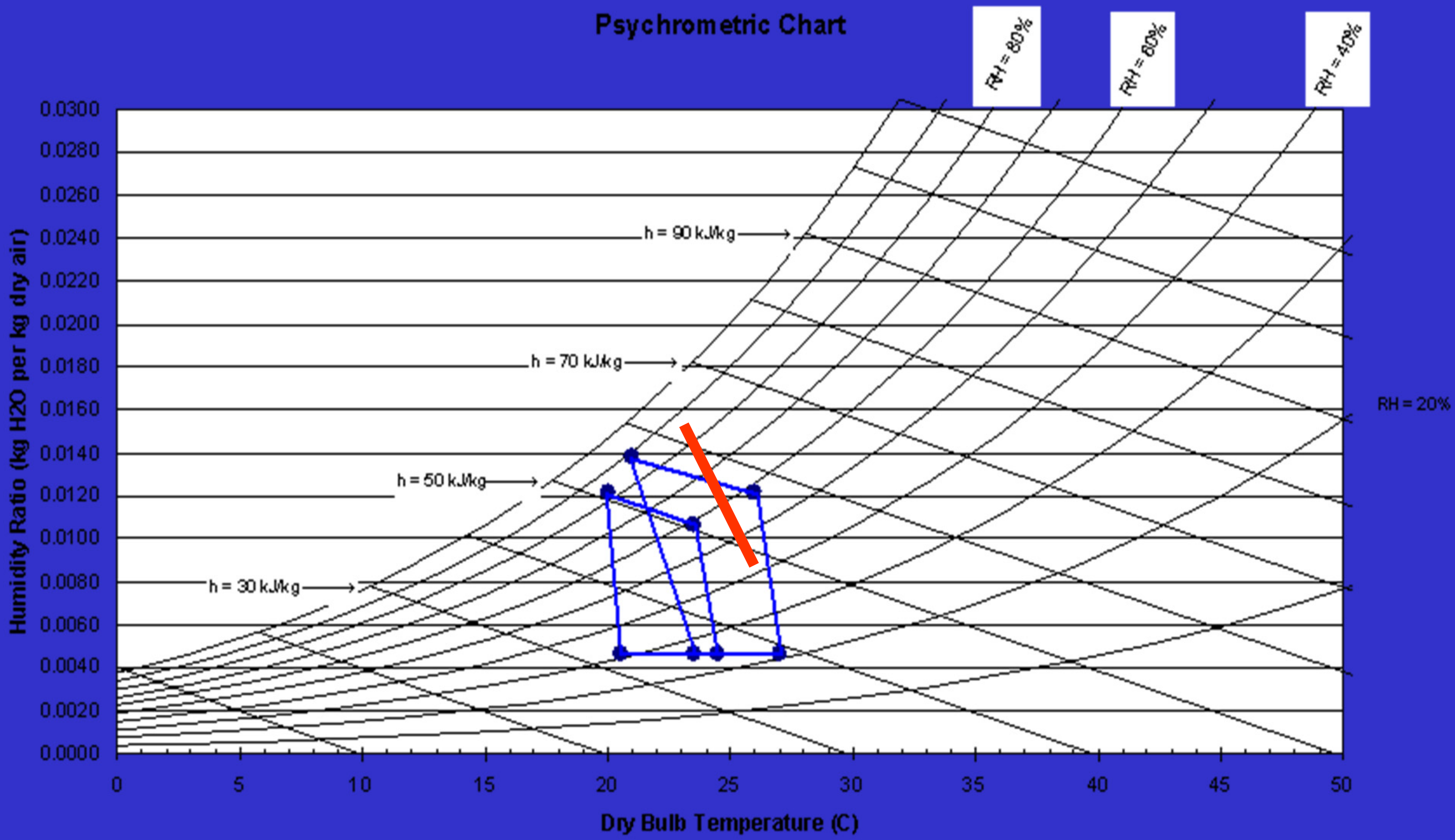
Adsorption cooling - Examples

Desiccant refrigeration

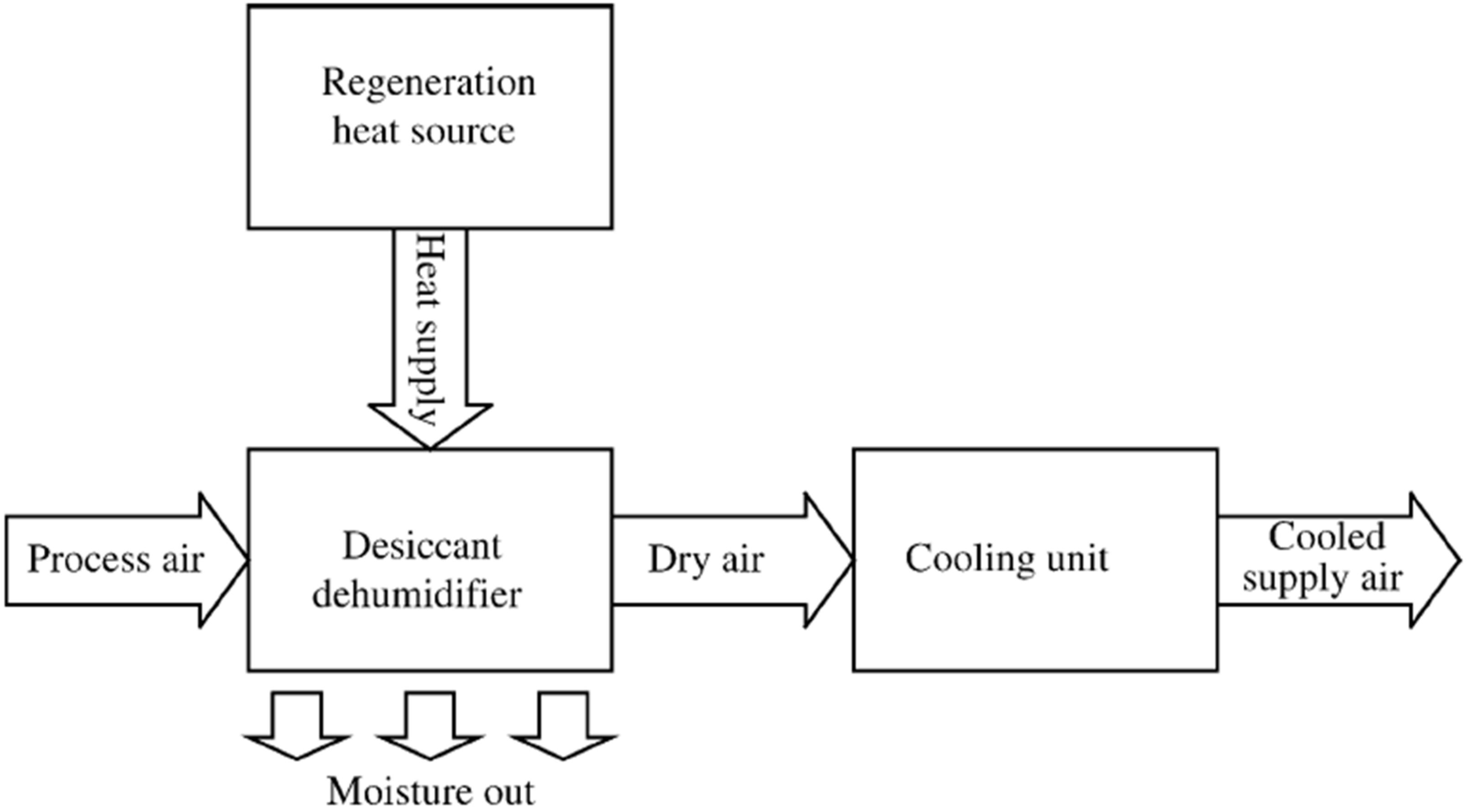
Addresses the issue of thermal comfort by modifying the water vapor content in a space.



Desiccant refrigeration principle



Desiccant refrigeration flow-chart

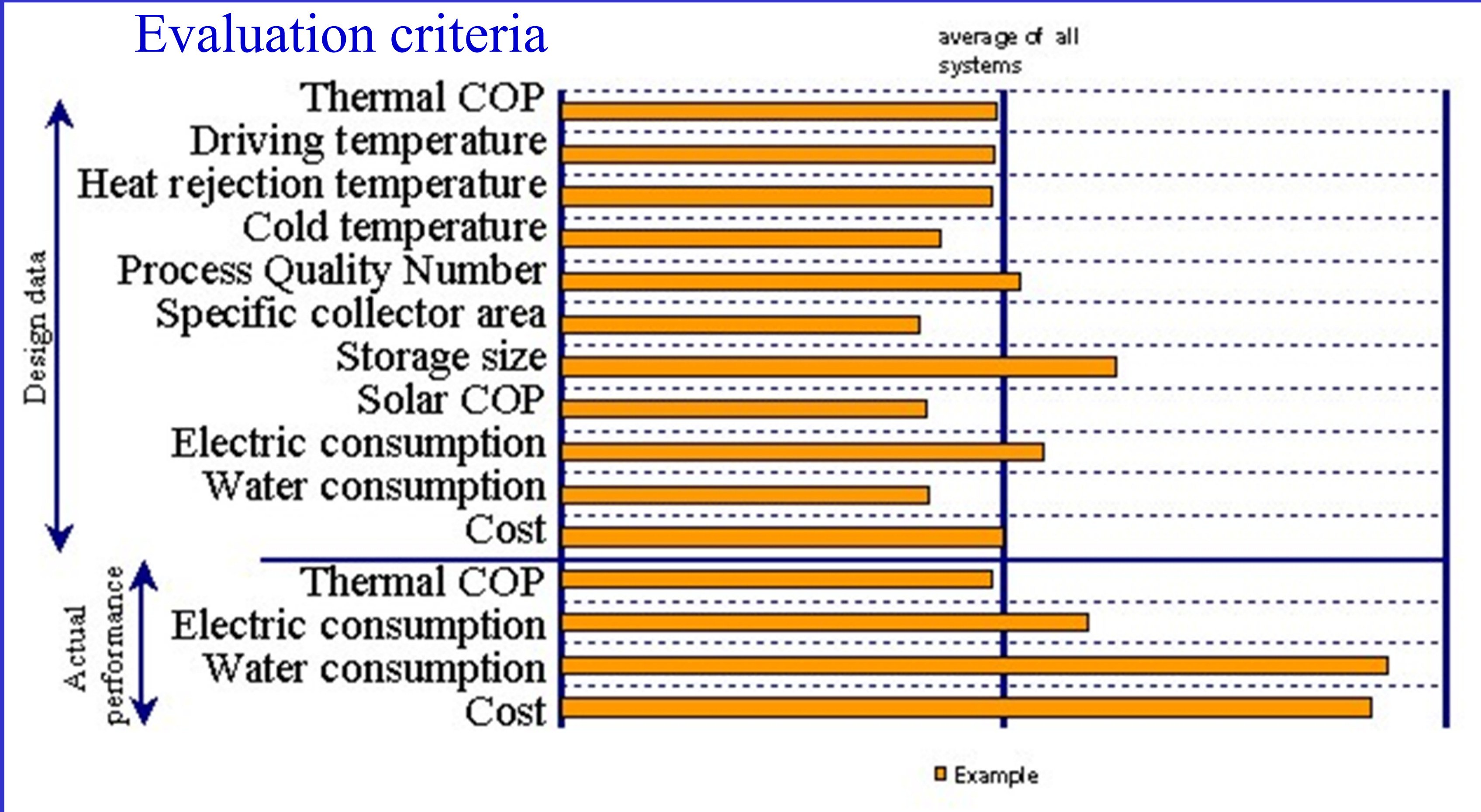


Solar cooling – Current status in Europe
(source: EU SACE project)

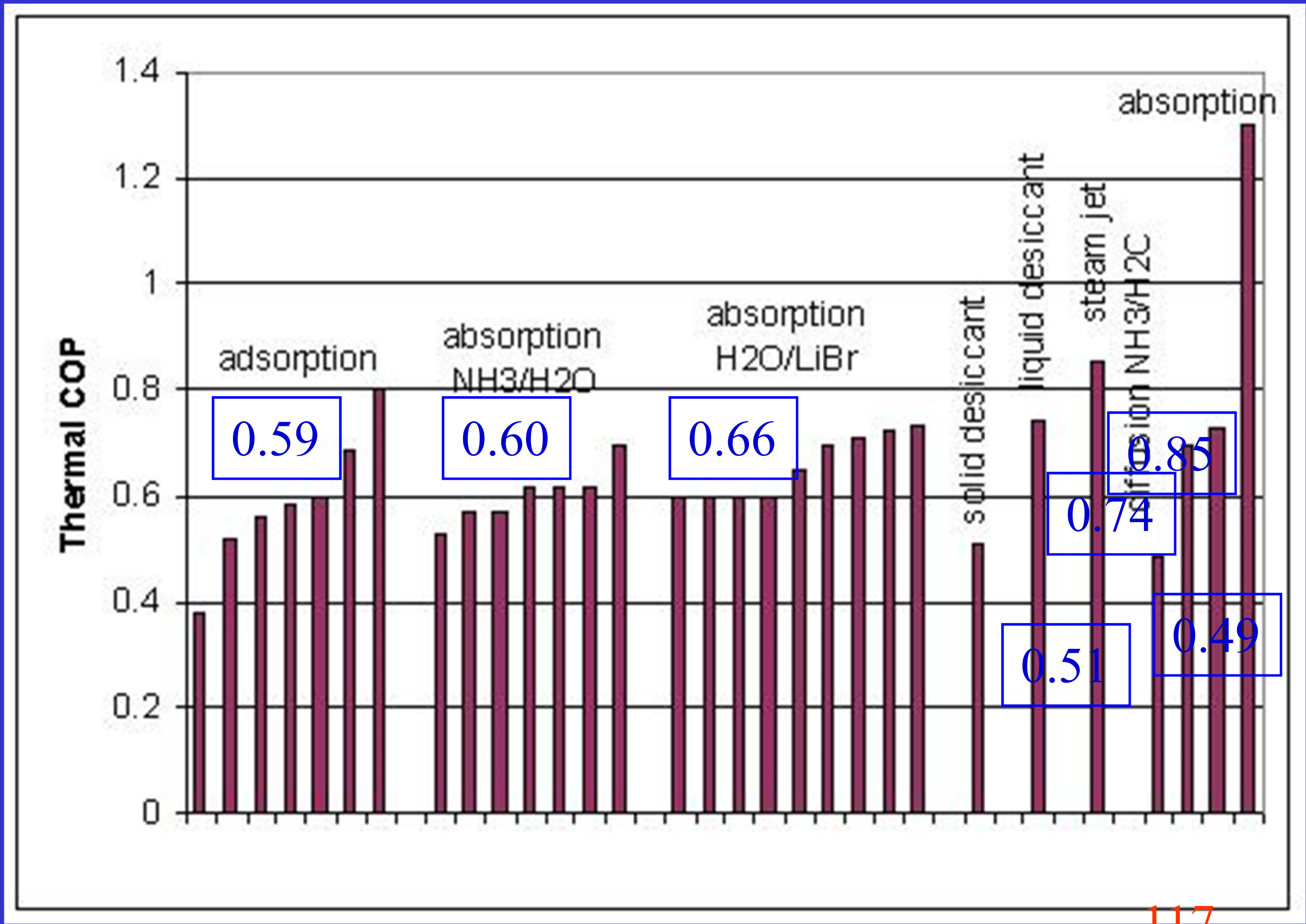
Projects & applications identified and evaluated:

- *12 in Germany*
- *2 in Austria*
- *3 in Malta*
- *1 in Croatia*
- *5 in Greece*
- *1 in Spain*
- *1 in Kosovo*
- *4 in Israel*
- *15 from Cordis*
- *10 IEA projects*

Comparative assessment



COP

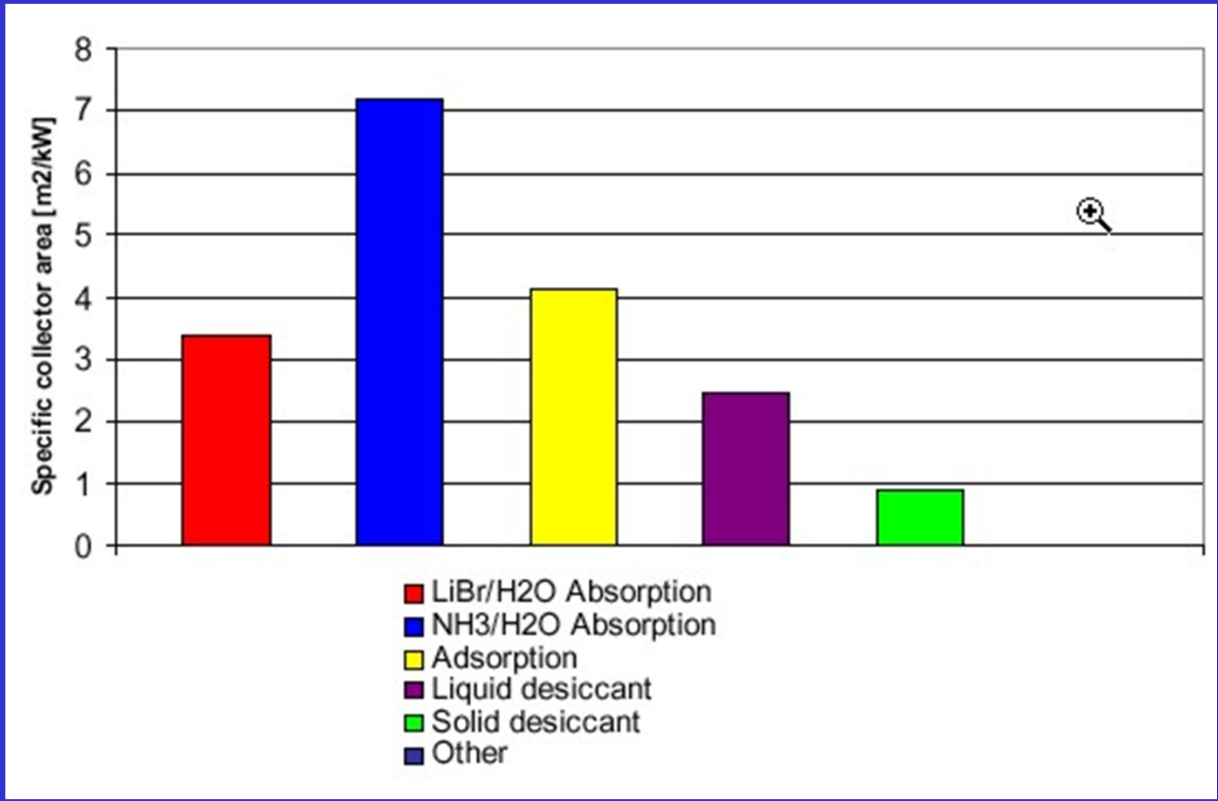


Διπλής βαθμίδας 1.3

T_{hot} (°C) 52-82 60-110 66 117 120

Solar collectors used

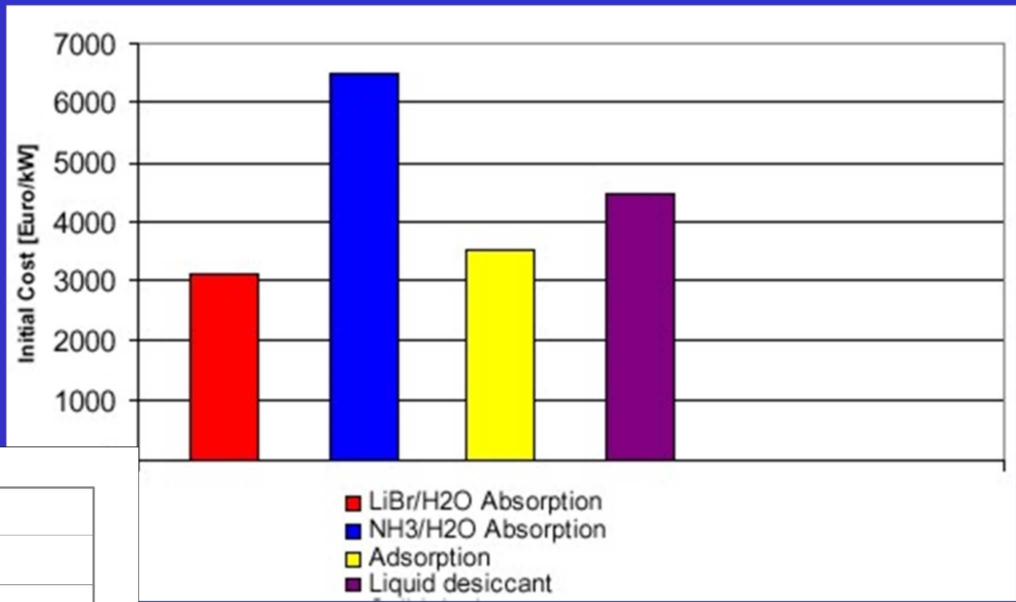
Flat-plated (63%)
Vacuum tube (21%)
Parabolic
- Fixed (10%)
- Moving (6%)

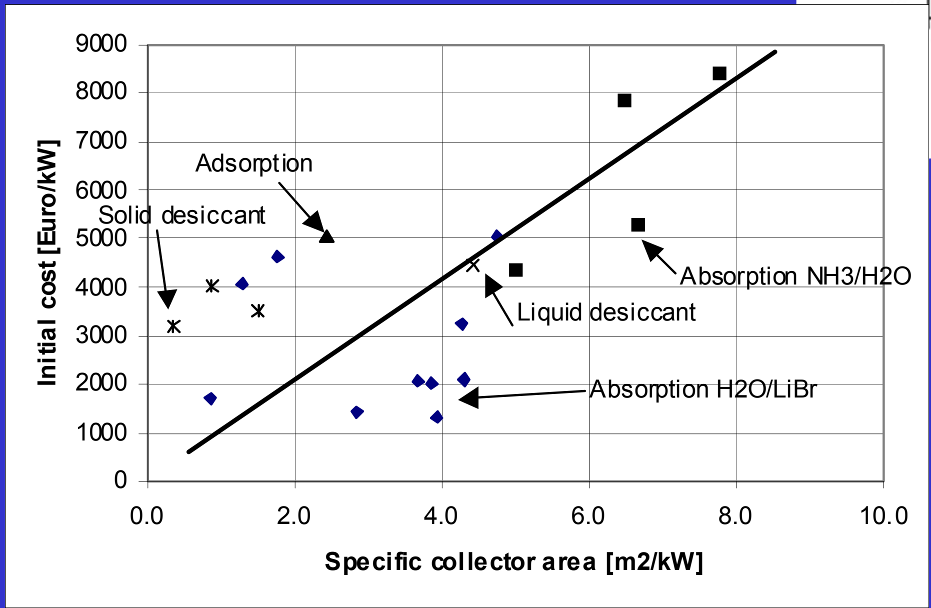


Average specific collector area
3,6 m^2/kW

Investment cost

Depends on:
- power rate
- collector type
- development phase
- operating principle





Average investment
4012 Ευρώ/kW

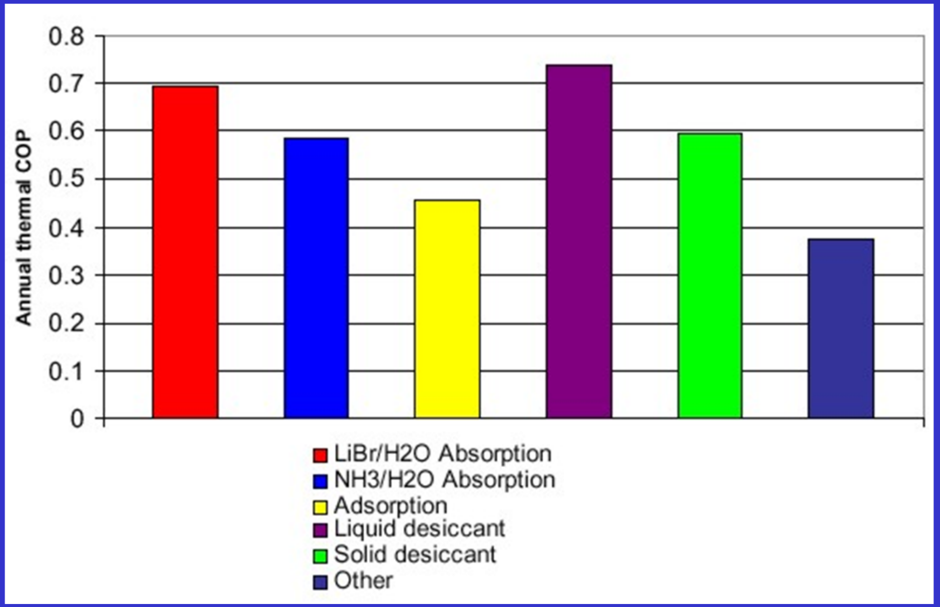
Performance data

Highest performance

LiBr / H_2O systems

Lowest performance

NH_3/H_2O diffusion system



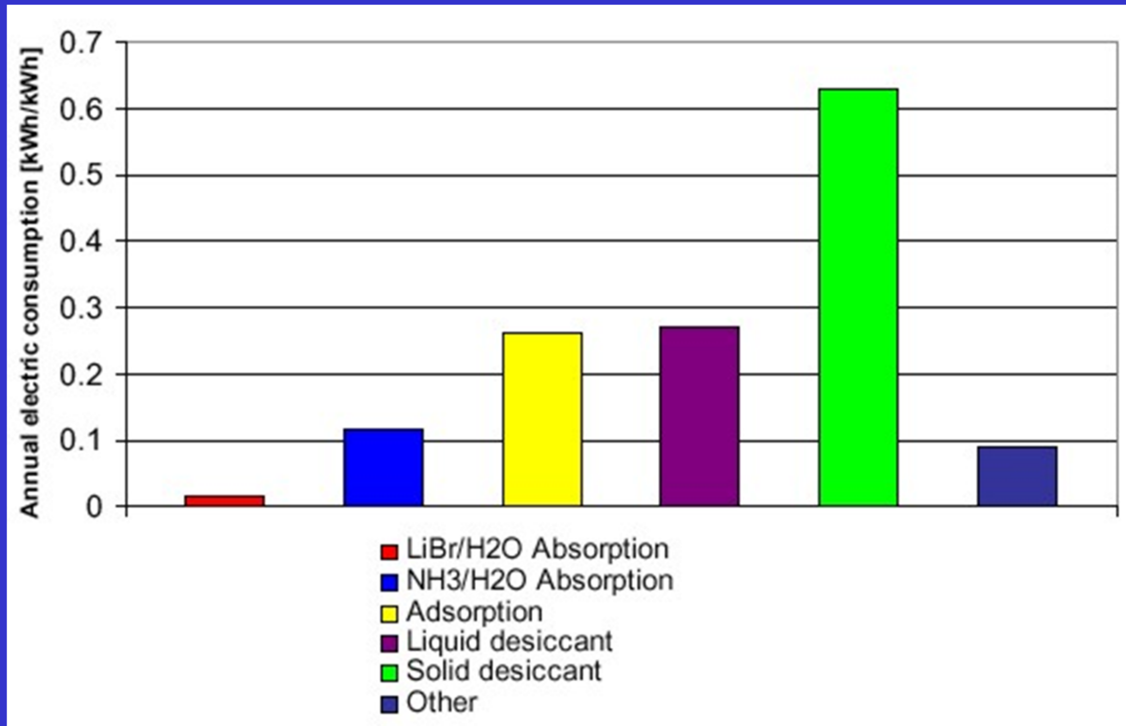
Average annual COP = 0.58

Consumption of auxiliary equipment

Lowest consumption:

Absorption systems

LiBr/H_2O systems = 0.018 kWh/kWh

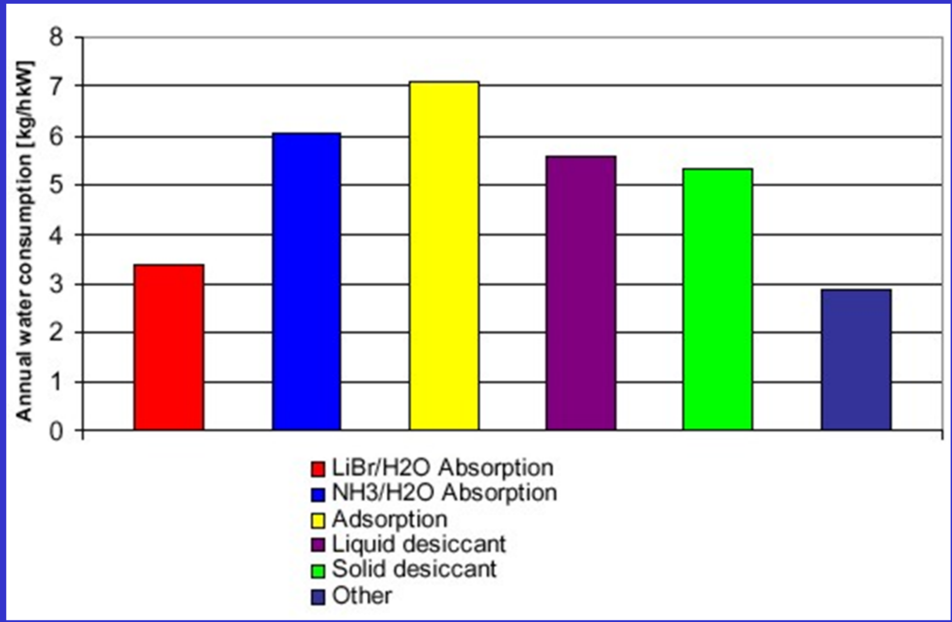


Mean annual electricity consumption of fans and pumps = 0.225 kWh/kWh

Water consumption

Highest consumption
Adsorption systems:
7.1 $kg.h^{-1}/kW$

Majority of systems:
4-6 $kg.h^{-1}/kW$



Mean annual water consumption
= 5.3 $kg.h^{-1}/kW$

Practical design guidelines

Detailed calculation of the energy budget of the application

Energy savings depend on other energy sources used, i.e. gas boiler, auxiliary cooler, pumps, fans etc.

Low COP coolers, require higher solar fraction and vice versa.

Combined solar heating / cooling systems are more interesting financially

Conclusions (1)

- Solar cooling is still in the development phase
- There are technological problems that need to be addressed mainly concerning the hydraulic circuit and the controllers
- Enough applications exist, but not enough performance data
- Reliable performance data and experience are available only from few systems

Conclusions (2)

- Additional experience regarding the operation of real scale installations is necessary in order to develop model projects and solutions regarding network design and automatic control.

- Their market penetration requires further subsidies,
  but
  only for systems that achieve important energy savings (e.g. >30%) with respect to conventional systems at a cost lower than a maximum price e.g. 0,1 € per kWh of primary energy.

Research priorities – LiBr systems

Increased performance and reduction of cost of solar collectors

Increased performance and reduction of cost of storage systems (e.g. thermochemical)

Development of low capacity absorption machines

Development of low capacity air-cooled absorption machines

Increased performance of the various heat transfer processes in the machine

Research priorities – NH_3 systems

Improved reliability, at low cost, independent control of the cooling medium

Improved pump reliability at low cost

Improved reliability of the fluid level sensors

Increased performance of the various heat transfer processes in the machine

Simplified system concepts