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Carbon Dioxide as Refrigerant

Applications in Mobile Air-Conditioning and Applications in Heat Pumps

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SINTEF location, Trondheim, Norway

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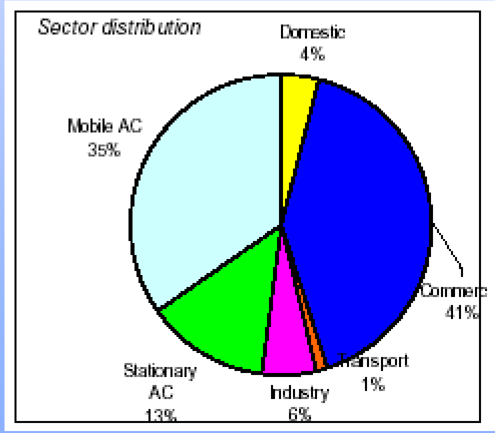
Outline

- Mobile air conditioning and heat pump systems
  - Mobile Air Conditioning
  - LCCP comparison
  - Mobile Heat Pumps
- Heat Pumps and AC for space conditioning
  - Heat pump water heaters
  - Other heat pump applications
- Some additional points
- Conclusion

Mobile Air Conditioning and Heat Pumps

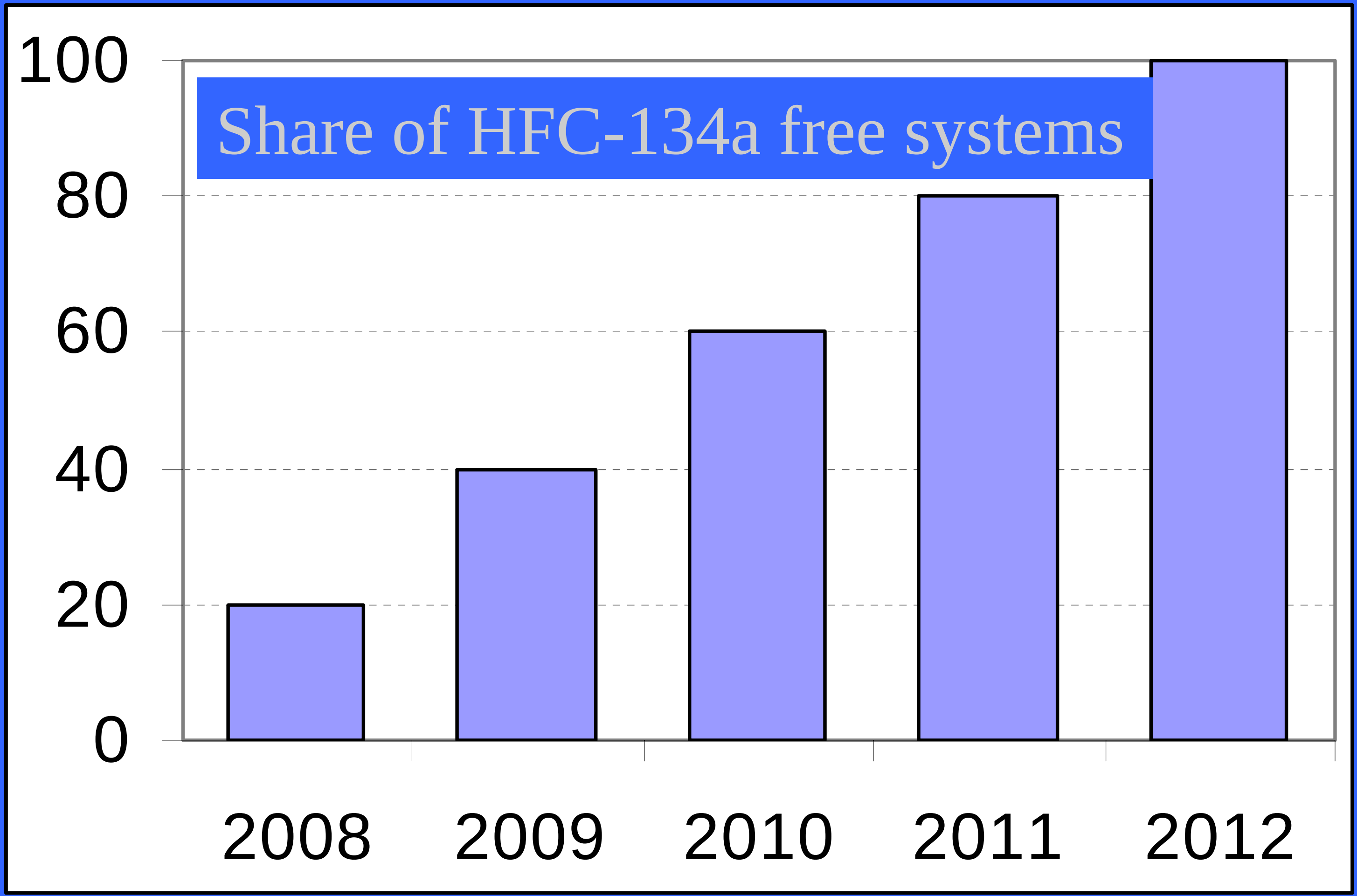
Application with largest emissions of HFCs
Second largest refrigerant emissions



Sector shares in 2002, expressed in CO_2 equivalent
Palandre et al, Earth Techn. Forum, Washington 2004

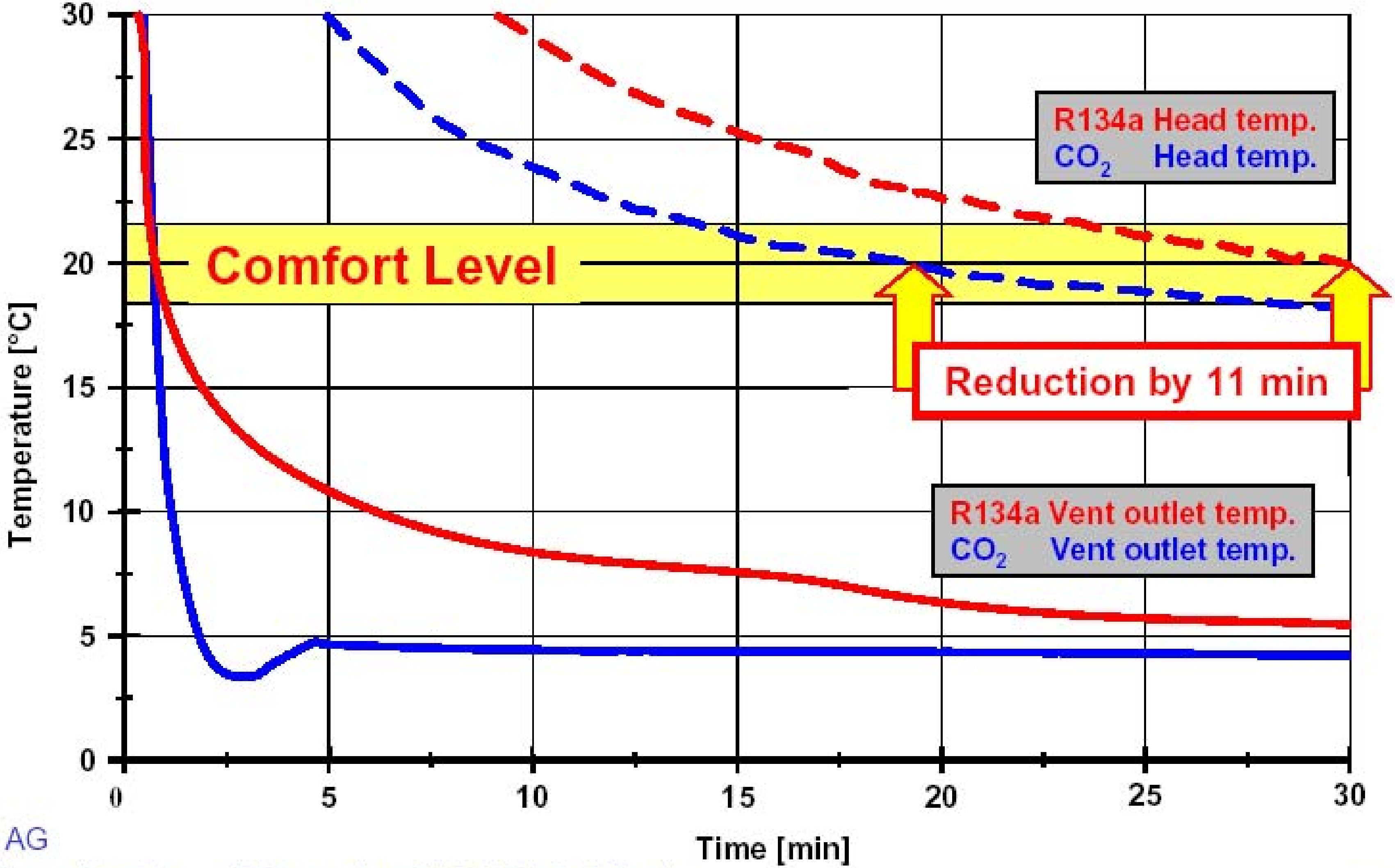
Current thinking: Phasing of HFC-134a free systems MAC

European Commission - DG Environment June 2003



What are the main advantages of using CO_2 instead of HFC-134a?

Performance - Cool down CO_2 vs. R134a (ident. system packaging)



Audi AG

Windtunnel test: $t_{amb.}$:40°C, sunload:1000W/m², 60km/h

Life Cycle Climate Performance (LCCP) of Mobile Air-Conditioning Systems with HFC-134a, HFC-152a and R-744

MOBILE AIR CONDITIONING SUMMIT
2004 Washington D.C.

Armin Hafner and Petter Nekså,
SINTEF Energy Research, Trondheim – Norway

Jostein Pettersen
Norwegian University of Science and Technology – NTNU
Trondheim – Norway

Overview

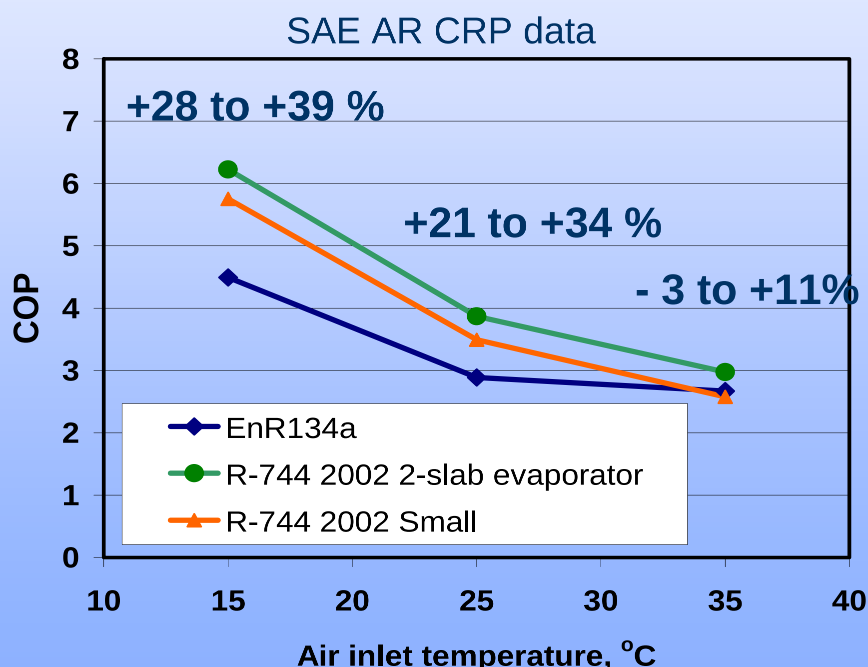
- Origin of the COP/Capacity from measurement (experimental) data
- Basis for the LCCP calculations
- Comparison of LCCP and seasonal energy use, for various climate locations
  - US-locations applying US FTP 75 driving cycle
  - European countries, applying NEDC
- Comments
- Conclusion

Life Cycle Climate Performance (LCCP) of Mobile Air-Conditioning Systems with HFC-134a, HFC-152a and R-744

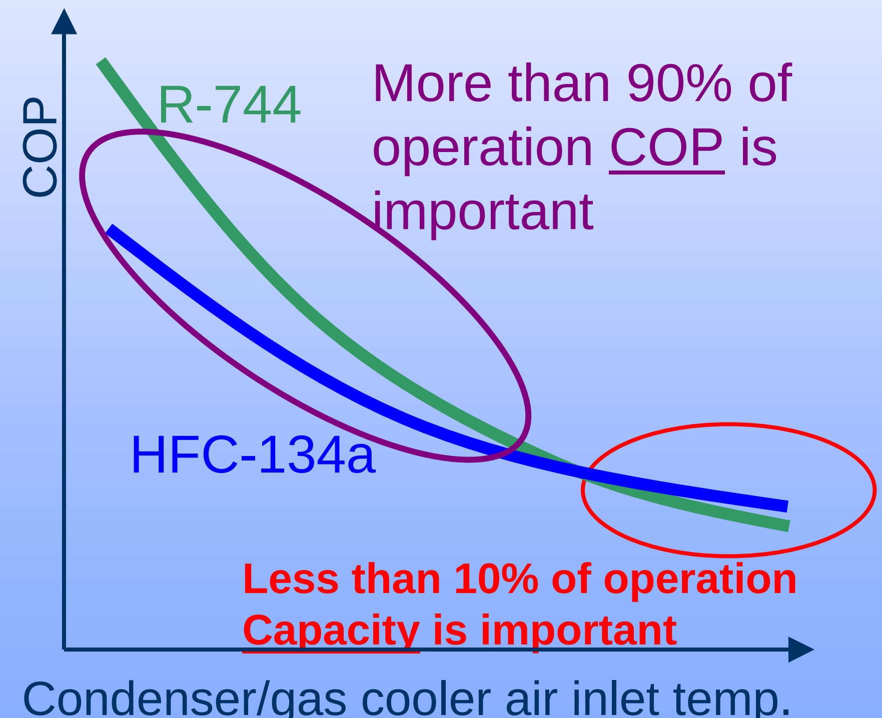
Origin of COP/Capacity data:

- *SAE AR CRP* data for ***Enhanced*** **HFC-134a** (*SAE ARCRP, 2002*)
- ***2002*** **R-744** Pilot Project data from (*SAE ARCRP, 2003*) – Small system
- *SAE AR CRP Phase II* data for *2003 Best Technology* ***BT*** **HFC-134a** (*SAE ARCRP II, 2004, preliminary results*)
- *SAE AR CRP Phase II* data for *2003* **HFC-152a** (*SAE ARCRP II, 2004, preliminary results*); (same system as BT HFC-134a)

COP data 2500 rpm 5ºC air from evaporator or equal capacity



Typical efficiency at varying condenser/gascooler air inlet temperature



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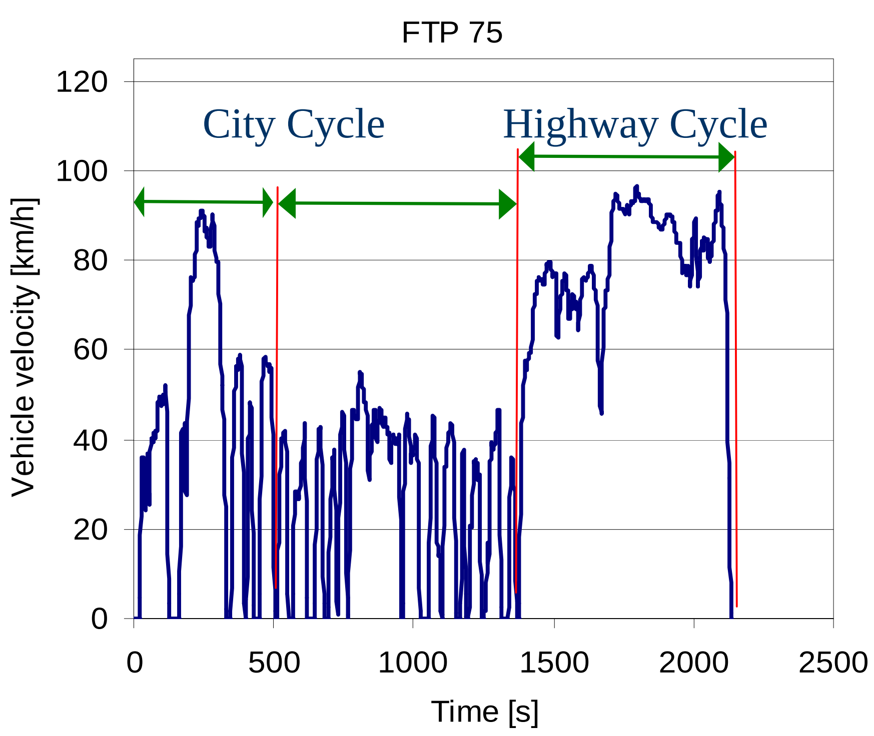
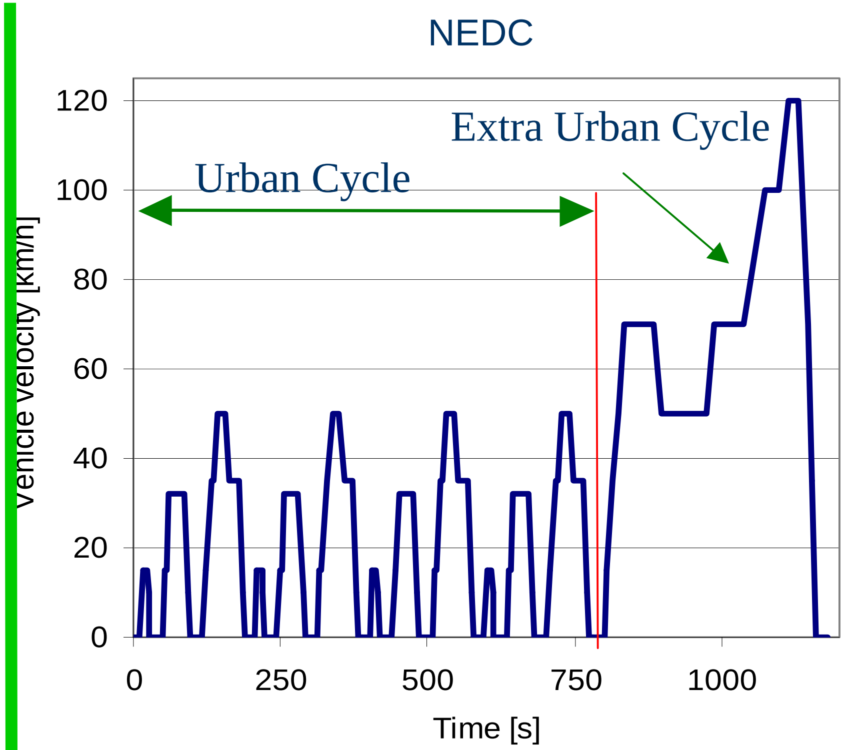
Driving Cycles





Applied for the US-locations

Mean vehicle velocity: 48 km/h

Applied for the European locations

Mean vehicle velocity: 26 km/h

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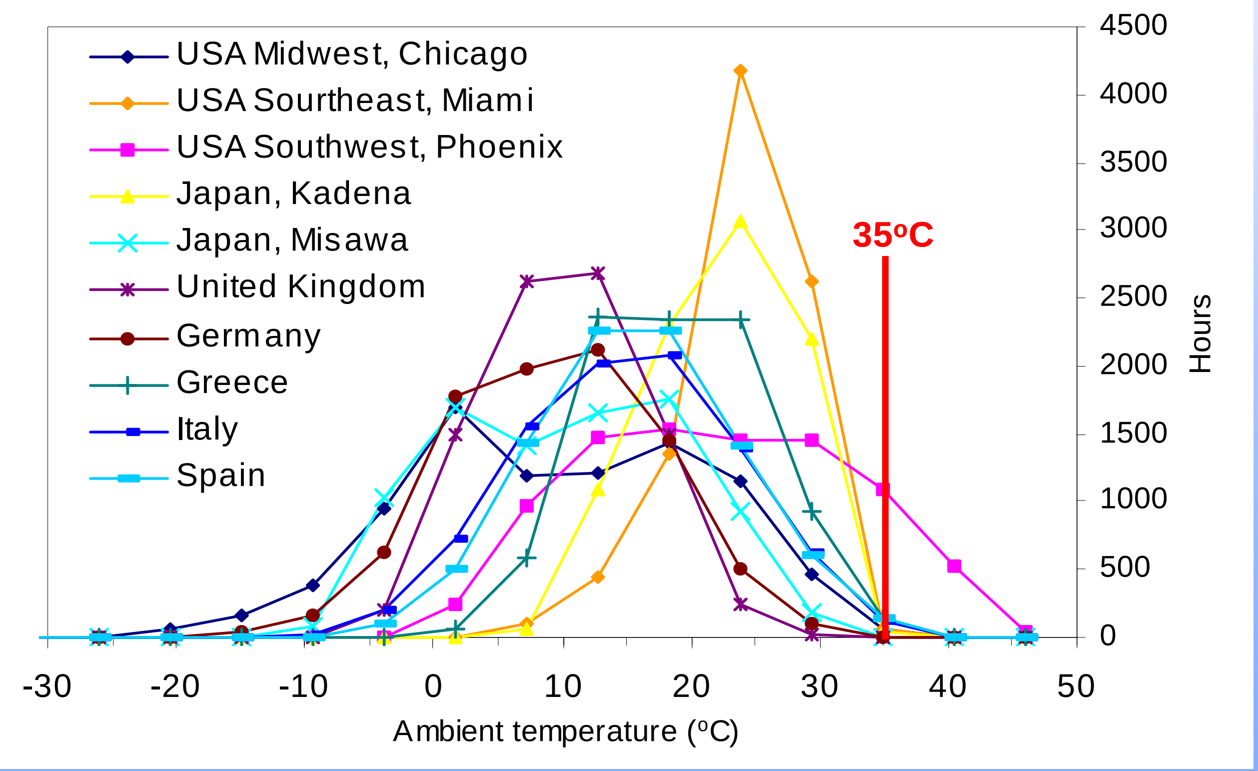
Selected Locations & Climate Data

USA:		**Europe:**	
Chicago:	**22.000 km/year**	**Germany:**	**13.321 km/year**
Miami:		**Spain:**	**10.738 km/year**
Phoenix:		**Greece:**	**13.321 km/year**



Temperatures above 35°C hardly ever occur

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LCCP

Indirect	Mass	Direct

System Mass [kg]

× Yearly driving distance [km/year]

× Fuel consumption rate for carrying and transport the AC system [litres/kg/km]

× Fuel consumption to CO_2 emission factor [kg CO_2/litre of gasoline]

× Vehicle life [years]

= Mass Contribution [kg CO_2]

System charge [g]

Yearly Leakage [g/year] *

Life time Services [-]

End of Life recovery rate [%]

Global Warming Potential of Ref.

Emission of producing a kg of Ref. [kg CO_2]

Re-processing emission during the end of life refrigerant recovery [kg CO_2]

Vehicle life [years]

= Direct Impact (kg CO_2)

*** Achievable total controlled losses of 35 g/yr <u>suggested</u> by *Fernqvist (2003)*, plus uncontrolled and service losses: total 60 g/yr (used in this analysis)**

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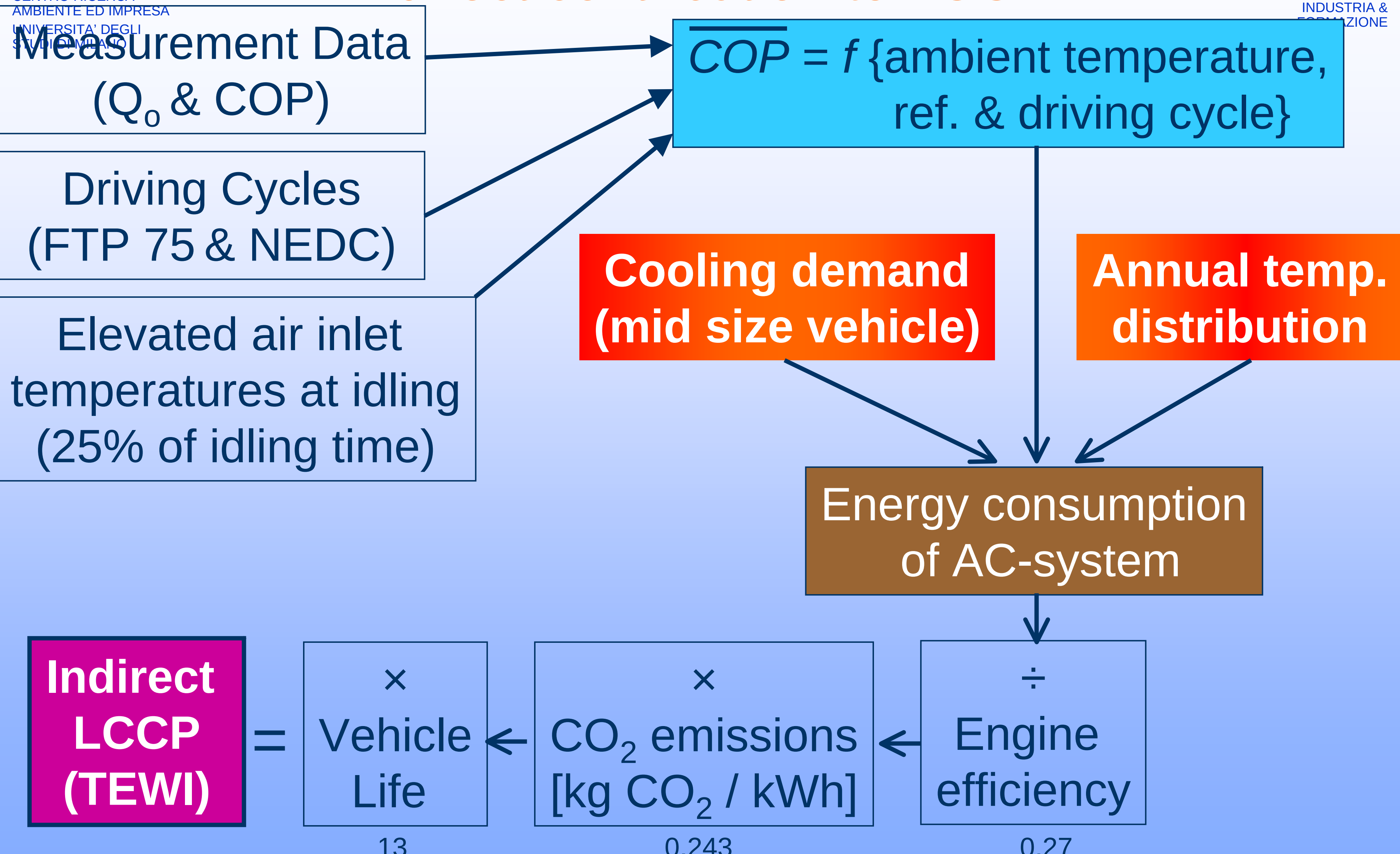
Indirect contribution to LCCP



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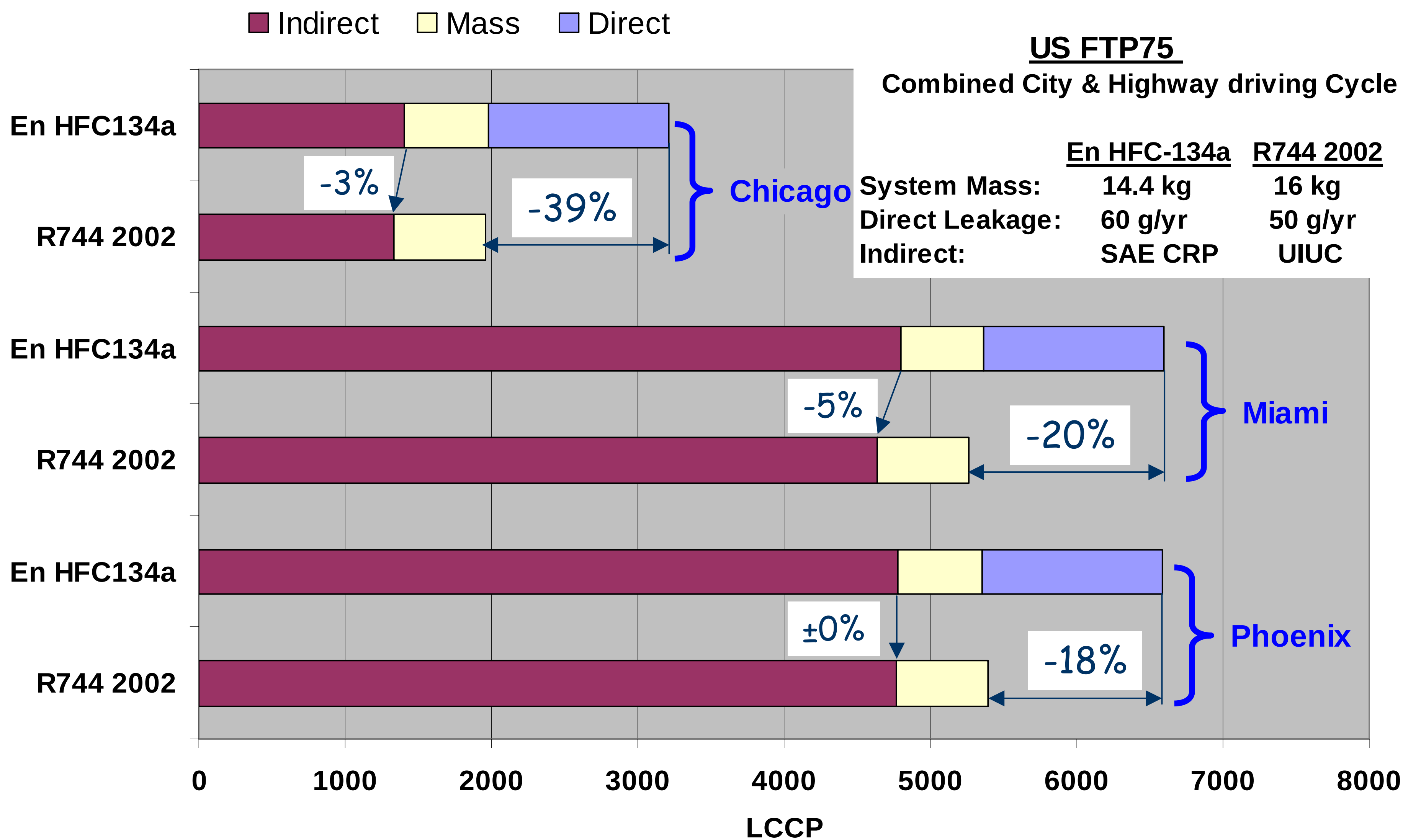
LCCP comparison *En* HFC-134a versus *2002* R-744

US locations & US FTP75



US FTP75

Combined City & Highway driving Cycle

	En HFC-134a	R744 2002
System Mass:	14.4 kg	16 kg
Direct Leakage:	60 g/yr	50 g/yr
Indirect:	SAE CRP	UIUC

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LCCP comparison *En* HFC-134a versus *2002* R-744

European locations & NE-Driving Cycle

NEDC

Driving Cycle European Union (93/116)

	En HFC-134a	R744 2002
System Mass:	14.4 kg	16 kg
Direct Leakage:	60 g/yr	50 g/yr
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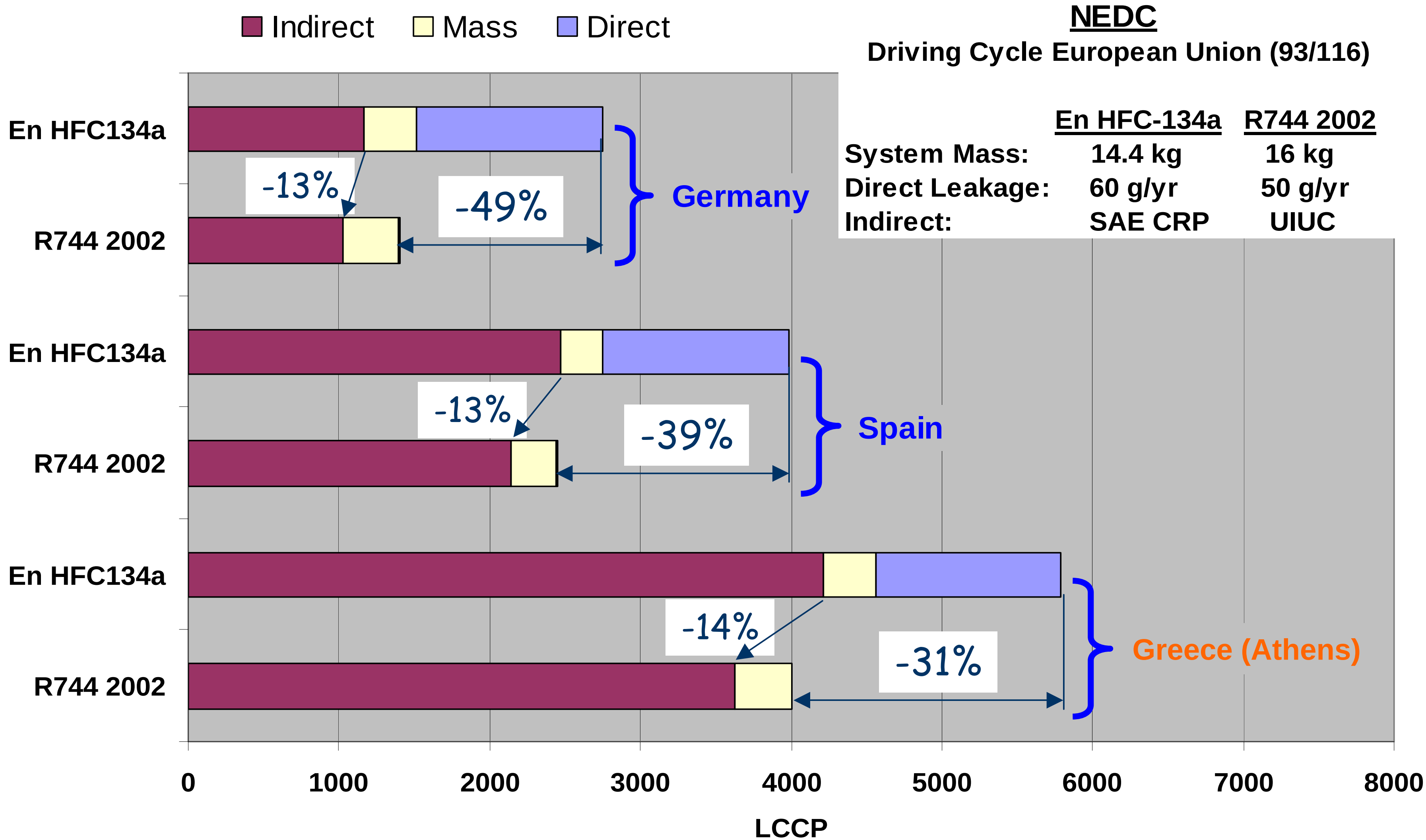

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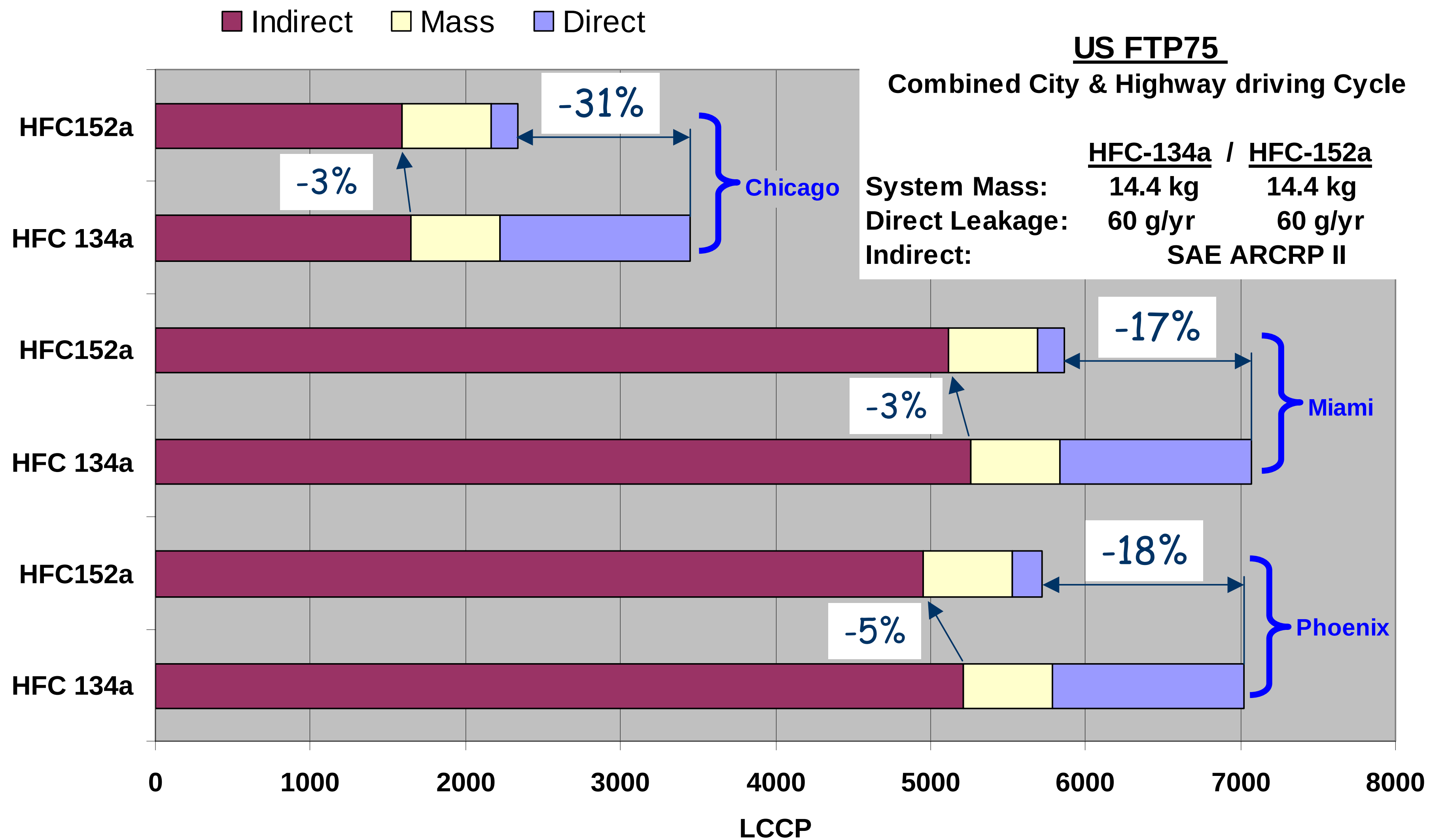
LCCP comparison

2003 Best Technology HFC-134a versus *2003* HFC-152a

US locations & US FTP75



US FTP75

Combined City & Highway driving Cycle

	HFC-134a	/	HFC-152a
System Mass:	14.4 kg		14.4 kg
Direct Leakage:	60 g/yr		60 g/yr
Indirect:	SAE ARCRP II		

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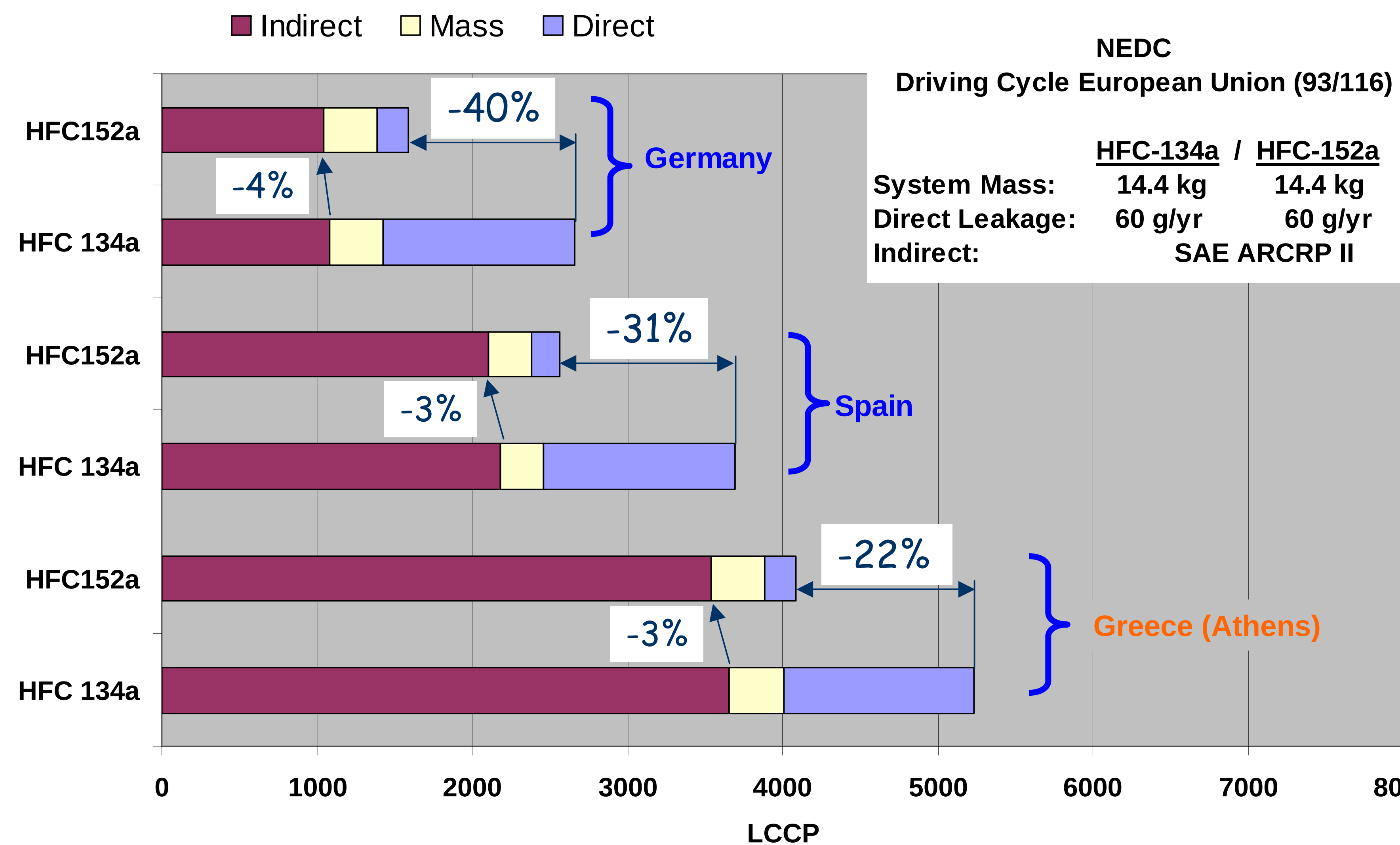
LCCP comparison

2003 Best Technology HFC-152a versus *2003 BT* HFC-134a

European locations & NE-Driving Cycle



NEDC
Driving Cycle European Union (93/116)

	HFC-134a /	HFC-152a
System Mass:	14.4 kg	14.4 kg
Direct Leakage:	60 g/yr	60 g/yr
Indirect:	SAE ARCRP II	

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Which refrigerant will be the alternative to HFC-134a?

Part of illustration from AutoBild 01/04

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Comments 1(2)

- ***Phase II*** **data cannot be directly compared to** ***Phase I*** **data, due to different system design.**
- **However, the relative LCCP improvement between HFC-152a and HFC-134a (*Phase II*) applied to the HFC-134a phase I data indicate that HFC-152a may approach the data of R-744.**
- **This analysis doesn't indicate that R-744 would have any problems to compete which HFC-152a.**
- **Not only hot climates should be considered in further LCCP analyses, focus should be given to vehicle population at all climate zones on earth.**

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Comments 2(2)

- **Heat pump operation of the AC system was not considered. (Promising option for R-744 systems, even for US climates)**
- **Increased air inlet temperatures to the condenser of a car at idling are 'platform'-specific problems. Only a few cars have this 'problem', others not. To assume an elevated temperature of +15 K at 25% of the idling time for the entire car fleet is a rather conservative assumption.**
- **'Best Technology' means best HFC 134a-system, available in 2003 as described in *SAE ARCRP II (2004)*.**
- **HFC-152a may only be possible with an indirect system arrangement.**
  (Hydrogen fluoride (HF) is a side product, when HFC-152a is thermally degraded. HF is highly toxic.)

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Conclusion MAC LCCP 1 (2)

- **The test data have reconfirmed that COP is no argument against R-744 systems.**
- **Fuel use of *2002* R-744 system is significantly lower than with *Enhanced* HFC-134a (up to 14% in Europe), even in the warm US climates (Phoenix) the total energy consumptions will be at the same level.**
- **LCCP of *2002* R-744 system is improved by 18 – 49 % compared to *Enhanced* HFC-134a system.**
- **The *2003* HFC-152a system uses 3 -5.% less energy (fuel) than *BT* HFC–134a system.**
- **LCCP of the *2003* HFC152a system is improved by 17 - 40 % compared to an *2003 BT* HFC-134a system.**

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Conclusion 2 (2)

All data show that R-744 is able to compete, both regarding Energy efficiency and LCCP

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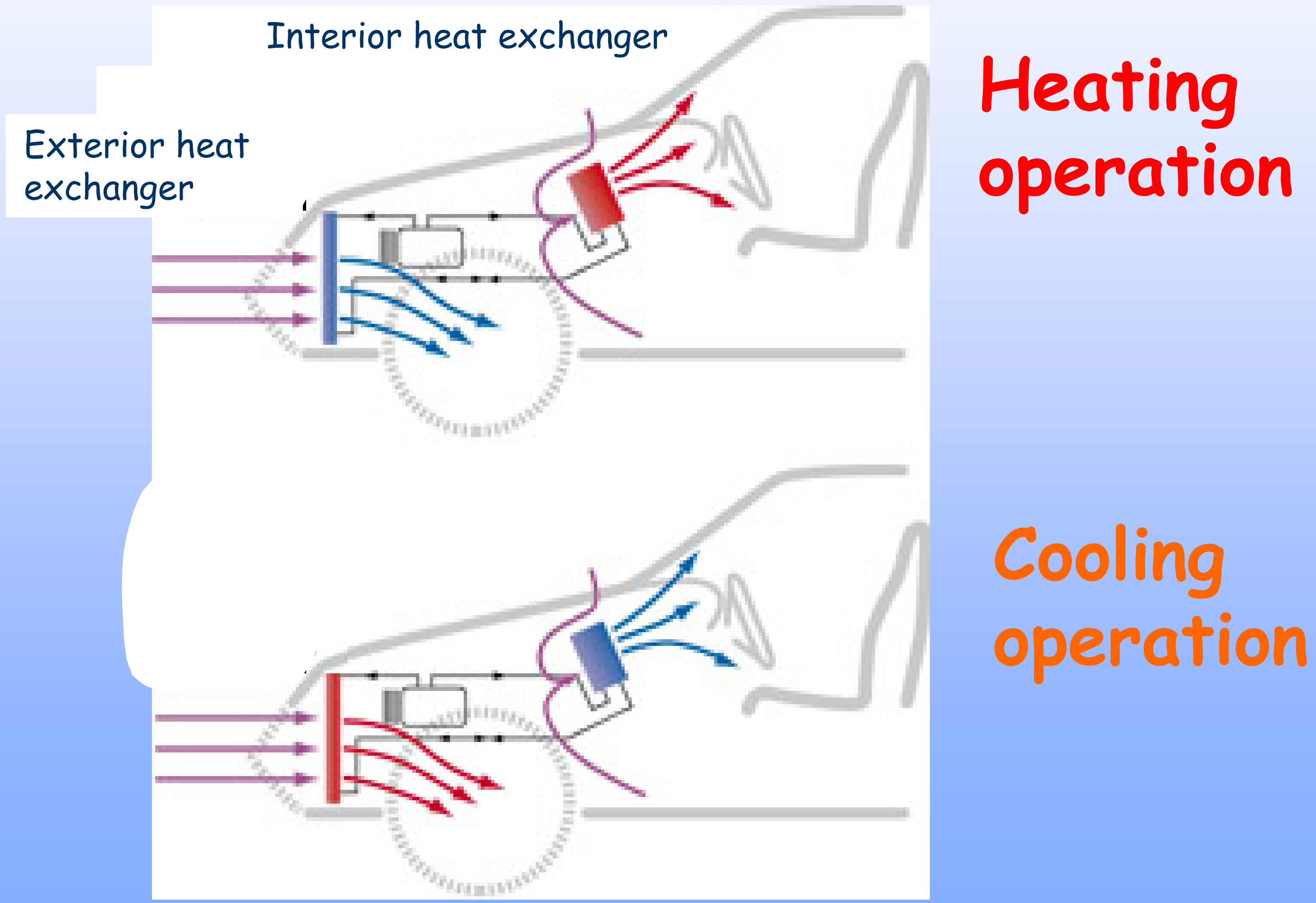
Mobile Heat Pump based on reversal of AC system (Ambient air as heat source)

CO_2 is an excellent refrigerant for a heat pump

Alternatives heat sources:
Engine heat
Gas cycles
Ambient air
Combinations



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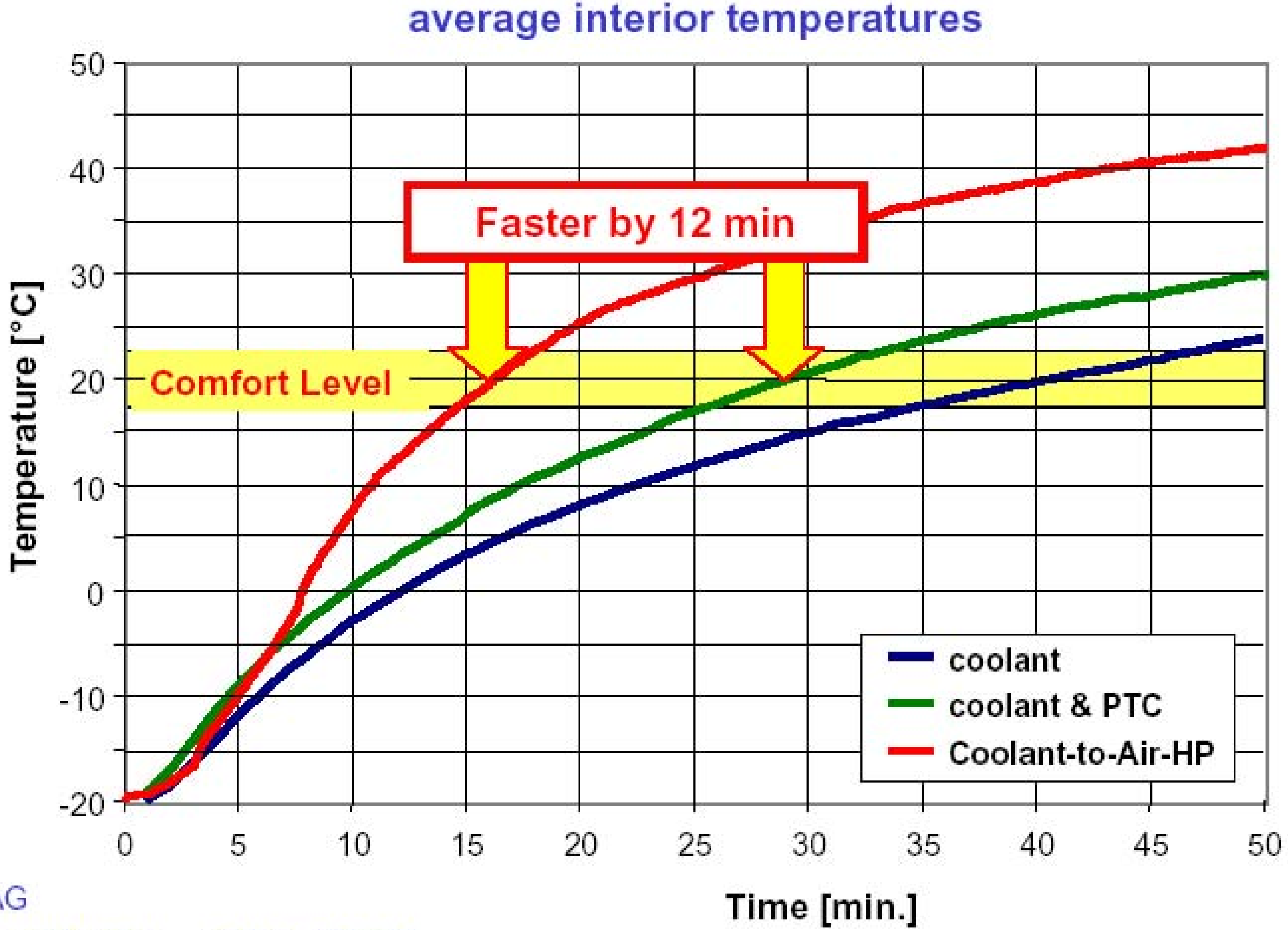
Why Mobile Heat Pump?

- Insufficient waste heat from modern fuel-injected engines, e.g. small diesels
- Higher demands for comfort (immediate heating expected)
- Safety (defrosting, defogging, driver attention)
- Instead of auxiliary fuel- or electricity-based heating system, use existing heat pumping circuit for both AC and HP, reducing total cost, weight and space requirements
- Electric vehicles have almost no waste heat

What are the main advantages of using CO_2 instead of HFC-134a?

Mac Summit 2003
10/ 11.02.03

Performance – heat pump system



Audi AG
Windtunnel test: $t_{amb.}$:-20°C, 50km/h

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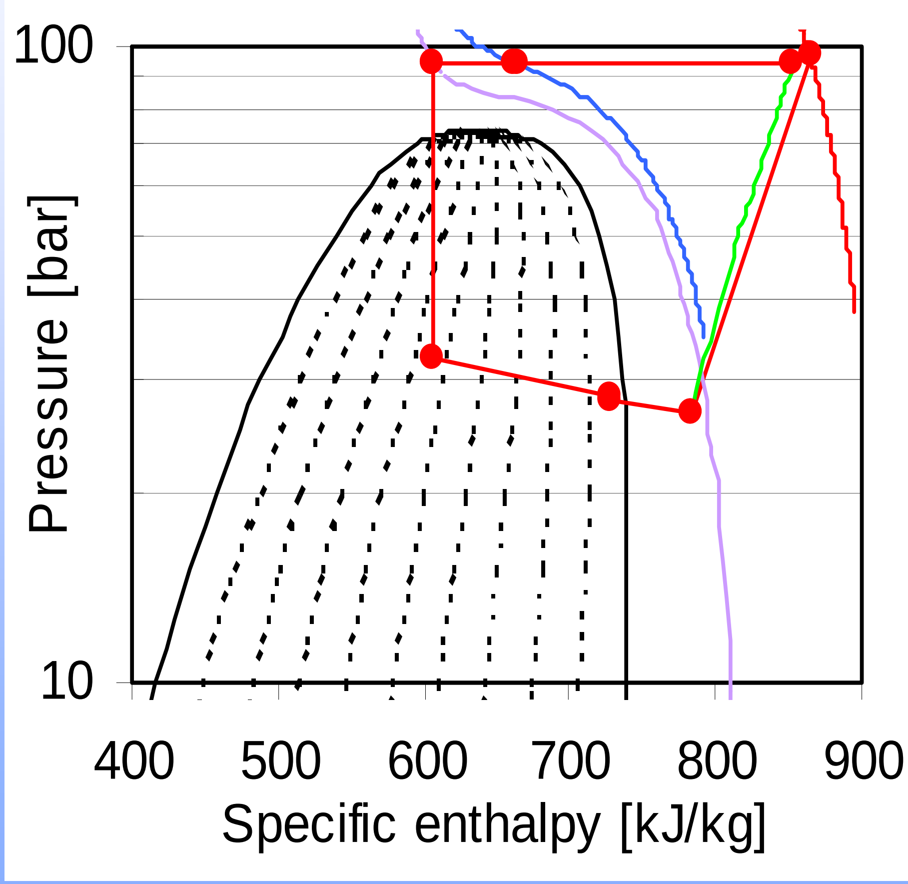
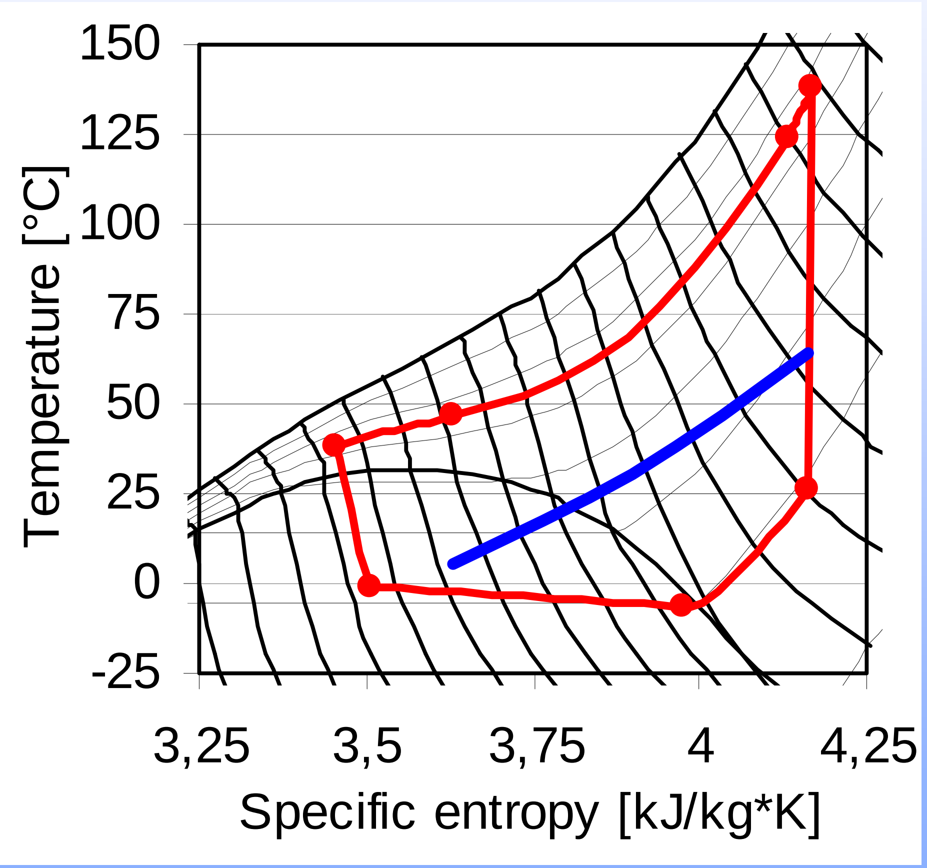
Heat pump operation





Heat Pumps and AC for space conditioning

Heat Pump Water Heaters

The ideal application for CO_2 as refrigerant

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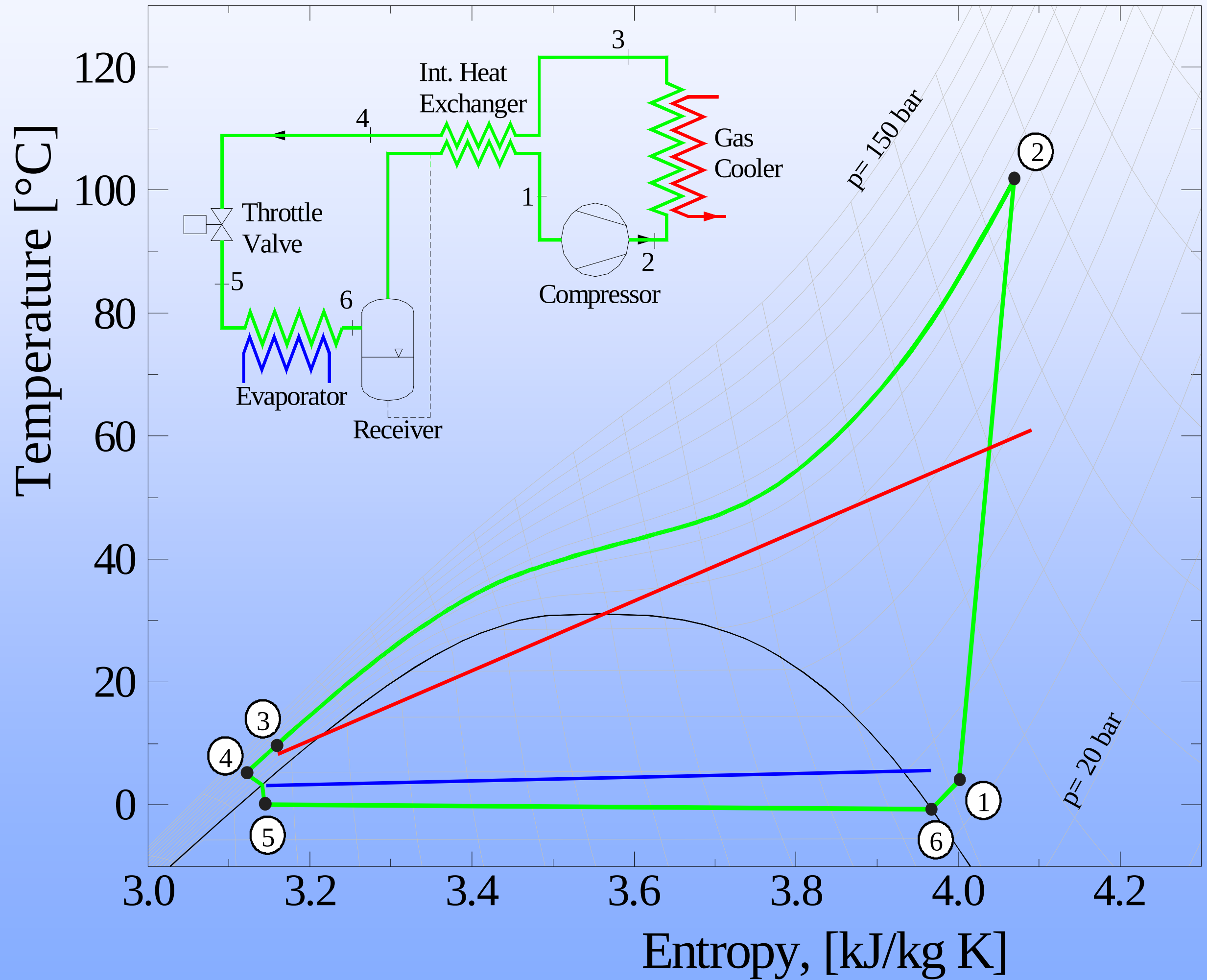
Heat Pump Water Heater using the transcritical CO_2 cycle



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CO_2 Heat Pump Water Heaters commercialized

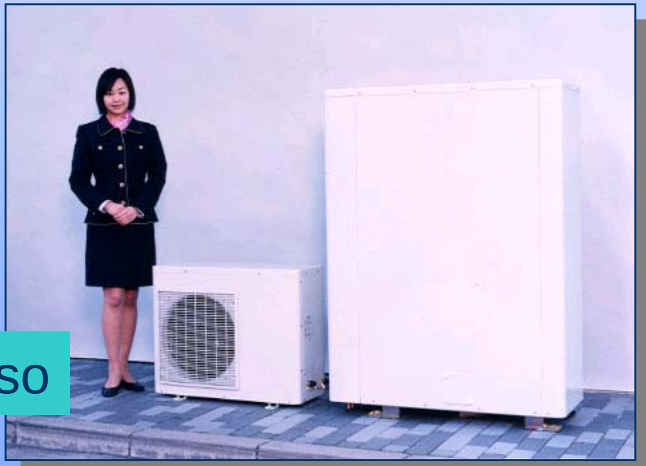
- commercialized in Norway (Development started 1989) and Japan
- based on Shecco Technology lisencees from Hydro Pronova

- Norway: Commercial sized system
- First system: AS Eggprodukter, Larvik, 22 kW heat output, 80°C
- Supplies h… water with 1/5 of the electricity … to resistan…
- In operati…

- Japan: Residential systems
- 4.5 kW heat output, 90°C water
- Average power cons. 1,3 kW
- About 120.000 sold in the Japanese market in 2004
- Shecco licence 2000

www.shecco.com
Shecco™ TECHNOLOGY


Finsam


Denso

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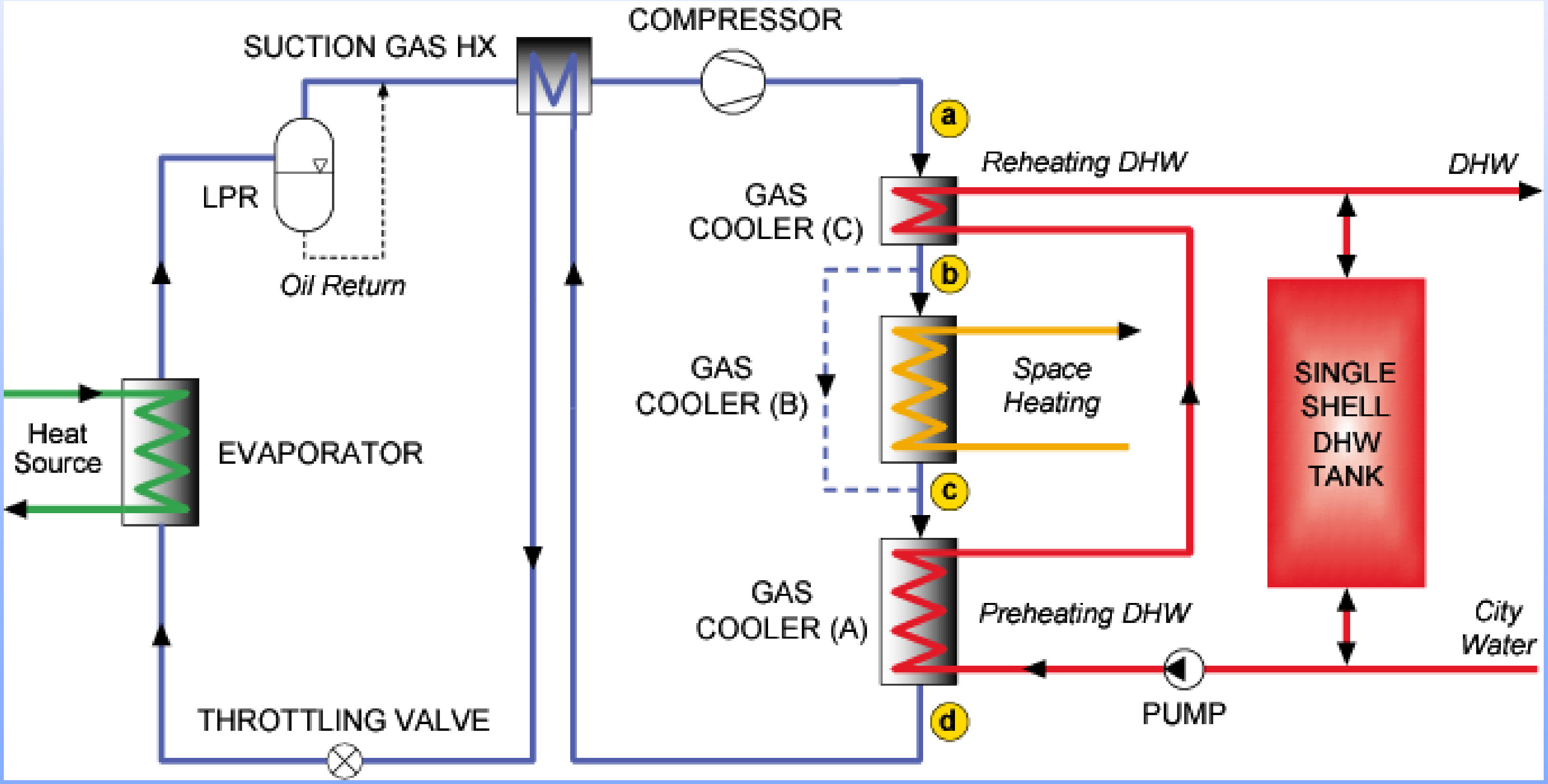
Brine to Water CO_2 Heat Pump System Principle [Stene, J., PhD NTNU, Trondheim, 2004]



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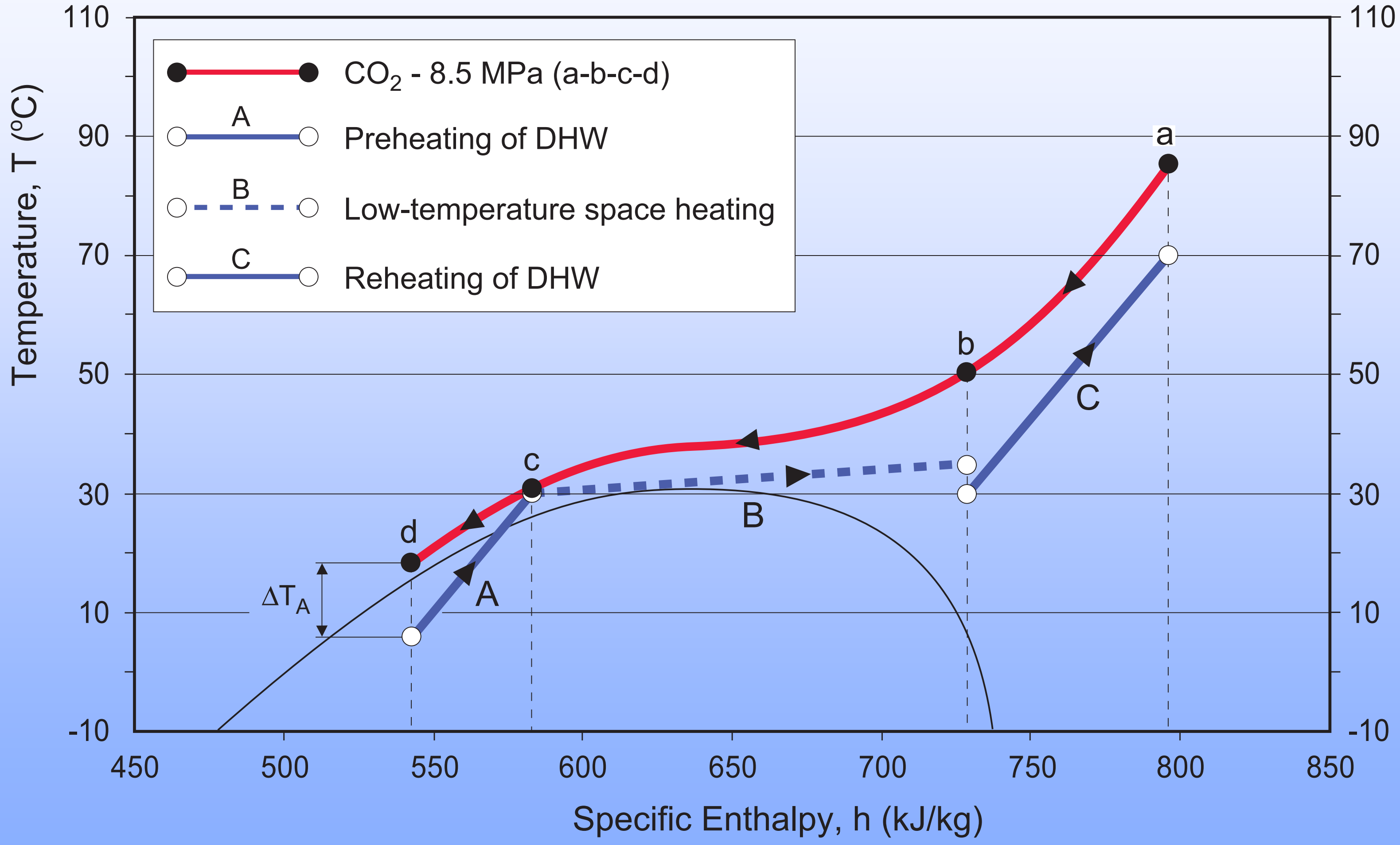
Heat Rejection Process – Combined Mode

[Stene, J., PhD NTNU, Trondheim, 2004]



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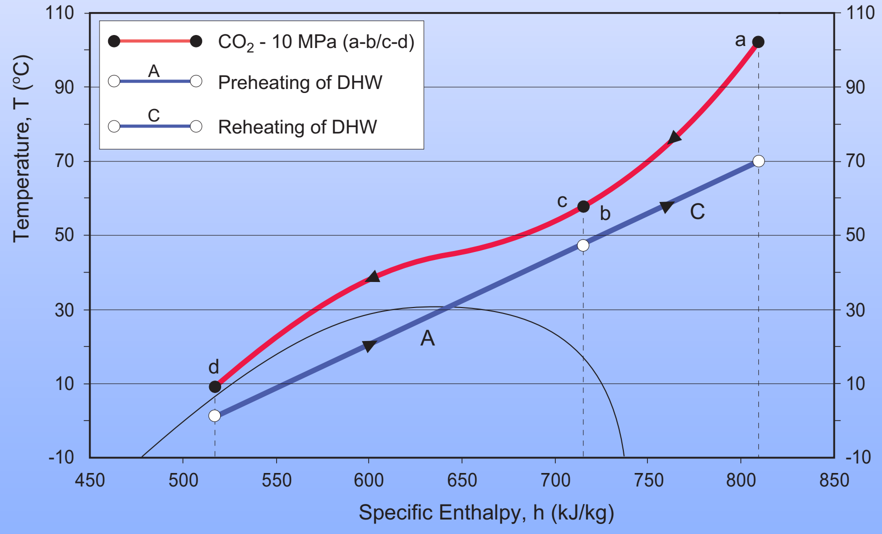
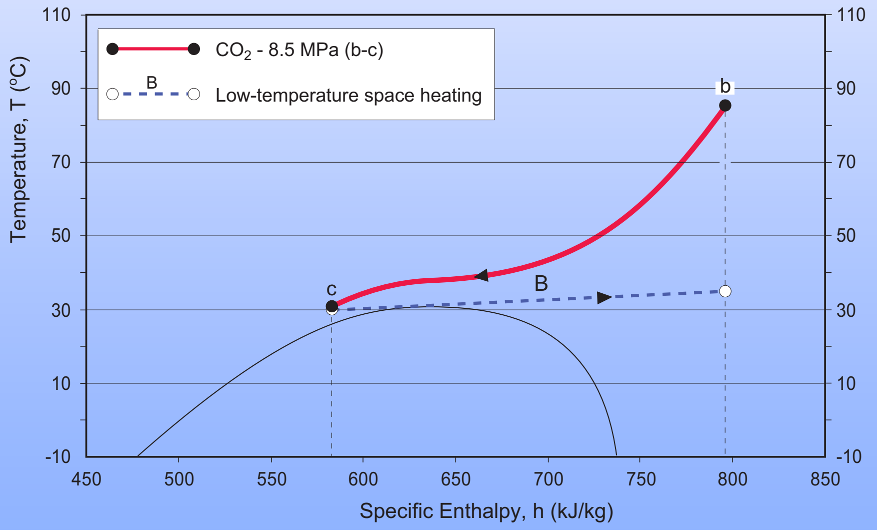
Heat Rejection Process – DHW Mode



Heat Rejection Process – SH Mode



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Laboratory Testing of a Prototype Plant

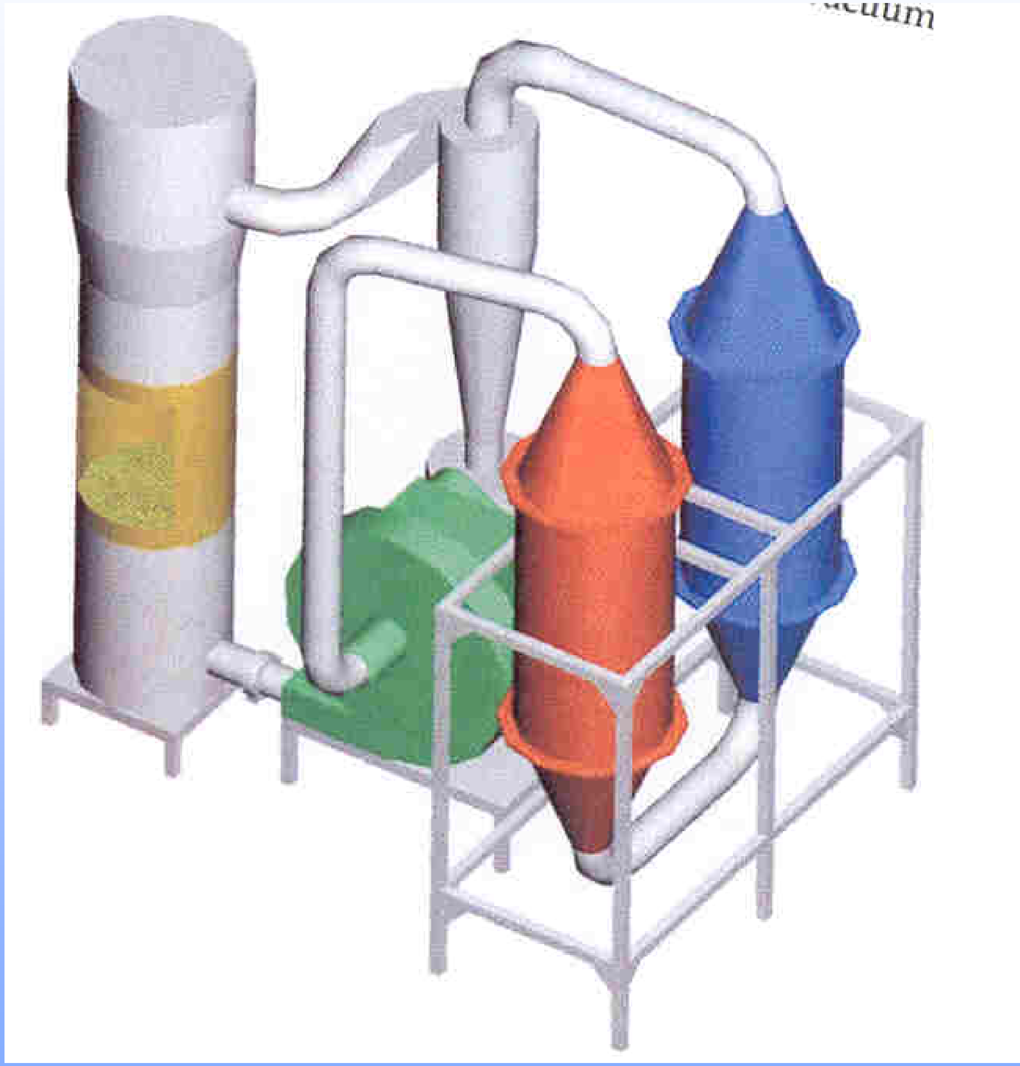
- The CO_2 heat pump unit:
  - 7 kW total heating capacity
  - Hermetic rolling piston compressor
  - Counterflow tube-in-tube evaporator
  - Counterflow tube-in-tube tripartite gas cooler
  - LPR system with back-pressure valve
  - Energy well as heat source

- Operating Conditions:
  - Evap. temp.: -10, -5 and 0°C
  - SH system: 33/28, 35/30 and 40/35°C
  - DHW system: 60, 70 and 80°C

Preliminary Conclusions (1)

- The SPF of an integrated CO_2 brine-to-water heat pump system may be competitive to the state-of-the-art systems as long as:
  - The annual DHW heating demand constitutes minimum 25 to 30% of the total annual heating demand of the residence
  - The return temperature for the SH system is sufficiently low (< 30°C)
  - The inlet water temperature from the DHW tank is low (< 10°C)
- During operation in the Combined mode and the DHW mode, the outlet water temperature from the DHW tank have a significant impact on the COP of the CO_2 heat pump unit. Consequently:
  - The design and operation of the DHW tank is of crucial importance in order to minimize mixing and conductive heat transfer in the tank during the tapping and charging periods

CO_2-Heat Pump Dryer



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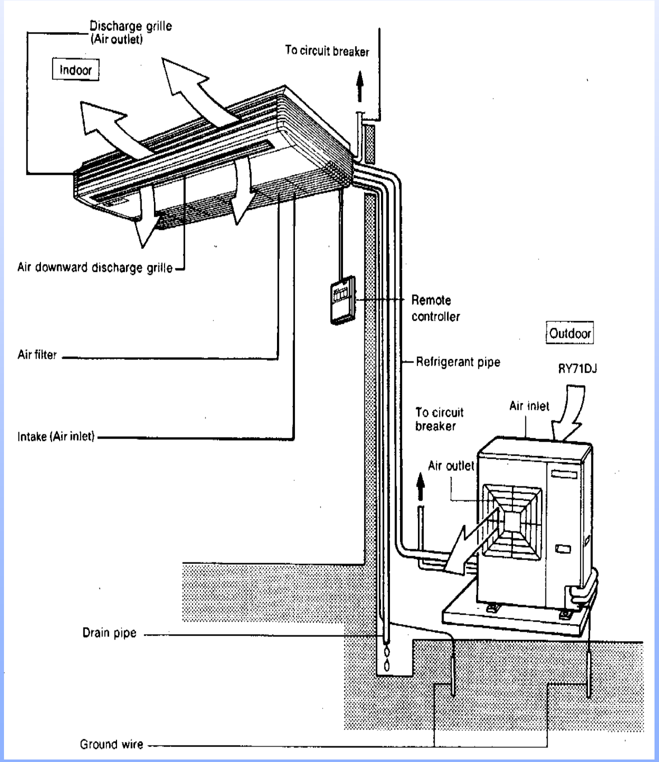
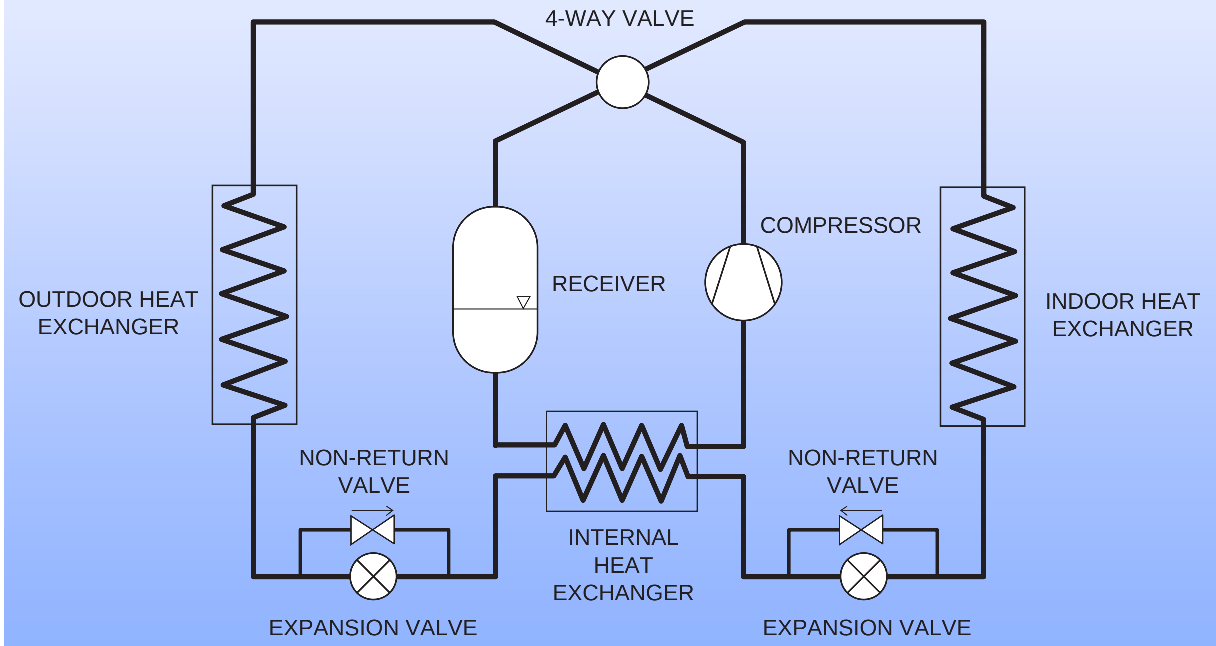
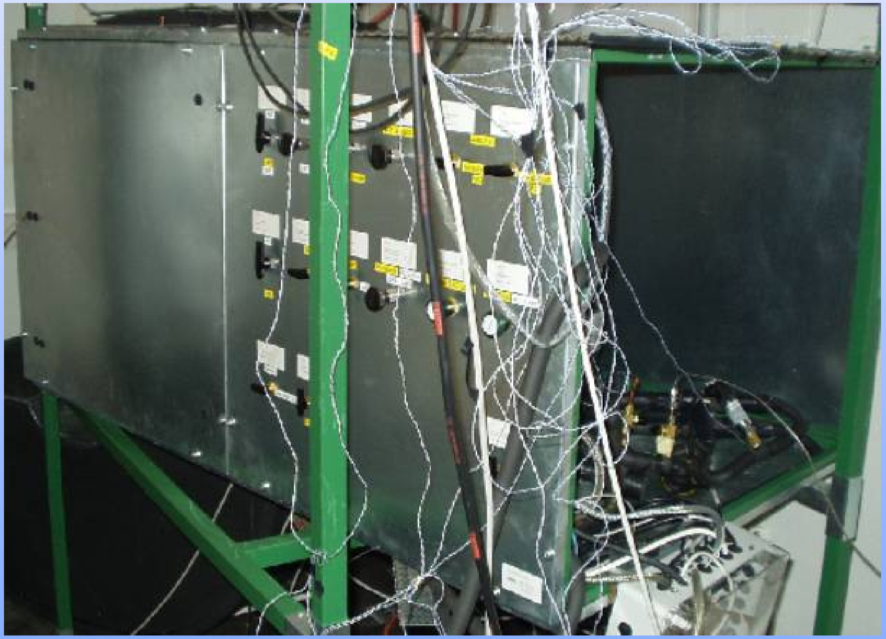
Reversible air/air heat pump Principle





Development of reversible air-air heat pumps

Heat pump mode competitive
Cooling mode currently less efficient, inefficient hx's in reversed mode operation



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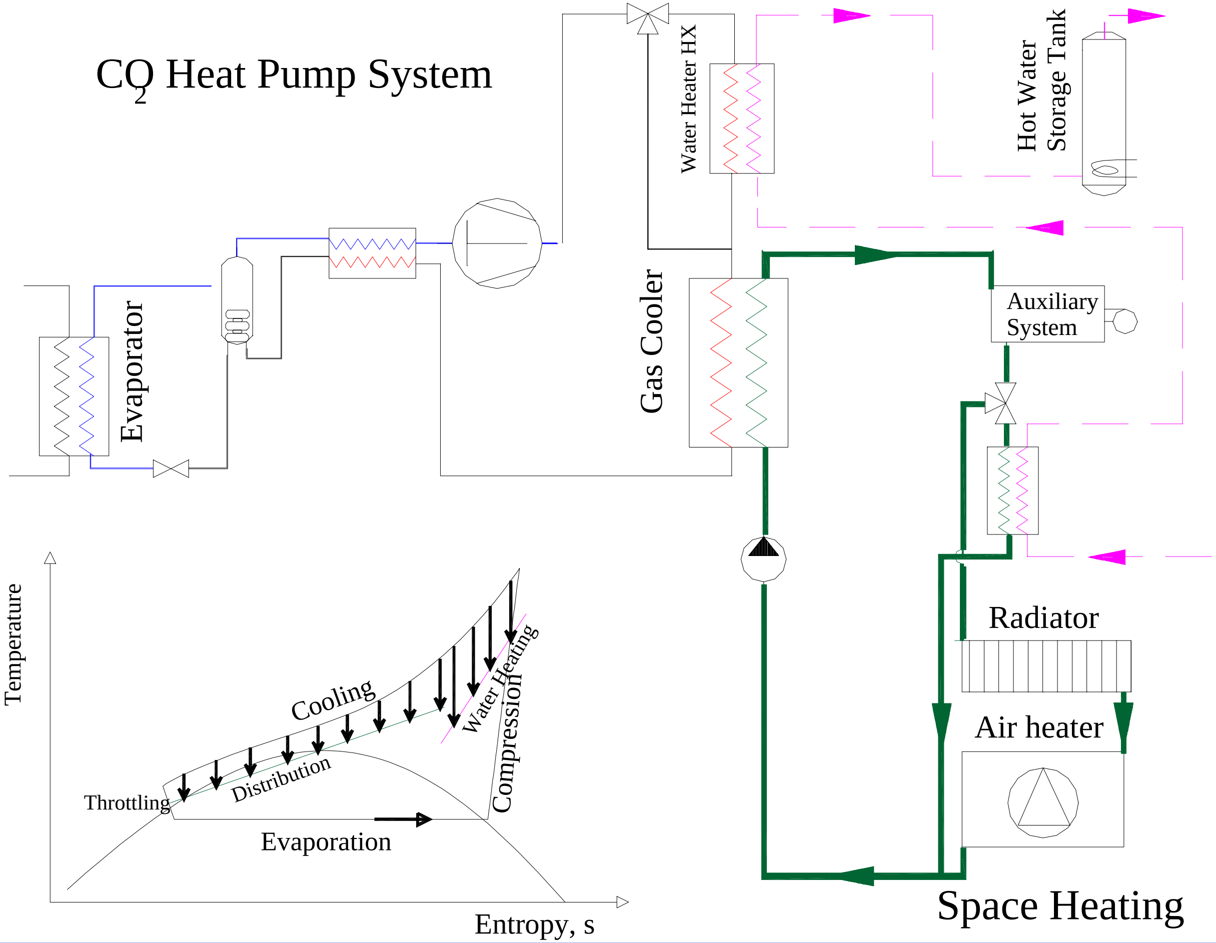
Space heating in commercial buildings



- Simulation show better SPF if air-heating represents more than 30% of the heating demand (rest hydronic)
- In Norway typically 50% of the heating demand is for air-heating

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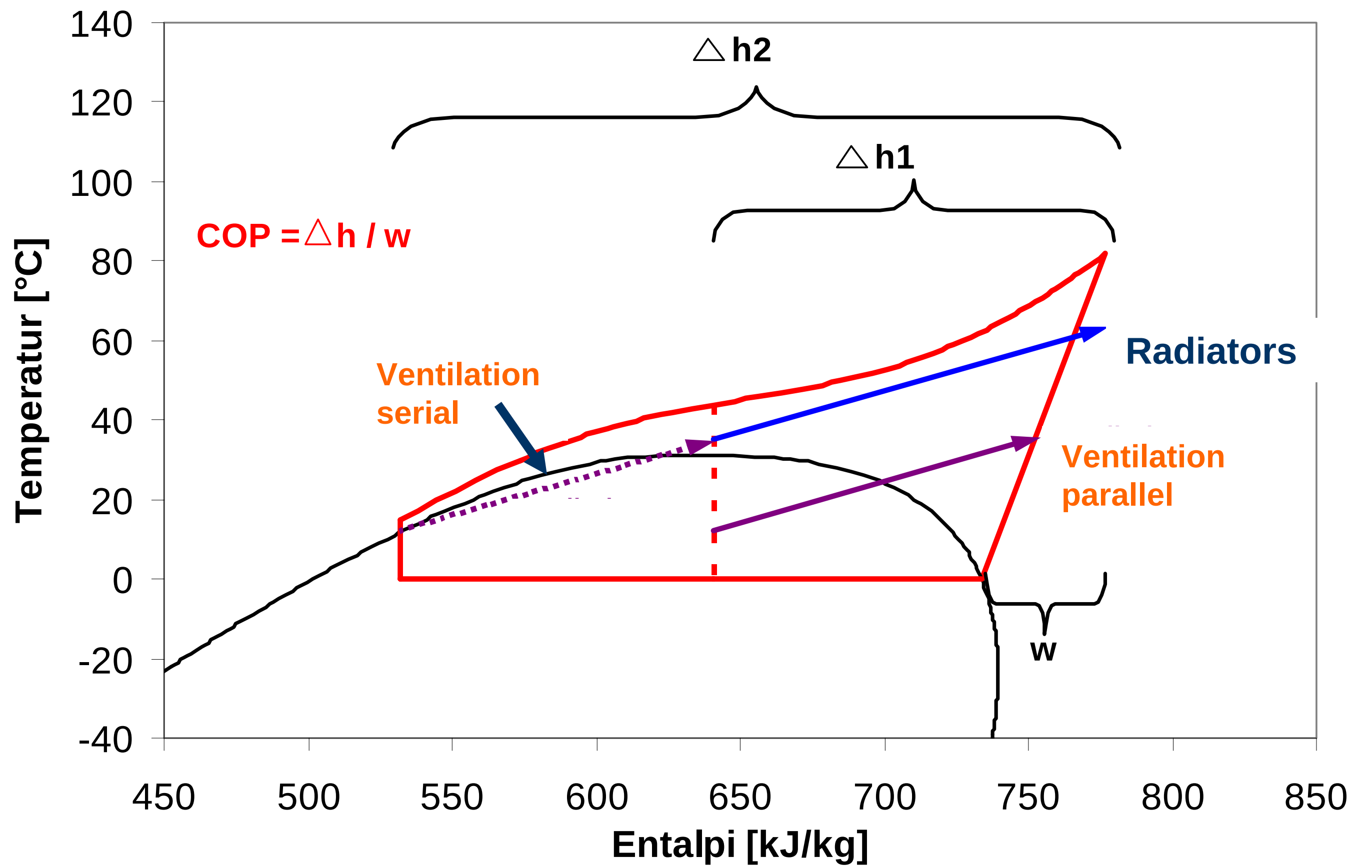
CO_2-heat pumps for commercial buildings
Serial- vs parallel connection of heat loads



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The design of the total system should be adapted to the refrigerant

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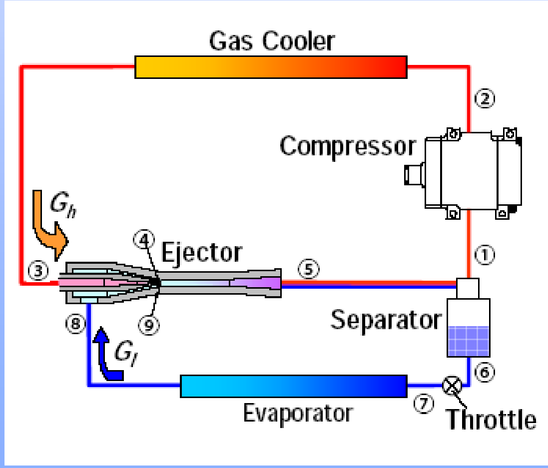
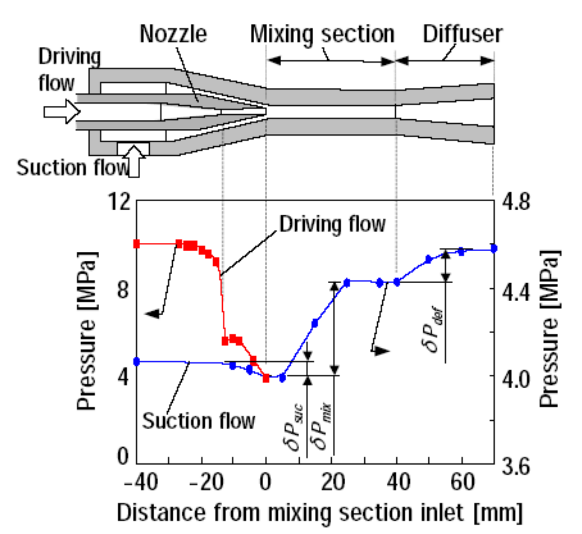
Improvements

- Cycle improvements can be implemented more or less easy and reduce losses differently depending on the refrigerant
  - Multistage compression
  - Liquid subcooling
  - Suction gas heat exchange
  - Expander
  - Ejector
- Optimisation is very much driven by economy, not only a technical fact





From Denso ejector development

Closing conclusions

- The revival of CO_2 as a refrigerant started in Europe more than 15 years ago, and there has been a strong development of new technology worldwide using this refrigerant in several application areas since then.
- Developments which initially were driven primarily by environmental concerns have often resulted in disclosing additional advantages by using CO_2, such as higher COP, higher cooling and heating capacity, better comfort, and added possibilities of heat recovery.
- Cost- and energy efficient systems have been developed and commercialised for some applications and more seems to come in the near future.
- With increasing focus on climate gas emission reductions, strict regulations on the use of HFC chemicals may be expected, possibly followed by phase-out targets and dates as announced by some European countries. These trends will clearly drive the interest in the direction of natural refrigerants in general and CO_2 in particular.

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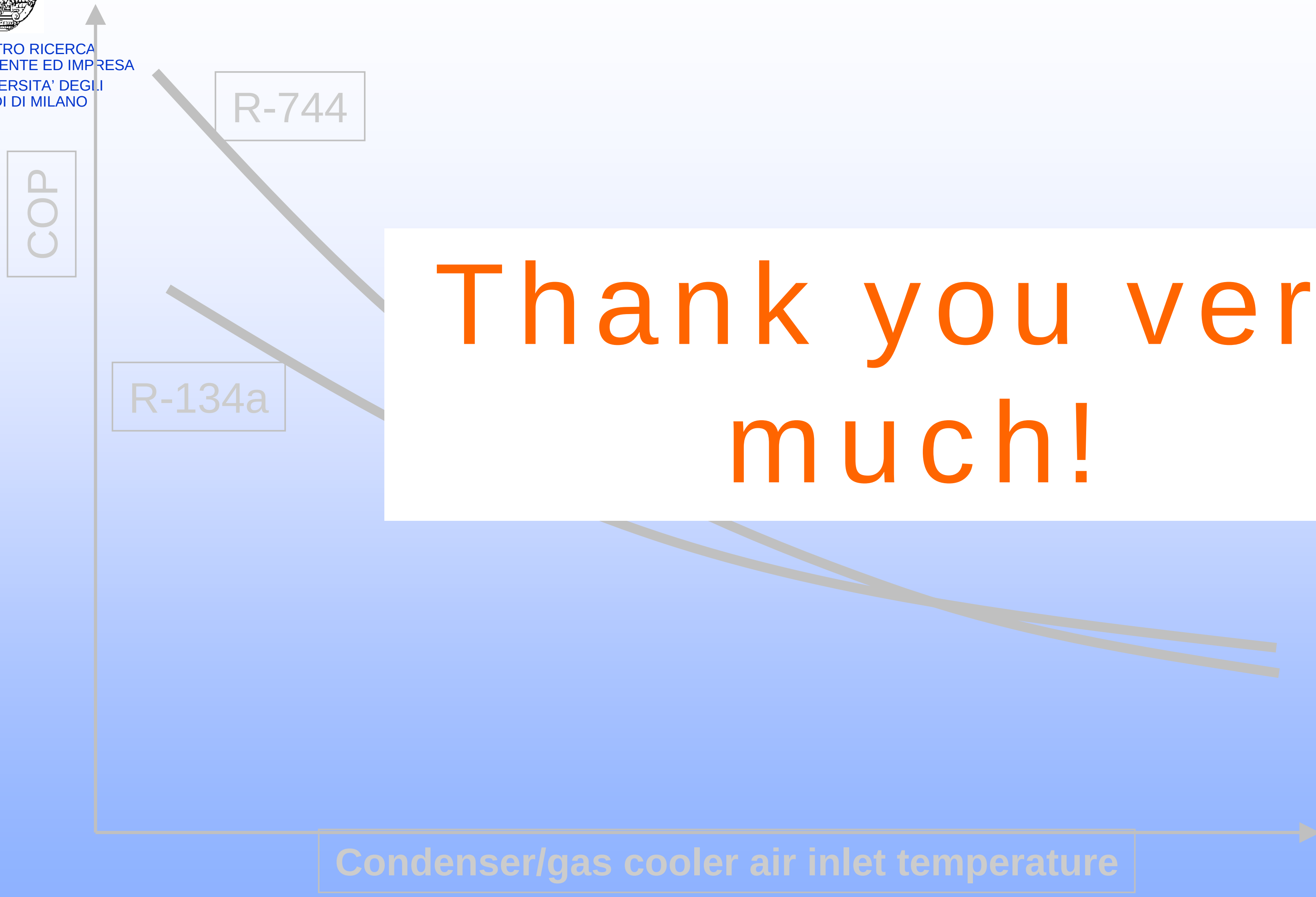

Thank you very much!