#1

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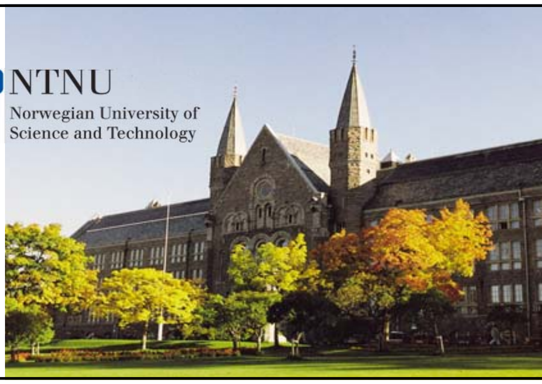

#2

Current status & outlook: Natural Working Fluids

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Content

- Introduction & Motivation
  - Fast phase in of NWF is needed,
  - Why unsaturated HFCs are not a sustainable solution
- The big three: CO_2, NH_3 and HC
- CO_2 systems a viable option for many applications
  - Mobile Air Conditioning & Heat Pumps
  - Marine Refrigeration → High Quality Fish
  - Hot water heat pumps → local environment
  - Commercial refrigeration → food safety
- Further Work & Cooperation's
- Summary

Non-Technological Barriers

#4

hinder diffusion of already existing energy efficient and natural-refrigerant based solutions

- Awareness barrier
- Knowledge barrier; Systems complexity increases, Interdisciplinary knowledge is required → **training**
- Social barrier; i.e. Some planners may not want to move from a technology they are very experienced in → **training**
- Organisational barrier
- Legislative barrier; i.e. No strong legislative incentive towards energy efficient supermarkets / systems as a whole and neither against inefficient ones

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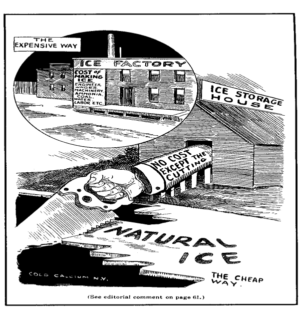
Three important 'drivers' in the late 19th century

Factors pushing the development of mechanical refrigeration technology from 1850 →

- "Artificial" ice production
- Transport of meat
- Brewing of beer (all year long)



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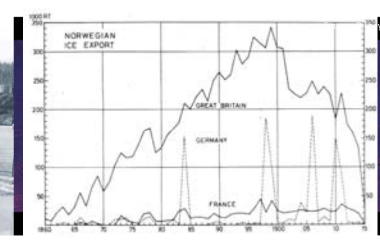
150 years ago: ICE = refrigeration



Norwegian Ice Export from 1860 to 1915

Natural working fluids also common in the US:

Advertisement in ICE and REFRIGERATION, 1922, vol. 63

Three important 'drivers' in the late 19th century

Factors pushing the development of mechanical refrigeration technology from 1850 →

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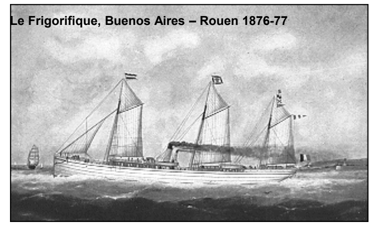

Le Frigorifique, Buenos Aires – Rouen 1876-77

Three important 'drivers' in the late 19th century

Factors pushing the development of mechanical refrigeration technology from 1850 →

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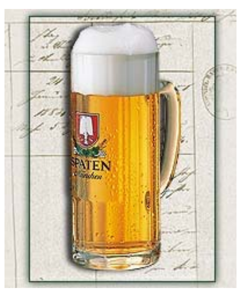
- Transport of meat
- Brewing of beer (all year long)



Carl von Linde (1842 – 1934)

Linde's articles on refrigeration technology had aroused the interest of **brewers who had been looking for a reliable year-round method** of refrigeration for the fermentation and storage of their beer.

Carl Linde (1868)

First industrial refrigeration machines: developed for a brewery

- Linde's first refrigeration system used *Dimethyl ether* as the refrigerant and was built by *Maschinenfabrik Augsburg* (now MAN AG) **for the Spaten Brewery in 1873**.
- He quickly moved on to develop **more reliable ammonia (R717)-based cycles**. These were early examples of vapor-compression refrigeration machines, and ammonia is still in wide use as a refrigerant in industrial applications.

The first Linde refrigeration machine. (1873)

Spaten → Heineken → Carlsberg →

Rotterdam based Heineken Brewery ordered an ice machine in 1877 for ice production. In his collaboration with the Heineken Brewery, Linde developed "natural convection cooling" with a system of cooling pipes under the ceiling of the cellar.

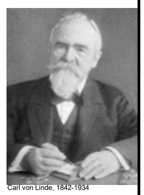
Fermentation cellar of a brewery with natural convection cooling

Linde came in contact with J.C. Jacobsen, head of the Carlsberg Brewery in Copenhagen, who ordered a large refrigeration unit in 1878.

Carl von Linde: ‘*godfather*’ of industrial refrigeration

#13

Linde’s **efficient new refrigeration technology offered big benefits to the breweries**, and by 1890 Linde had sold **747** ammonia refrigeration machines. In addition to the breweries, other users for the new technology were found in slaughter-houses and cold storage facilities all over Europe.


Carl von Linde, 1842-1934

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Refrigerants – history and the way forward

Until 1930 Use of natural working fluids – Air, ethyl ether, SO_2, methyl chloride, ammonia, propane, isobutane, CO_2, etc.

1930-50 Introduction of synthetic working fluids, like CFC12 and HCFC22

1987 *Montreal protocol* established, CFC and HCFC ozone depletion due to chloride/bromine. Phasing out CFC (1995) and HCFC (2010) in Europe

1987 Hydrogen-Fluor-Carbons (HFC) introduced

1997 *Kyoto protocol* established, HFC regulated due to high GWP values

2006/2007 EUs F-gas directive – Phase down of high GWP fluids

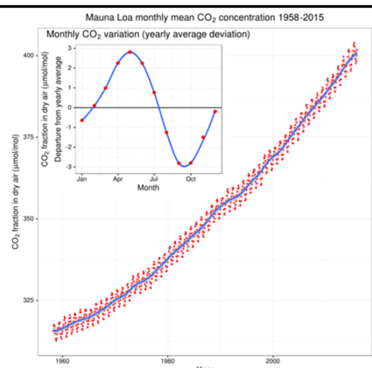
2016 Kigali amendment to the Montreal protocol, global HFC phase down

1990-now Increasing focus on use of natural working fluids, especially ammonia, hydrocarbons & CO_2

Current status: Natural Working Fluids Workshop at IIT Madras, March 2018 NTNU

CO_2 Concentration in air

Example: Hawaii (Mauna Loa)



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1998 Children’s Painting Competition by UNEP

LARGE NEED FOR NEW SOLUTIONS !!

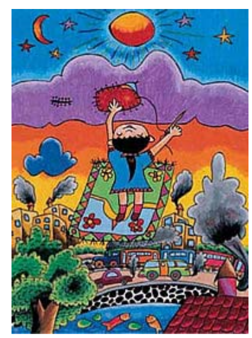


Image taken from the 2001 UNEP DTIE **OzonAction Programme Children’s Painting Competition**. Painting by **Laila Nuri**, aged 8, **Indonesia**

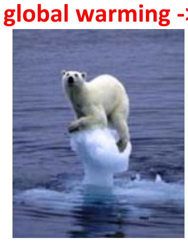
Current status: Natural Working Fluids Workshop at IIT Madras, March 2018 NTNU

Image taken from the 2001 UNEP DTIE **OzonAction Programme Children’s Painting Competition**. Painting by **Mariam Salman Al Oraibi**, aged 12, Bahrain

Current status: Natural Working Fluids Workshop at IIT Madras, March 2018 NTNU

Motivation:

Consequences of global warming ->



Far away…

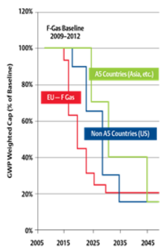
However, when the permafrost is melting…

Piz Cengalo Switzerland 24th Aug. 2017

Current status: Natural Working Fluids Workshop at IIT Madras, March 2018 NTNU

F-gas Regulation (in a nutschell)

Present conventional refrigeration systems **are not future long-term solutions:**
- Ban refrigerants GWP>150 from 2022 (centralized refrigeration system >40 kW, Primary Cycle in cascade configuration >1500)
- 79% Reduction of GWP related emission by 2030



Which options are available for stakeholders?

» **Business as usual** until 2020 and then usage of recycled gas until 2030;
- Availability/cost of the gas and equipment
- Future ban of service and maintenance
- Stricter leak detection and refrigerant recovery processes

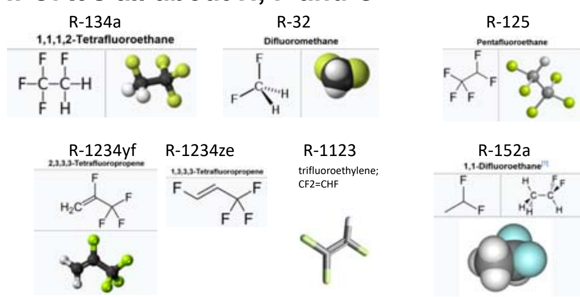
» Convert/retrofit with **new synthetic low-GWP refrigerants;**
- **Total environmental impact un-known**, future regulation?
- Cost of the refrigerant?

» **Natural Refrigerant** business orientation.
- **Long term solution**
- **Investment cost no longer higher than traditional HFC**

'New' synthetic refrigerants with ultra low GWP

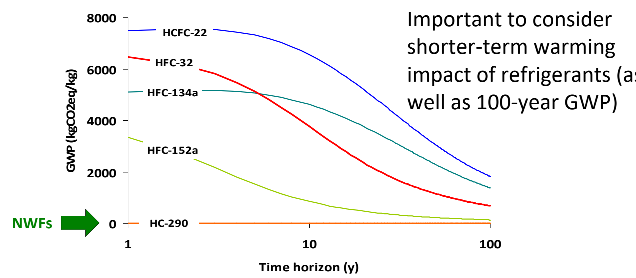
Even if some people gave these new fluids another name, they are HydroFluoroCarbons (unsaturated HFCs), i.e. organic compounds that contain only hydrogen, fluorine, and carbon atoms + a weak double=bond

HFC: It's all about H, F and C



Source: Wikipedia

Environmental characteristics



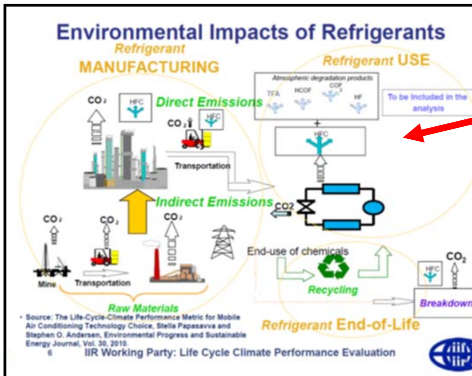
Important to consider shorter-term warming impact of refrigerants (as well as 100-year GWP)

Source: Data from IPCC AR4

'New' synthetic refrigerants with ultra low GWP due to short lifetime

How do we measure environmental impact?

- Which are the main parameters for the GWP-value?
  - The ability of the fluid to absorb infrared radiation
  - The **lifetime** in the atmosphere
- What includes the LCCP value?
  - CO_2 emissions from 'cradle to grave'…



Focus today: only

GWP

Global **W**arming **P**otential

HFCs with ultra low lifetime do have a very low GWP value. Nevertheless all the other equally important **environmental aspects are either unknown or secret**

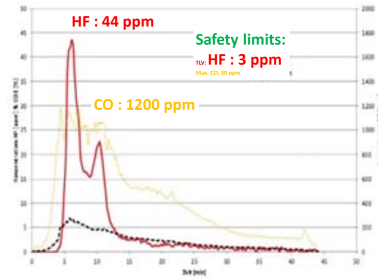
‘New’ synthetic refrigerants with ultra low GWP

Safety / HSE / Responsibility

- <u>inflammable, liable to catch fire, combustible</u>
- end user
- service people
- rescue personal

Take a look into the date sheets!

DUH did tests with R-1234yf



0 min

10 min

http://www.bild.de/auto/auto-news/klimaanlage/killer-kaeltemittel-r1234yf-eu-kommission-streit-gefahr-test-deutsche-umwelthilfe-duh-34334896.bild.html

HF:
TLV (Threshold Limit Value) = 3 ppm
IDLH (Immediately dangerous to life or health) = 30ppm
May also happen with HFC-134a
IDLH for ammonia is 300 ppm (30 min escape)

Daimler Test = HFK-1234yf is pyrophoric

Performed and documented by Daimler with an B 180 class Mercedes

Federal German authority for physical and chemical tests of materials and facilities (BAM)
https://**www.bam.de**/_SharedDocs/DE/Downloads/Jahresbericht2014.pdf?__blob=publicationFile&v=5 Page 96 →

....

Carbonyl difluoride (COF2) may also develop in the case of fire. Carbonyl difluoride is the fluorine analogue of phosgene, <u>the substance used as a poison gas in some wars</u>. Fluorine phosgene (= carbonyl difluoride) can therefore be assumed to have a similar effect. The only question is whether COF2 is present long enough – or at all – to cause a health hazard to people present in the accident scenarios to be considered.

...

This has encouraged BAM experts dealing with safety engineering and analysis to investigate more scenarios and conditions under which COF2 is formed.

http://www.dailymail.co.uk/video/news/video-1005013/Daimler-video-claims-1234yf-dangerous-VW-says-CO_2-best-refrigerant.html

http://www.sciencedirect.com/science/article/pii/S0009261407015813
Chemical Physics Letters 450 (2008) 263–267

…The <u>atmospheric lifetime</u> of **(R1234yf) CF3CF CH2** is dictated by its reaction with OH radicals and is <u>approximately 11 days</u>. We show here that **<u>CF3C(O)F</u>** is the major atmospheric oxidation product of CF3CF CH2. The atmospheric fate of CF3C(O)F is hydrolysis which occurs on a time scale of approximately 10 days to give CF3C(O)OH (TFA)…

What happens to people inside maskin rooms, workshops, service cars, etc.?

<u>CF3C(O)F</u> + H_2O → CF3C(O)OH + HF

The acidity of Trifluoroacetic acid (TFA) is approximately 34,000 times stronger than that of acetic acid. TFA is harmful when inhaled, causes severe skin burns and is <u>toxic for water organisms even at low concentrations</u>

Upon contact with moisture, including tissue, hydrogen fluoride (HF) immediately converts to hydrofluoric acid, which is <u>highly corrosive and toxic</u>, and requires immediate medical attention upon exposure. <u>Breathing in hydrogen fluoride</u> at high levels or in combination with skin contact <u>can cause death</u> from an irregular heartbeat or from fluid buildup in the lungs.

U.S. Department of Health & Human Services

https://**emergency.cdc.gov**/agent/hydrofluoricacid/basics/pdf/facts.pdf

- Hydrogen fluoride goes easily and quickly through the skin and into the tissues in the body. There **it damages the cells** and causes them to not work properly.
- The seriousness of poisoning caused by hydrogen fluoride depends on the amount, route, and length of time of exposure, as well as the age and preexisting medical condition of the person exposed.
- **Breathing hydrogen fluoride can damage lung tissue** and cause swelling and fluid accumulation in the lungs (pulmonary edema).
- **Skin contact with hydrogen fluoride may cause severe burns** that develop after several hours and form skin ulcers.

http://**www.solvay.com**/en/binaries/trifluoroacetic_acid_GPS_rev0_Dec12-139538.pdf

General Statement

‘Trifluoroacetic acid (TFA) is a **strong carboxylic acid**, widely used in organic chemistry.
TFA is an important building block in the synthesis of pharmaceuticals, agrochemicals and performance products.

TFA is a liquid substance, colourless to pale yellow and with a pungent odour.

TFA is a strong acid, it may **cause irreversible skin burns** and eye damage and vapours may cause an irritation of the upper respiratory tract.

<u>TFA is harmful to aquatic environment with long lasting effects; any release to the environment must be avoided.</u>

The pure substance is only used in industry or for professional purpose; it must be handled under stringent safety conditions at the workplaces, in accordance with the risk management measures to control the risk of exposure and preserve human health and environment. Consumer exposure to TFA is not expected.

'New' synthetic refrigerants with ultra low GWP

- **What happens if the fluid leaks:**
  - **Into the machine room?**
  - **Into the workshop?**
  - **Inside the service van?**
  - **During service/assembly of systems?**

Who has the responsibility for health damages of people ?

R1234yf

~~A2L~~ => B2L

ASHRAE-Nummer	Formel	Name	CAS-Nummer
R-1216	C3F6	Hexafluorpropen	116-15-4
R-1225ye	C3HF5	1,2,3,3,3-Pentafluorpropen	5528-43-8
R-1225zc	C3HF5	1,1,3,3,3-Pentafluorpropen	690-27-7
R-1234ye(E)	C3H2F4	1,1,2,3-Tetrafluor-2-propen	115781-19-6
R-1234ye(Z)	C3H2F4	1,1,2,3-Tetrafluor-2-propen	730993-62-1
R-1234yf	C3H2F4	2,3,3,3-Tetrafluorpropen	754-12-1
R-1234ze(E)	C3H2F4	1,3,3,3-Tetrafluorpropen	29118-24-9
R-1243zf	C3H3F3	3,3,3-Trifluorpropen	677-21-4
R-1270	C3H6	Propen (Earlier: Propylen)	115-07-1

Substance: 2,3,3,3-Tetrafluorpropene
CAS No.: 754-12-1

	Limit value - Eight hours		Limit value - Short term	
	ppm	mg/m^3	ppm	mg/m^3
Germany (AGS)	200	950	400 (1)	1900 ('
Germany (DFG)	200	940	400(1)	1880 ('

	Remarks
Germany (AGS)	(1) 15 minutes average value
Germany (DFG)	(1) 15 minutes average value

This means that 2,3,3,3-Tetrafluorpropene (R1234yf) is a B2L substance

What about R-1234ze

According to the manufacturer:

- A unique characteristic of this refrigerant is the absence of flammable mixture with air under 30°C of ambience. [1]
- Atmospheric Decomposition of R-1234ze breaks down into the same by-products of other commonly used fluorinated compounds at levels much lower than naturally present. F atoms degrade into HF which is then rained out and mineralised with no additional effect on Ozone or on Climate*. [1]

Are we sure? =>

What about the effect on human beings in dense populations?

[1] HFO-1234ze Technical Data Sheet, Honeywell

R-1234ze

$CF_3CH=CHF \rightarrow HC(O)F$ and CF_3CHO

- **Formyl fluoride:** CHFO
  - HC(O)F → HF + CO

- **2,2,2-Trifluoroethanol :** $C_2H_3F_3O$
  - Safety: Trifluoroethanol is classified as **toxic to blood**, the reproductive system, bladder, brain, upper respiratory tract and eyes. Research has shown it to be a **testicular toxicant** in rats and dogs (***only?***).

Background on A2L hazards

Ed 6 FDIS of **60335-2-40** on A2Ls

Critical point of clarification – A2L refrigerants are flammable and can be ignited with common sources of ignition

Ignition of R1234ze

Full-scale experiment to evaluate the combustion hazard of refrigerants with low global-warming potential in a conceivable accident scenario

Tomohiko Imamura, Yasutaka Yoshida, Yoshinari Ota, Koji Naito, Osami Sugawa

Background on A2L hazards

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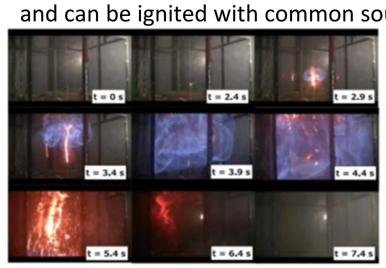
Critical point of clarification – A2L refrigerants are flammable and can be ignited with common sources of ignition



Ignition of R32

Full-scale experiment to evaluate the combustion hazard of refrigerants with low global-warming potential in a conceivable accident scenario

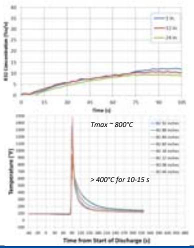
Tomohiko Imamura, Yasutaka Yoshida, Yoshinari Ota, Koji Naito, Osami Sugawa

Ed 6 FDIS of 60335-2-40 on A2Ls

Background on A2L hazards

Another example

Ignition of **R32** close to LFL



7s after Energizing Electric arcs

AHRTI Report No. 9007-01
BENCHMARKING RISK BY WHOLE ROOM SCALE LEAKS AND IGNITIONS TESTING OF A2L REFRIGERANTS
Final Report
June 2017

Ed 6 FDIS of 60335-2-40 on A2Ls

Background on A2L hazards

Secondary consequences

High temperature + sustained flame → secondary fire

Generation of **high levels of hydrogen fluoride (HF)**; NIOSH IDLH (immediately dangerous to life or health) = 30 ppm

Flammability and consequences must be considered in light of proposals

1 kg A2L burns for 10 to 40 seconds at 500 to 1000°C

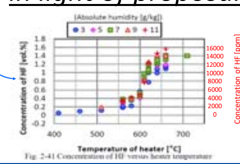
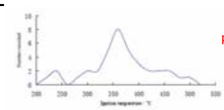


Fig. 2-41 Concentration of HF versus heater temperature



Most common textiles, papers, materials ignite after a few seconds above 200°C

Table 2.2 Ignition Time Data

Time(s)	1.50	1.63	1.75	1.88	2.00	2.13	2.25
Yes	0	1	2	2	3	3	4
No	4	3	2	2	1	1	0

HF

TLV (Threshold Limit Value) = 3 ppm
IDLH (Immediately dangerous to life or health) = 30ppm

Thermal decomposition of HFC-32

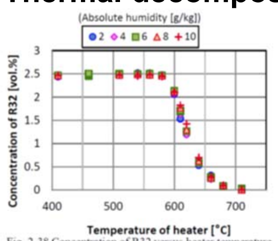


Fig. 2-38 Concentration of R32 versus heater temperature (Total flow rate of 200 ml/min; 2.5 vol. % R32 with air; Inconel 600 tube)

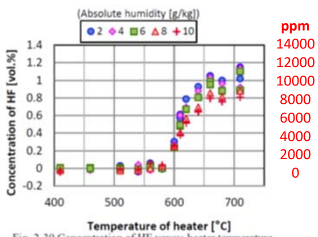


Fig. 2-39 Concentration of HF versus heater temperature (Total flow rate of 200 ml/min; 2.5 vol. % R32 with air; Inconel 600 tube)

HF

TLV (Threshold Limit Value) = 3 ppm
IDLH (Immediately dangerous to life or health) = 30ppm

Thermal decomposition of HFC-1234yf

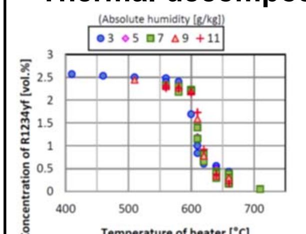


Fig. 2-40 Concentration of R1234yf versus heater temperature (Total flow rate of 200 ml/min; 2.5 vol. % R1234yf with air; Inconel 600 tube)

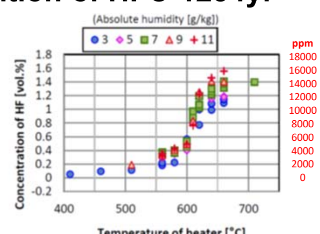


Fig. 2-41 Concentration of HF versus heater temperature (Total flow rate of 200 ml/min; 2.5 vol. % R1234yf with air; Inconel 600 tube)

Ed 6 FDIS of 60335-2-40 on A2Ls

“Flame” symbol

Clause 7.6

Warning symbol is misleading

	A2L symbol	warning; low burning velocity material

Should be “warning”, “alerting”, clear and explicit

In present state, it will not mitigate accidents
It does not represent the hazard in any way

To date, several servicing accidents with A2Ls because Technicians had been informed it is “mildly” flammable.

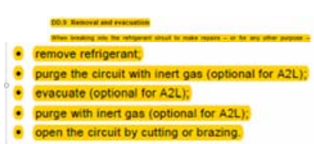
Information should warn technicians, not try to camouflage the hazard

Ed 6 FDIS of 60335-2-40 on A2Ls

Instructions

Clause DD.9

Encourages poor practice



- remove refrigerant;
- purge the circuit with inert gas (optional for A2L);
- evacuate (optional for A2L);
- purge with inert gas (optional for A2L);
- open the circuit by cutting or brazing.

Good practice should be promoted!

Purging system with N2 is necessary practice for ALL refrigerants, flammable or non-flammable

Guidelines should not encourage bad technician practices

A2L's (unsaturated HFCs) are not retrofit options!!!

This is the second edition of the PURR report, which contains updates on the latest replacement options for R404A, including those classified as A2L or lower flammability. **It must be stressed that these A2L alternatives are NOT suitable as retrofit options, but can only be used in new systems replacing an existing R404A system.** We have also extended the scope of the report to look at replacements for R410A in air conditioning systems, as this is a topic which is becoming of more interest to the industry.

Report of British Refrigeration Association Action Group

On

Putting into Use Replacement Refrigerants (PURR)

2nd Edition – January 2018

..new systems replacing existing R404A systems.

NWF

?

A2L

A2L's (unsaturated HFCs) are not retrofit options!!!

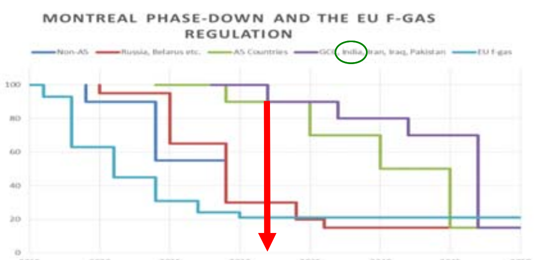
USE OF A2L REFRIGERANTS

IT IS VITAL TO UNDERSTAND THAT A2L REFRIGERANTS **MUST ONLY** BE USED IN SYSTEMS DESIGNED SPECIFICALLY TO TAKE INTO ACCOUNT THEIR FLAMMABILITY CHARACTERISTICS. THEY SHOULD **NEVER** BE USED TO REPLACE NON-FLAMMABLE REFRIGERANTS IN RETROFIT SITUATIONS **without a full risk assessment and necessary modifications.**

This is because of safety issues and the possibility of a relatively large charge of an A2L being released by accident into an area that has not been risk assessed for use with this class of refrigerants.

Due to their lower flammability, A2L refrigerants are intended for use in equipment specifically designed for these products and should always be used in accordance with the relevant national and international standards. Please consult the appropriate equipment manufacturer regarding which refrigerants can be used in the equipment

Outcome of the Kigali meeting October 2016



Can you afford to wait another 14 years to start?

In Europe

Clever strategy after Paris COP, Kigali & Marrakech Meetings:

Companies focusing on

Natural Working Fluids

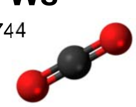
will face no risk to invest into technologies being on the **phase out agenda** in the future

<=>

Safe & sustainable investment

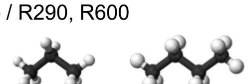
The big three NFWs

- Carbon Dioxide / CO_2 / R744
  - Hot water heat pumps
  - Commercial refrigeration



- Ammonia NH_3 / R717
  - Industrial refrigeration and heat pumps

- Hydrocarbons (Propane, Butane, etc.) / R290, R600
  - Residential split units
  - Light commercial refrigeration
  - Home appliances (fridges and freezers)

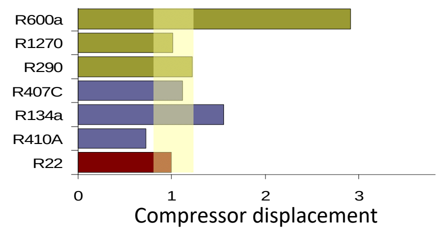


Hydrocarbons HC

- Godrej R290 Split Units ->
  - Leapfrog technology 'Made in India!

HC: Thermophysical properties and implications

Volumetric refrigerating capacity indicates the required size (displacement) of the compressor



Charge size limits for HC

Location of system parts	Category A (public spaces)	Category B (private spaces)	Category C (authorised)
	AC&R	AC&R	AC&R
Not in machinery room	1 – 1.5 kg	1 – 2.5 kg	10 kg
HP in machinery room/ outside	1 – 1.5 kg	1 – 2.5 kg	25 kg
All in machinery room/ outside	5 kg	10 kg	No limit
All in special enclosure	5 kg	5 kg	No limit

Subject to practical limit, between 3 – 8 g/m³ depending upon equipment

Public pressure and awareness helps → Example: light commercial refrigeration

#52

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Light commercial ref. units / standalone units

Important players are joining:

Refrigerants, Naturally!

Coca-Cola PEPSICO Red Bull Unilever

They have installed more than <u>3.5 million units using natural refrigerants</u> – both in developing and industrialised countries.

This is real PHASE-IN of natural refrigerants!

CONGRATULATIONS

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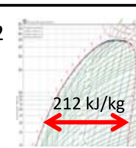
Ammonia / NH_3 / R717

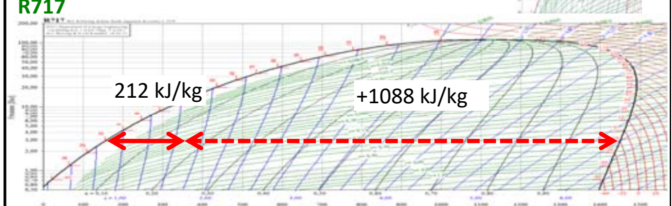
Example R22 versus R717
@ -10°C saturation temperature

Heat of evaporation
6xR22 = R717

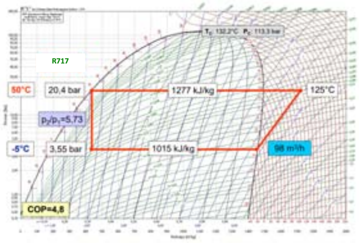
R22

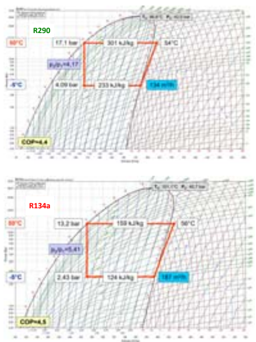


R717



Ammonia Heat Pump
ex: -5°C → +50°C



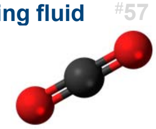


Ammonia / NH_3 / R717

- Past:
  - high refrigerant charges
  - locally assembled
- Nowadays:
  - 60 bar high side pressure
  - excellent energy efficiency for chillers and heat pumps
  - small refrigerant charge (≤50 kg)
  - factory-assembled, pre-commissioned

R744 / CO_2 – environmentaly friendly working fluid

#57



Molar mass: 44.01 g/mol

- **Only real A1 fluid!**
- CO_2 – appear naturally in the atmosphere
  - CO_2 concentration ca. 400 ppm (0,04%) ↑
- ODP = 0
  - Ozone Depletion Potential – reference ODP CFC11=1,0
- GWP = 1,0
  - Global Warming Potential – reference GWP CO_2=1,0
  - GWP CO_2=0 when used as working fluid – no new production of CO_2
  - Does not contribute to smog in the cities
- No environmental pollution at production
- Odour-free, not immediate toxic, not flammable (fire - extinguishing)
  - TLV 5.000 ppm (0,5%) – IDLH 50.000 ppm (5%)

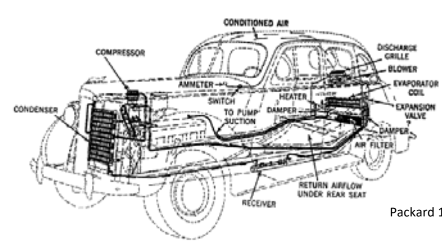
Let's focus on integrated CO_2 systems

- It is possible to outperform current technology with non-natural-working-fluids on:
  - **Energy efficiency**
  - **Total cost of ownership**
  - **Environmental impact**

Focus areas

- Mobile Air Conditioning & heat pump systems
- Hot water heat pumps
- Marine refrigeration systems
- Commercial refrigeration

The start of MAC in 1939



Packard 1939

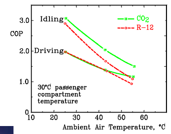
First automotive air conditioning system (CFC-12) developed and implemented by Packard

Mobile Air-Conditioning

The start: 1989-91 in Trondheim

Main issue: Energy efficiency of R744 MAC system

R744 lab. prototype system (left) and BMW 520 CFC-12 system (right)

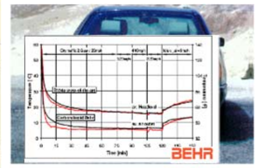


	n, rpm R-12	CO_2	u, m/s
Idling	700	640	1.0
Driving	1740	1600	2.5

20 years ago!

CO_2 MAC in 1998: soon ready…

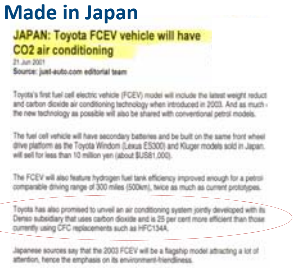
…the greenhouse gas effect of the car AC system **can be cut by a third** when applying carbon dioxide as a refrigerant

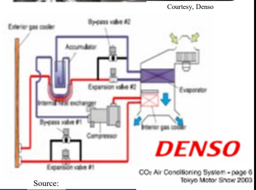


BEHR- Prototype Vehicle with CO_2 – Cycle, Death Valley 1998

Worlds first CO_2 Car AC system

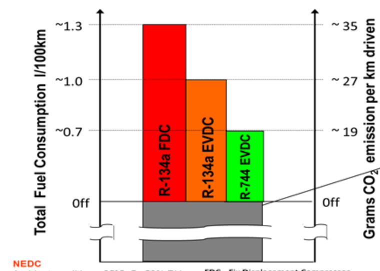
Made in Japan





And even with a heat pump option!

11 years ago: CO_2 MAC: 30% lower fuel consumption



Off line for 2008 average

Fuel consumption due to drag torque, according to 99 / 100 7 EG

Total l/100km: 5,8

CO_2-Emission: 156 g/km

Values without A/C

R-134a with EVDC

+ 0,1l/100km (off mode)

R-744 with EVDC

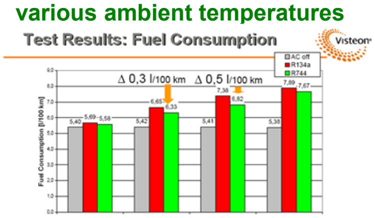
+ 0,05l/100km (off mode)

NEDC
Ambient conditions: 25°C @ 50% RH
no sun load; Mode: fresh air

FDC - Fix Displacement Compressor
EVDC- Externally controlled Variable Displacement Compressor

Cooling Cars with Less Fuel, Paris, October 2006

Fuel consumption of a Toyota Yaris (MY 2006) with different mobile AC systems when driving a NEDC at various ambient temperatures



- Significant, absolut fuel reduction of 0,3 and 0,5 l/100 km at ambient temperature of 25°C and 35°C for R744
- Add on fuel reduction of 25 % at 25°C and 35°C of R744 in comparison to R134a

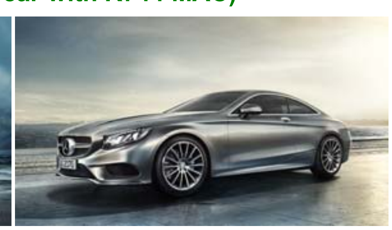
- Engine 3 cylinders, 1,0 l, 51 kW
- Test vehicle with 15.000 km
- TXV system
- Compressor with external control valve (90 cc)

VDA Alternate Refrigerant Winter Meeting 2007, Saalfelden, Austria.

FINALLY

Mercedes-Benz S-Class

Since autumn 2016: Available with CO_2 AC (1st serial production car with R744 MAC)



R744 MAC should became mandatory for new sustainable cars

Marine R744 applications

- ✓ Premium quality fish from R744 equipped vessels
- ✓ Fishing vessels with R744 RSW unit outside Africa

Premium quality fish from R744 equipped vessels

CO_2 (R744) DEEP-FREEZING PLANT FOR *M/S ROALDNES*

Helge Hansen & Yves Ladam

M/T ROALDNES

- Stern trawler
- Length : 33,95 m
- Width : 10,3 m
- Trawling:
  - haddock & pollock
- Capacity:
  - 120 metric tonn

Premium quality fish from R744 equipped vessels

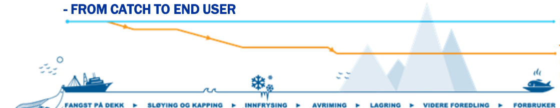
CONVERSION FROM HCFC 22 TO CO_2 (R744)

DEEP-FREEZING WITH CO_2 VS HCFC 22

	R 744 /CO_2	HCFC 22
Metric tonn/day	40	30
Freezing time	140 min	190 min
Defrost	faster	

Faster Freezing = Higher Food Quality

QUALITY
- FROM CATCH TO END USER



No delays on board after catch No reduction in fish quality	No delay prior freezing No reduction in fish quality	25% faster freezing Lower freezer temp. = smaller crystals = better/ premium quality	Faster de-icing No boiling of fish surface Preventing discoloration	Excellent part load performance 50% reduction in energy use	«Refreshed» No reduction in quality Low wastage	Socio-Economically profitable. Ethically correct Better quality than fresh fish. Higher price accepted

Premium quality fish from R744 equipped vessels

SUMMARY R744 (CO_2) IN MARIN APPLICATION

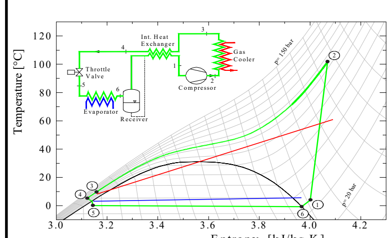
- deep-freezing time is reduced by 25%
- requires less space onboard
  - allows to apply smaller tubes / piping
  - approx. 20% less space for the unit
  - less freezers required for same freezing capacity
- CO_2 plate freezers achieve better food quality
- in general: service & maintenance becomes better and more easy

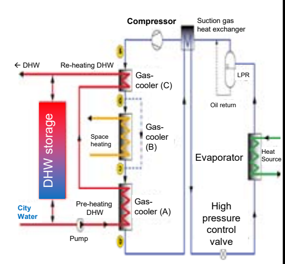
OTHER CO_2 UNITS FOR FISHING BOATS

Refrigerated Sea Water UNIT

One Vessel equipped with
CO_2 – RSW unit
was in operation around the Canarian Islands and is now outside Mauretania !

Water heating heat pumps
a perfect application for CO_2





Water heating heat pumps

#73

Example Japan:

- **First EcoCute* system in the market May 2001**
- **1.700.000 units installed between 2001 and 2008**
- **By the end of March 2016: 5.000.000 units installed**

Large market potential for other regions towards 2020.

*** natural refrigerant heat pump water heater**

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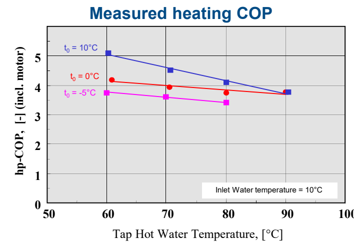
50 kW heat pump water heater
laboratory prototype at SINTEF/NTNU (1995)



Current status: Natural Working Fluids Workshop at IIT Madras, March 2018 NTNU

Chillers applying NR

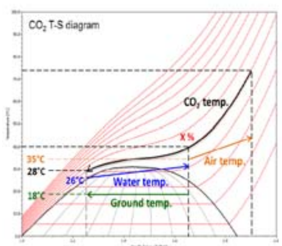
provide comfort AC in building complexes and commercial buildings

#75

Split-Gascooler-Design

Simulation results show:

- COP increased by up to 20% to standard CO_2 chiller.
- Additional 10-20% COP increase expected by applying **ejectors.**



A new PHASE-IN application until 2020!

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Ref.: *Jin, Zhequan; Eikevik, Trygve M.; Nekså, Petter; Hafner, Armin. Investigation on CO_2 hybrid ground-coupled heat pumping system under warm climate. International journal of refrigeration 2015*

Transport refrigeration in India?

#76

- Refrigerated transport of valuable food needs sustainable refrigeration technology to preserve the food and limit the environmental footprint.
  - Fishing vessels (HCFC 22 -> R 744)
  - Road transport (HFC xxx -> R 744)
- Public transport:
  - Train (HFC xxx -> R 744 or air)
  - Cars - MAC (HFC 134a & HFC 123xxxx -> R 744)

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How to make real systems for a successful introduction to India?

#77

- **Ejectors** are widely used in refrigeration systems to pump lubricant inside compressors
- Since a few years many European OEM's are developing R744 ejectors for units with a cooling capacity above 5 kW:
  - Supermarkets require high efficient systems with natural working fluids all across Europe and **abroad**
  - Laboratory and real pilot units are required for development
- More advanced system configuration requires good understanding during the design and implementation phase

Training and technology transfer is important

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next
Commercial refrigeration

+ Market trends from Asia

Current status: Natural Working Fluids Workshop at IIT Madras, March 2018 NTNU

#79

next

Latest technology for high efficiency and the future of supermarket refrigeration for high-ambient climate zones

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Commercial Refrigeration; Supermarkets

In future: supermarket refrigeration system provides entire energy flow and demand in the building (and surrounding)

- ✓ **Air Conditioning** (direct or chilled water)
- ✓ **Heat recovery**: hot water production, space heating, ice protection
- ✓ **Heat pump function** & export of heat

CO_2 (R744) is the preferred alternative of the end-users across Europe for new installations

- ✓ Predictable – no restrictions
- ✓ CO_2 booster units are proven technology with potential to further improve COP (parallel compression + ejector technology)
- ✓ Training and support is key for success

Promising global perspectives for a successful Phase-in

Commercial Refrigeration; Supermarkets

The average annual refrigerant leakage rates:

- in Europe: **15-20 % of the total charge,** mainly HFC-404A
- Worldwide about **30 % of the charge**, mainly HCFC-22

Evolution of R744 Commercial Refrigeration since 2003:

SEER + 10% | SEER + 10-20%

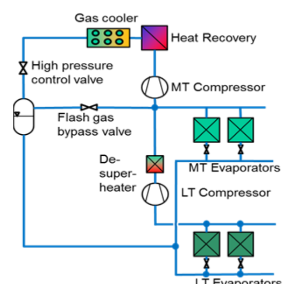
R744 simple Booster → **Parallel Compression (PC)** → **PC with Ejector Support**

SEER: Seasonal Energy Efficiency Rating

CO_2 Commercial refrigeration: Generation 1

Standard CO_2 booster unit

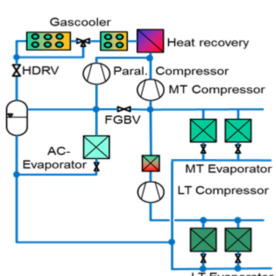
- First unit in 2004/Switzerland (Linde)
- > 6000 units worldwide
- Higher SEER as HFC units in moderate climate regions
- No efficient integration of AC (only MT temperature level



CO_2 Commercial refrigeration: Generation 2

CO_2 Parallel Compression Booster

- First unit in Switzerland 2008 (enex)
- > 500 units worldwide
- Higher SEER as HFC units in most European regions
- Good / Efficient integration of AC possible



#84

Evolution of R744 Commercial Refrigeration

SEER + 10% | SEER + 10-20%

R744 simple Booster (Baseline)

- simple
- many units in the market
- flash gas bypass
- low cost (below HFC in Scandinavia)
- COP / SEER baseline for moderate – cold ambient temp.

Parallel Compression

- advanced system
- higher investment cost
- flash gas (auxiliary) compression

Ejector System

- advanced system
- flooded evaporators: **possible**
- **simple (no pump)**
- **pre-compression**
- **higher load on auxiliary compressors**

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Ejector system ≠ Ejector system

#85

Classic Ejector

- High pressure control with needle in motive nozzle
  - High eff. at design point
- Part load operation challenges
  - Low motive flow rate and
  - Large mixing chamber
- Requires oil return strategy
- Ejector off (low pumping ability) – superheat operation of evaporators
- Discontinues operations

Liquid Ejector only

- Enables flooded evaporators all year
- Applicable for booster and parallel compression system
- Simple on/off control
- Requires low pressure accumulator

Venturi type

- Part load challenges

Ejector supported parallel Compression

- Fixed nozzle ejectors: designed for pumping liquid and pre-compressing vapour (ex: Multi-Ejector block)
- Enables flooded evaporators all year, requires small low pressure accumulator
- Higher load on auxiliary compressors.
- **Pressure lift can be adapted to provide efficient AC**

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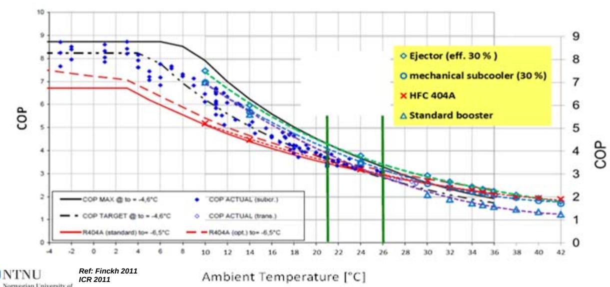
Performance of commercial refrigeration systems

#86



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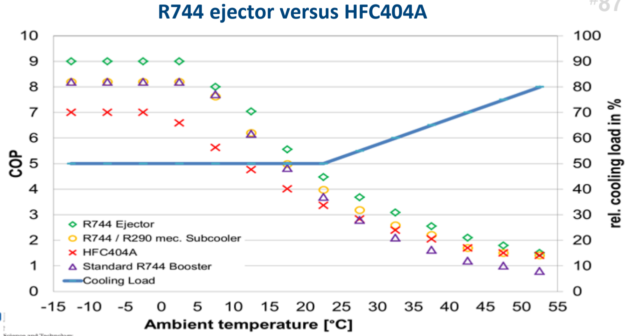
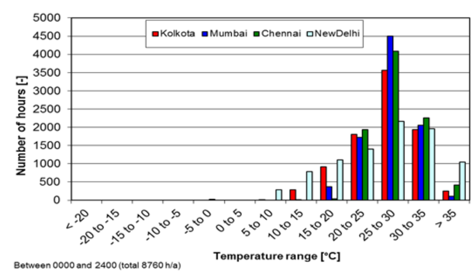
R744 ejector versus HFC404A

#87



Annual temperature bins for selected cities (Example India)

#88



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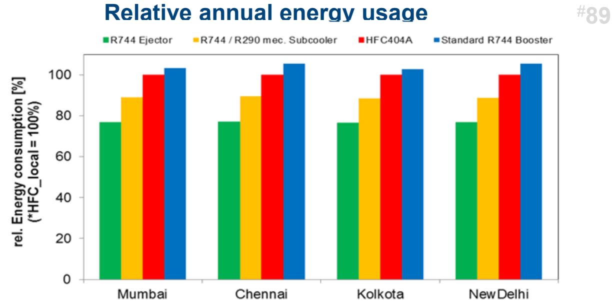
Relative annual energy usage

#89



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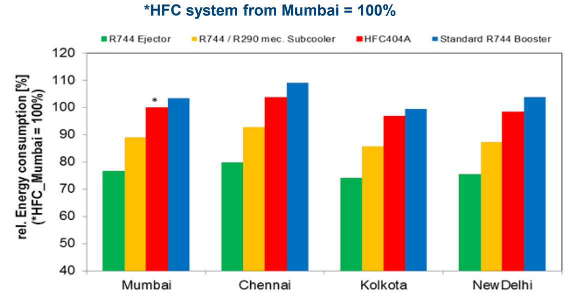
Relative annual energy usage

***HFC system from Mumbai = 100%**

#90



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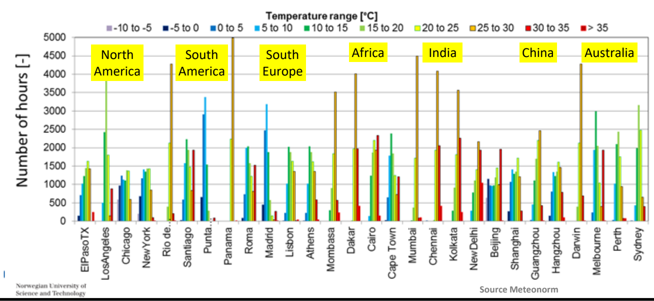
Annual temperature bins for selected cities

#91

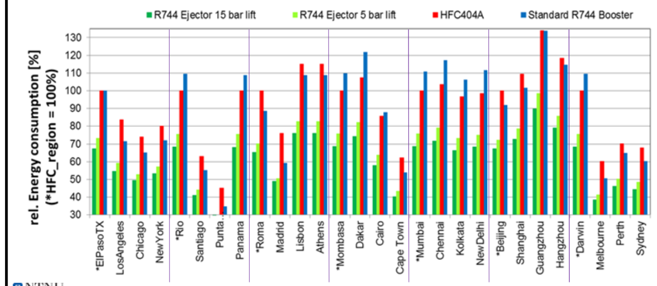


Source Meteonorm

Relative annual energy usage

(exclusive AC part)

#92



Number of transcritical CO_2 supermarkets

First supermarket in a HAT country (Jordan) opened in 2018!

Made by:

High Ambinet Temp Countries

Source: sheccoBase (August 2017)

Example Supermarket

Lawson Convenience Store, Japan

#94

Energy efficiency measures implemented:

- Double-skin façade with insulation function
- Ground source heat pump
- 60 % energy reduction comparing to 2010 consumption levels of Lawson standard convenience stores

Standard Panasonic CO_2 systems are on average 27 % more efficient than the conventional HFC solutions in Lawson convenience stores

21 % energy saving in an Okinawa Lawson supermarket (hot and humid climate), comparing CO_2 and R404A convenience store solutions

Market trends from Asia: Japan

HFC → R744 -27% energy usage

1600 stores with R744 in 2016

Source: http://www.atmo.org/events.details.php?eventid=36

Market trends from Asia : Indonesia

Result and Further Development of the Project

- **Benefit**
  - -Energy saving 20%
  - -Increasing average sales 15%
  - -Ambience store to be more comfort
- **Problem to be solved**
  - -High cost investment

12 stores with R744 in Indonesia!

World Bank should help here!!!

Source: http://www.atmo.org/events.details.php?eventid=36

This is good news for INDIA!!!

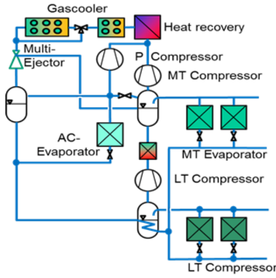
- Energy efficient R744 systems for small shops are available!
- If they operate successfully in Indonesia (below the equator), why not in INDIA?

CO_2 Commercial refrigeration: Europe

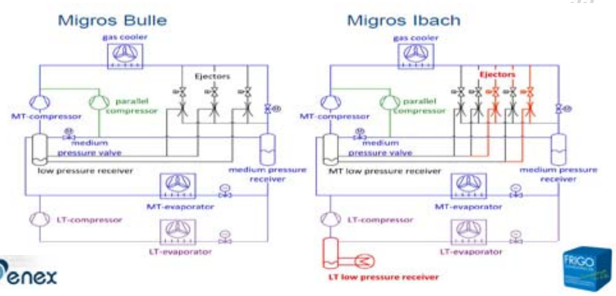
Generation 3

CO_2 Parallel Compression Booster with Ejector Support

- First unit in Switzerland 2014
- < 100 units worldwide
- Higher SEER as HFC units globally
- Simple & efficient integration of AC
- Flooded evaporators all year

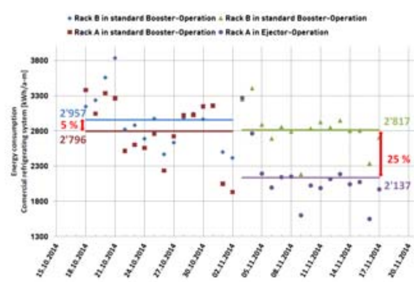


Pioneer R744 Ejector Installations



Ref: Eric Wiedenmann, ATMOsphereEurope 2015

Pioneer R744 Ejector Installations



R744-PC with and without Ejector

Field test results from Ibach / CH

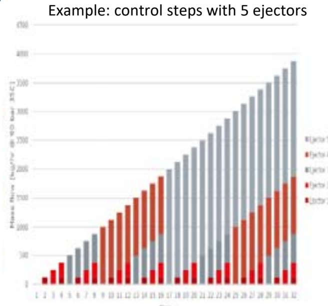
2 identical R744 Racks

Ref: Eric Wiedenmann, ATMOsphereEurope 2015

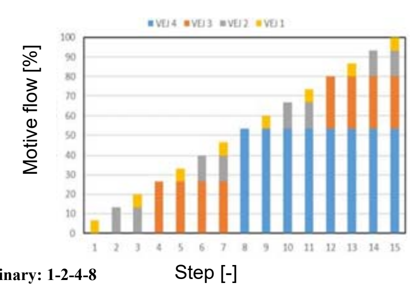
Example: Multi-ejector module

- Modular design (ejector cartridges placed into a monoblock casing) developed by Danfoss in cooperation with SINTEF/NTNU
- Up to six fixed-geometry ejectors → high flexibility to control the high side pressure

Example: control steps with 5 ejectors



Example: Control of Flow (4 mulit-ejectors)

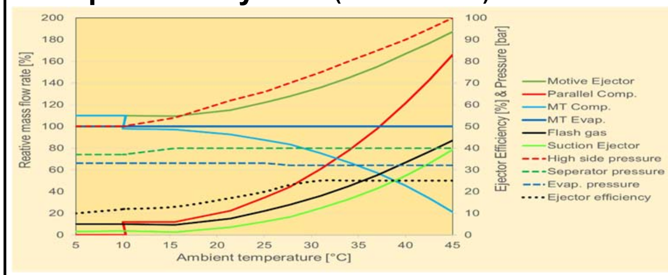


binary: 1-2-4-8

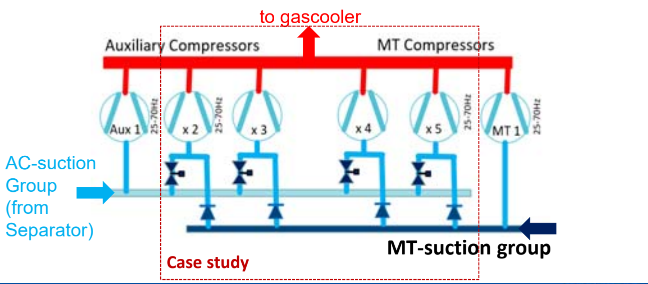
Current target developments

- Evaporative condensers
  - → very energy efficient when applicable / doable (dry climates)
- Reduce number of compressors per ref. rack
  - → Pivoting compressor
- Reliable booster systems for the Nordic market
  - → Winter – mode – solution
- Integrated solutions
  - → All in one solution to replace all H(C)FC applications in a supermarket
  - → Direct heating and cooling inside the shopping area (no water loop)
- Lower cost R744 commercial refrigeration
  - → INDEE - II

Behaviour of ejector supported parallel compression system (Generation 3)



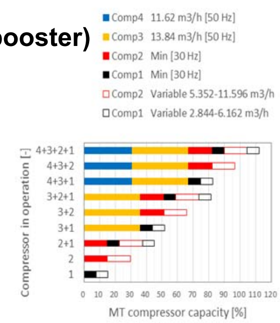
Example: 4 Pivoting Compressors



Example 4 Compressors: single suction unit (simple booster)

Fits very well in Nordic region

- 8-100% capacity range without gap



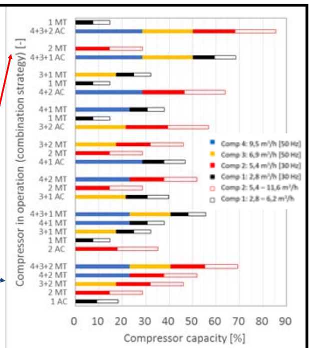
Example 4 Compressors:

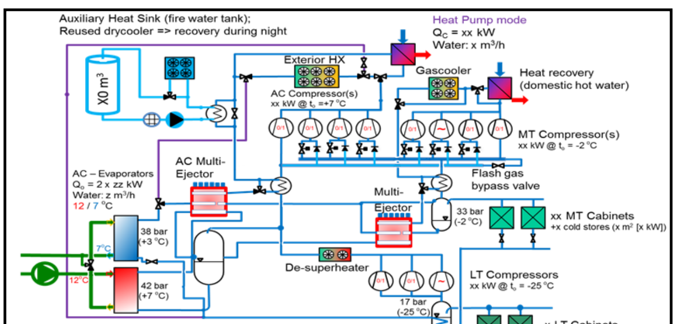
MT and AC suction unit
(parallel compression)

Pivoting principle:

- Four compressors:
  - -> min/max suction flow rate: 2,8 / 34,2
- High summer AC load
- Low load on parallel compressor (spring/fall)

Reduction in investment cost!



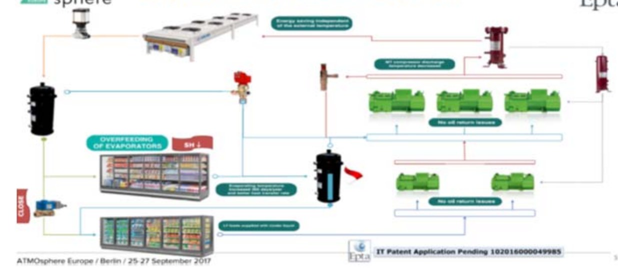


Advanced CO_2 refrigeration Pack

Examples from Europe

Flooded MT Evaporators

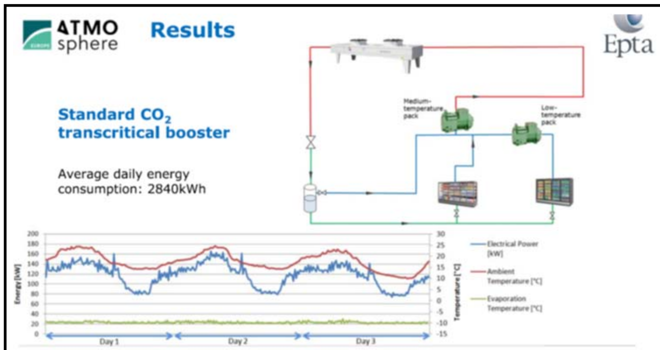
ATMO sphere **CO_2 Transcritical FTE System** Epta



ATMO sphere **Results** Epta

Standard CO_2 transcritical booster

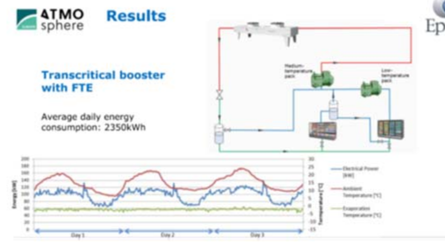
Average daily energy consumption: 2840kWh



ATMO sphere **Results** Epta

Transcritical booster with FTE

Average daily energy consumption: 2350kWh



Remark:
There might be challenges with the oil return form the LT compressors, since the amount of lubricant distributed towards the low pressure side may be higher than what the compressors are capable to return towards the MT compressors.

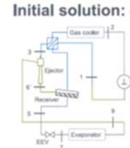
Carrier
United Technologies

FURTHER ENHANCEMENTS IN
THE APPLICATION OF MODULATING EJECTORS
SASCHA HELLMANN

ATMO sphere Business Case for Natural Refrigerants 25-27/09/17 · Berlin

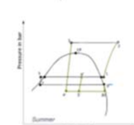
HIGH EFFICIENCY TECHNOLOGIES

Initial solution: ejector system with economizer cycle



First applications of high-efficiency technologies:

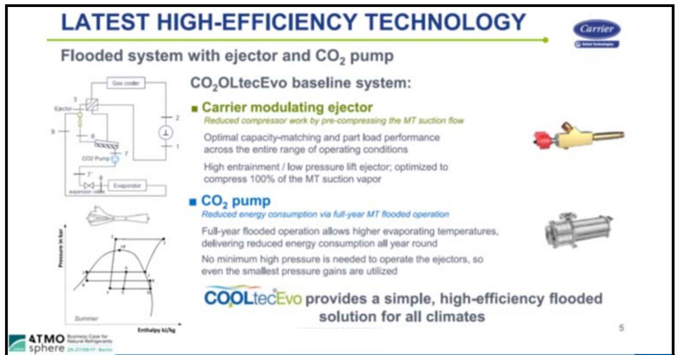
- Baseline standard transcritical CO_2 system
- Economizer cycle (parallel compression)
  Additional compressor to compress flash gas at a higher pressure level
- Carrier modulating ejector
  Pre-compression of 100% of the MT suction flow



Annual rack energy savings up to 20%[1], vs. initial transcritical CO_2

Especially beneficial for warm climates

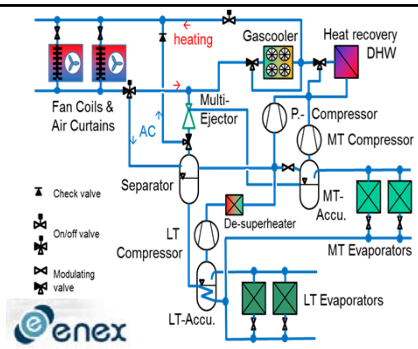
ATMO sphere



CO_2 ref. - Pack

Integration of direct heating and cooling

- Alternative MultiPACK * solution



* www.ntnu.edu/multipack

CO_2 ref. - Pack

Integration of direct heating and cooling

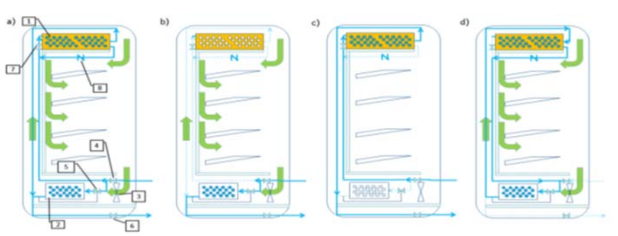
- Alternative MultiPACK * solution

Direct heating and cooling fan coil unit inside a Supermarket (Girotto 2016).

* www.ntnu.edu/multipack

Local cold storage with centralized CO_2 units

a) Charging & normal mode   b) normal mode   c) Charging mode   d) Discharge (thermosiphon)



Further work

- Inform the end-users & exchange information
  - SuperSmart: www.supersmart-supermarket.info
- Further improve the energy efficiency

  Show demonstration projects:

  Europe: MultiPACK: www.ntnu.edu/multipack

  India: *INDEE-II*

  → lower cost R744 commercial refrigeration systems

  → industrial R744 refrigeration and heat pumping technology
- Training & Technology Transfer

Further development

We are looking for a Indian partner to get this pilot compressor ready for the global market.

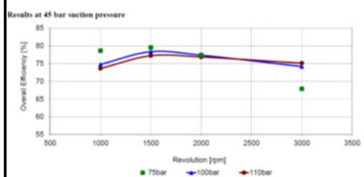
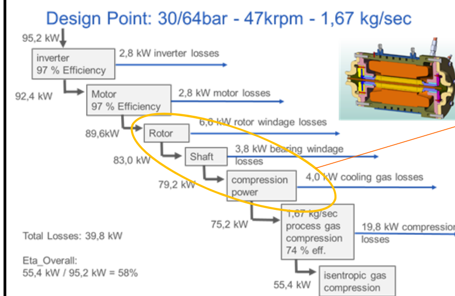


Table 2 Main Compressor data

	Value / Range
Height x Width x Length [mm]	500 x 440 x 830
Weight [kg]	286
Volume flow rate [m^3/h]	18 - 90
Displacement [cm^3]	380
Max power consumption [kW]	100
Revolutions per minute [rpm]	800 – 4 000
Frequency range [Hz]	53 - 267

R744 Turbo: Efficiencies and Loss Mechanism



These three losses (14,4 kW) are responsible for an reduction from 68 % down to 58 % for the isentropic efficiency!

However:
For low temperature applications ($t_{evap.}$ = -50°C) R744 oil free turbo compressors might be a very suitable technology!

Summary (I of III)

- Knowledge transfer regarding the risks of introducing another kind of HFC has to be improved and expanded :

  END USERS must be aware of that applying working fluids which can turn into **substances used as a poison gas** in some wars are not real alternatives

- Remarkable development of R744 / CO_2 since the revival in the late 1980s

Summary (II of III)

- When focus is given to further development of systems to improve the energy efficiency
  - evaporative condensers (where feasible),
  - parallel compression with ejector support,
  - flooded evaporation , etc.

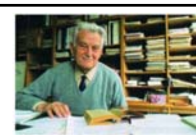
  → successful introduction at reduced total cost of ownership.

- The integration of further functions → key success factor → replacing HCFC and HFC systems globally (leapfrog for NWFs)

Summary (III of III)

- **Governmental purchasing power** should be applied towards cooling technologies that use natural working fluids.
- **World Bank**:
  - should not push for introduction of un-saturated HFCs in various sectors where NWF are applicable. (Foams, AC, etc.)
  - should support implementation / phase-in of NWF by giving **low (no) interest rate loans to end-users** to **cover the additional investment cost** of current high energy efficient NWF units.

23 years ago a wise person said:



Prof. Gustav Lorentzen (1915-1995)

We have heard a great deal lately of the **harmful effects to the environment when halocarbon refrigerants are lost to the atmosphere**. This should **not really** have come as **a surprise** since similar problems have happened over and over again. Numerous cases are on record where **new chemicals**, believed to be a benefit to man, **have turned out to be environmentally unacceptable**, sometimes even in quite small quantities (DDT, PCB, Pb etc.).

In the present situation, when the CFCs and in a little longer perspective the HCFCs are being banned by international agreement, it does not seem very logical to try to replace them by another family of related halocarbons**, the HFCs, equally foreign to nature**.

International Journal of Refrigeration 9. Vol. 18, No. 3, pp 190 197, **1995**

Thank you very much!

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