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Air Conditioning in High Ambient temperatures. Comparisons of Alternative Fluids.

Paul de LARMINAT
PhD, PE, Member ASHRAE
paul.delarminat@jci.com

Anthony WANG
Member ASHRAE

Johnson Controls

Outline/Agenda

- General presentation of fluids for A/C (chillers and D-X).
  - Why blends versus pure fluids ?
  - Fluids in the study.
  - Behavior of blends.
  - “Constant LMTD Analysis” for zeotropic blends.
  - Comparisons of COP and Volumetric capacity.
- Focus on alternatives to R-22 and R-410A
  - Zoom on these alternatives
  - Correction for COP of fluids depending on their capacity in retrofit tests.
- Conclusions.

Acknowledgement

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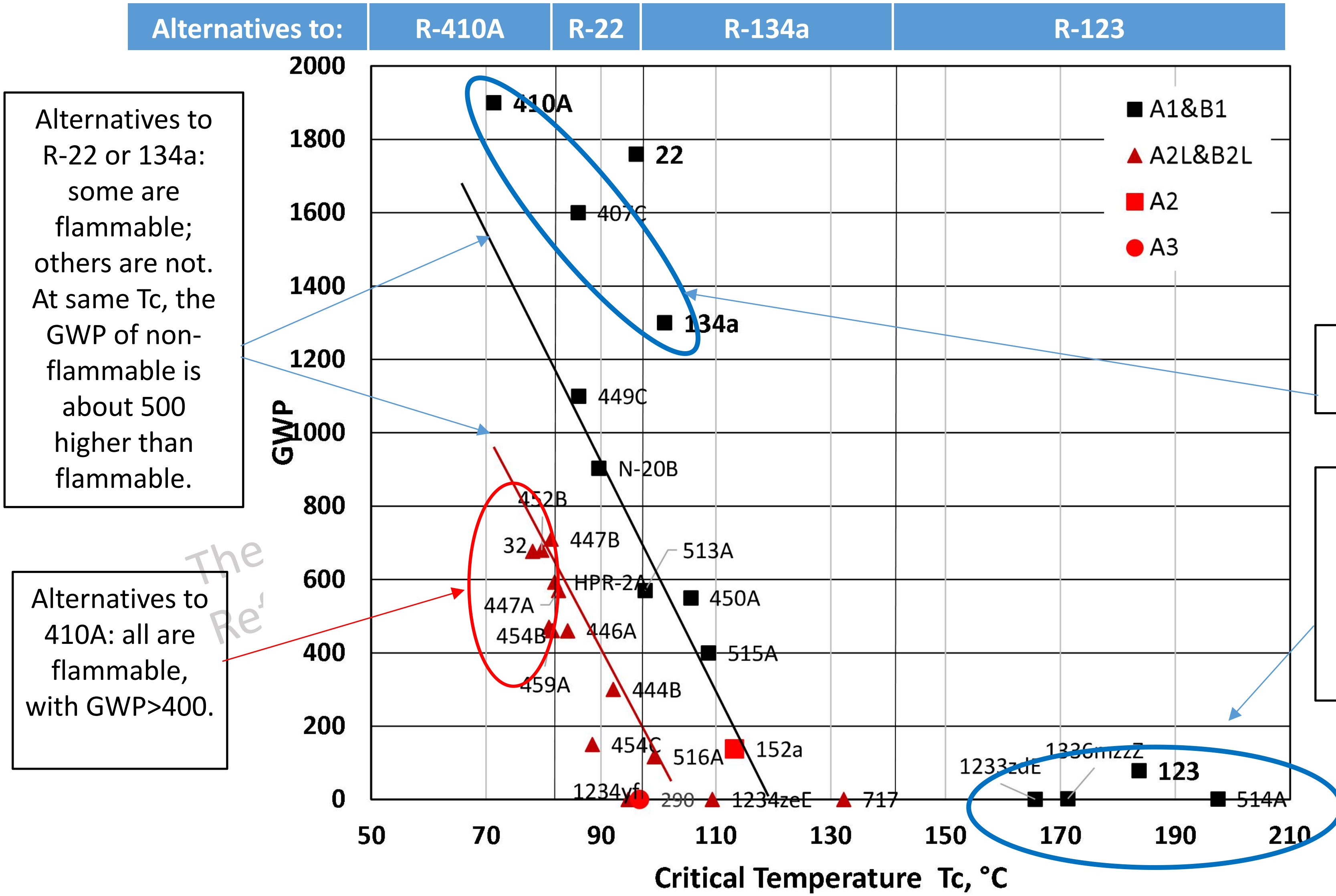
Context and purposes

- Four “benchmark” fluids are currently used in A/C (Chillers and D-X): R-123, R-134a, R-22 and R-410A.
- The phase-out of R-123 and R-22 is completed in “developed countries”, and ongoing in Art-5 countries.
- Lower GWP alternatives to R-134a and R-410A are desired.
- So, alternatives are being investigated for **all** the fluids currently used in A/C.
- One of the proposed alternatives (R-290) is highly flammable; many others alternatives have lower flammability (“2-L” class)
- It is agreed that alternative solutions should not result in lower energy efficiency.
- The quest for alternatives results in a trade-offs between flammability, GWP, energy efficiency and cost.
- **A purpose of this presentation is to shed light of some of these trade-offs.**

An Overview of the Fluids



More details on the fluids

The alternatives to the base line fluids are ranked by Critical Temperature.

Higher Critical Temperature tends to lower pressure and capacity.

Alternatives blends to 410A have moderate glide (I.3 to 4.2 K)

Alternatives blends to R-22 have higher glide (4.5 to 7.7 K)

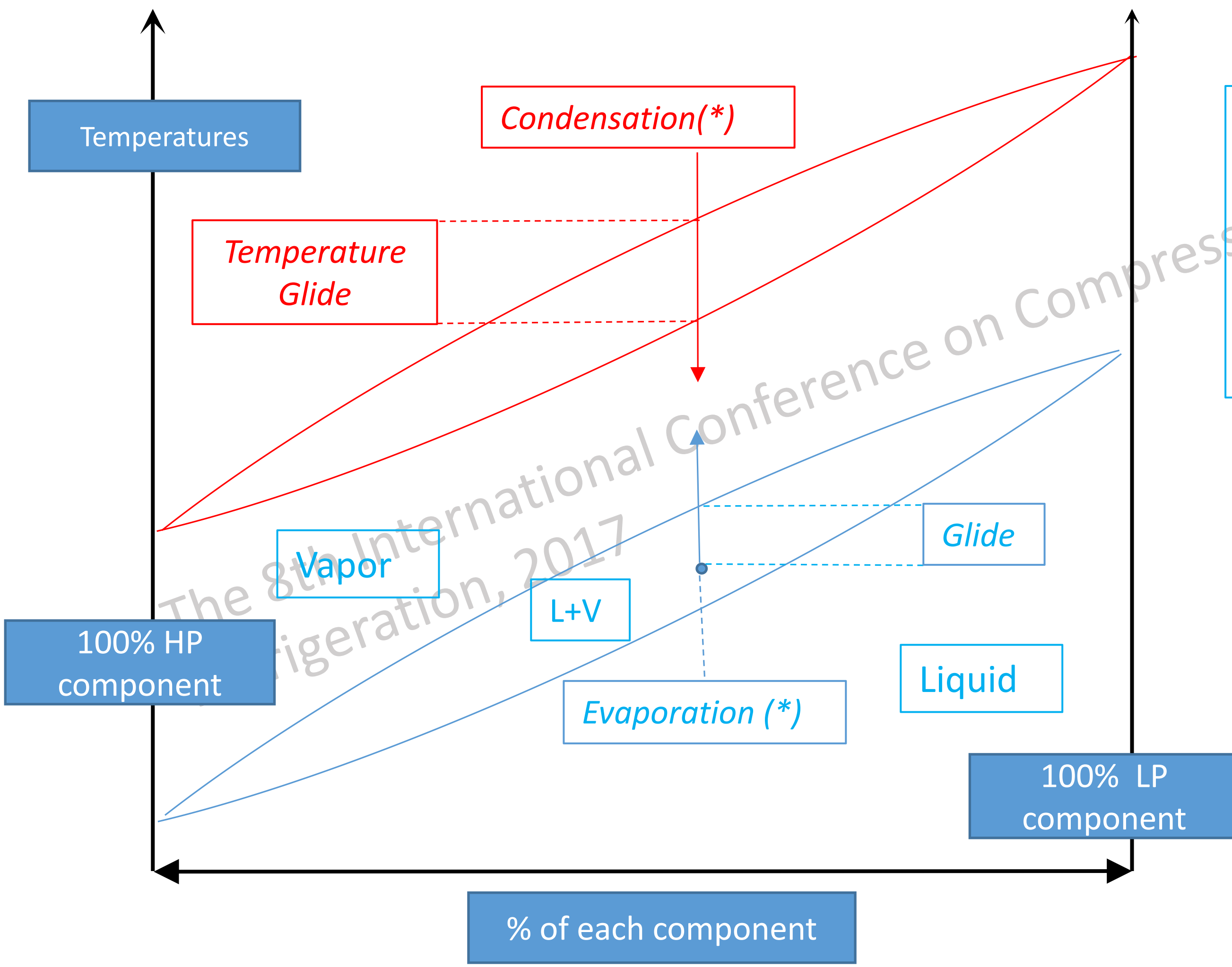
Alternatives to 134a and 123 have little (<0.6 K) or no glide.

Refrigerant	Critical Temperature		Alternative to R-N°:				At 40°C (104°F)		GWP 100	Safety class
							Pressure	Glide		
R-N°	°C	°F	123	134a	22	410A	Bar-a	K	(AR5)	\
125	66.0	151				O	20.1	/	3170	A1
410A	**71.3**	**160**				**O**	**24.2**	**0.1**	**1900**	**A1**
32	78.1	173				√	24.8	/	677	A2L
452B	79.7	175				√	22.6	1.3	680	A2L
454B	80.9	178				√	22.3	1.5	470	A2L
447B	81.3	178				√	21.4	3.9	710	A2L
459A	81.5	179				√	21.9	2.0	*461*	A2L
HPR-2A	81.9	179				√	21.7	3.0	*593*	A2L
447A	82.6	181				√	20.8	3.9	570	A2L
446A	84.2	184				√	20.7	4.2	460	A2L
407C	86.0	187			O		16.4	5.0	1600	A1
449C	86.1	187			√		16.3	4.6	1100	A1
454C	88.5	191			√		15.6	6.3	150	A2L
N-20B	89.6	193			√		14.5	4.5	*904*	A1
444B	92.1	198			√		15.9	7.7	300	A2L
1234yf	94.7	202		√			10.2	/	<1	A2L
22	**96.1**	**205**			**O**		**15.3**	/	**1760**	**A1**
290	96.7	206			√		13.7	/	0	A3
513A	97.7	208		√			10.7	/	570	A1
516A	99.3	211		√			10.5	0.0	131	A2L
134a	**101**	**214**		**O**			**10.2**	**/**	**1300**	**A1**
227ea	102	215		O			7.0	/	3350	A1
450A	106	222		√			8.9	0.6	550	A1
515A	109	228		√			7.6	/	400	A1
1234zeE	109	229		√			7.7	/	<1	A2L
152a	113	236		√			9.1	/	138	A2
717	132	270			√		15.6	/	0	B2L
1233zdE	166	330	√				2.2	/	1	A1
1336mzzZ	171	340	√				1.3	/	2	A1
123	**184**	**363**	**O**				**1.5**	**/**	**79**	**B1**
514A	197	387	√				1.5	/	1.7	B1

Why are blends proposed?

- For each of the base line fluids (R-123, R-134a, R-22, R-410A), the idea is to find alternatives with relatively similar capacity.
- To replace R-22, the only pure compounds with "similar" cooling capacity are Ammonia (R-717) and Propane (R-290).
- Ammonia is toxic, and as of today, it is not suitable for D-X systems (material compatibility and high discharge temperature).
- R-290 is highly flammable.
- No other applicable pure compound has similar cooling capacity.
- Blends to replace R-22 are using a combination of:
  - 2 fluids with higher pressure and capacity:R-125 and R-32.
  - 3 fluids with lower pressure / capacity: R-134a, and the HFO's R-1234ze and yf.
  - Plus occasionally small amount of other fluids: R-152a and R-227ea (close to 134); R-290.

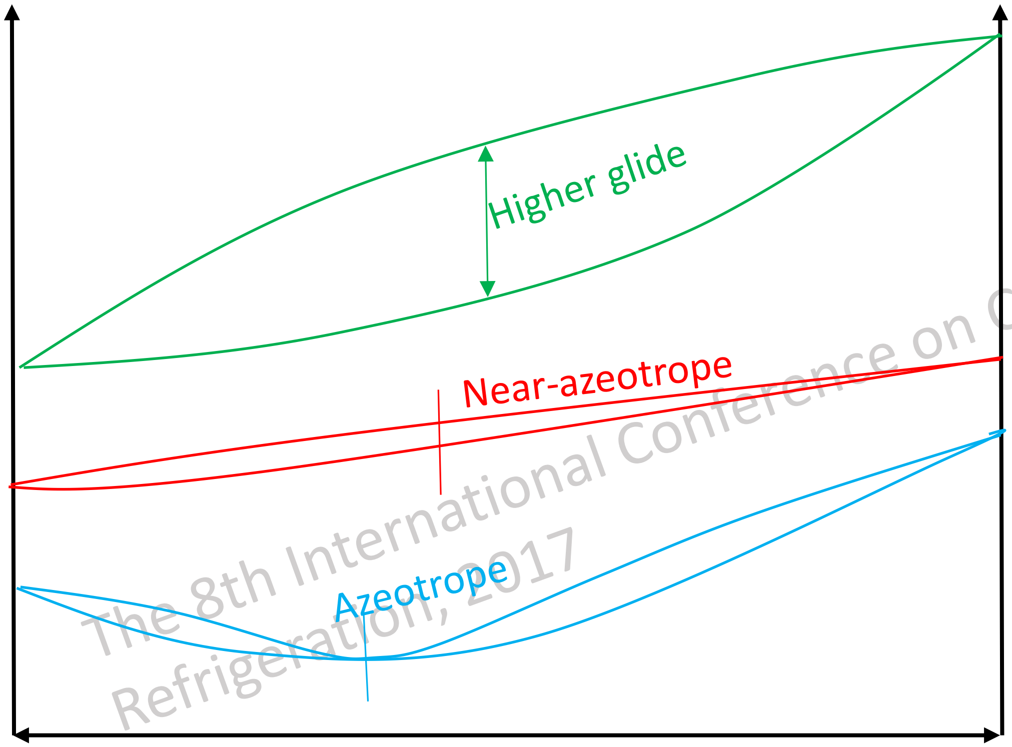
Non-azeotrip, 2 components blend



Each fuse-shape curve is at constant pressure, but both are at 2 different pressure levels, showing condensation or evaporation pressure

(*) Condensation and Evaporation are represented here at constant composition. This happens in case of in-tube phase change.

Different blend behaviors



Alternatives to **R-410A and R-22** are blends of **HP and MP** fluids. Large temperature difference between components at equal pressure gives high glide.

Alternatives to R-134a and R-123 are blends of fluids with relatively similar properties. Such blends have low glide (near azeotropes), or give azeortopes more easily.

Reminder: - A pure fluid or azeotropic blend has no temperature glide.
- A zeotropic (or non-azeotropic) blend has some glide.
- A near-azeotrope (or quasi-azeotrope) has very low glide (e.g. R-410A)

Composition of the blends / Pressures

Ref. fluid	Brand name	ASHRAE R-N°	Compositions by mass						Glide (K) @ 40°C	Safety class	GWP 100 (AR-5)
			R32	R125	134a	1234yf	1234ze	Others			
R-410A		410A	50	50					0.12	A1	1900
	DR-5A	454B	68.9			31.1			1.53	A2L	470
	DR-55	452B	67	7		26			1.34	A2L	680
	L-41-1	446A	68				29	R-290, 3%	4.19	A2L	460
	L-41-2	447A	68	3.5			28.5		3.94	A2L	570
	ARM-71A	459A	68			26	6		2.04	A2L	461
	L41z	447B	68	8			24		3.43	A2L	710
	HPR-2A	/	76		6		18		2.97	A2L	593
R-22	L-20A	444B	41.5				48.5	R-152a, 10%	7.71	A2L	300
	N-20B	/	13	13	31	43			4.54	A1	904
		407C	23	25	52				5.00	A1	1600
	DR-3	454C	21.5			78.5			6.29	A2L	150
	DR-93	449C	20	20	29	31			4.62	A1	1100
R-134a	XP10	513A			44	56			0.00	A1	570
	N-13	450A			42		58		0.63	A1	550
	HDR115	515A					88	R-227ea, 12%	0.00	A1	400
	ARM-42	516A			8.5	77.5		R-152a, 14%	0.01	A2L	131
R-123	DR-10	514A	1336mzz, 74.7% ; R-1130E, 25.3%						0.00	B1	1.7

Pressure color code:	High	Medium-High	2	3
Alternative to:	R-410A	R-22	R-134a	R-123

Alternatives to **R-410A and R-22** are blends of **HP and MP** fluids.

Alternatives to **410A** have more HP components and less MP than alternatives to R-22.

Alternatives to **134a** are blends of **only MP** fluids (134a, HFO's 1234yf or ze, 227ea; 152a).

Alternative blend to **R-123** is a blend of LP fluids.

Composition of the blends / Flammability

All the alternatives to 410A are flammable.

Some alternatives to R-22 or 134a are flammable. Some others are not.

None of the alternatives to R-123 is flammable.

Ref. fluid	Brand name	ASHRAE R-N°	Compositions by mass						Glide (K) @ 40°C	Safety class	GWP 100 (AR-5)
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R-123	DR-10	514A	1336mzz, 74.7% ; R-1130E, 25.3%						0.00	B1	1.7

Flammability color code:	1	2L	2	3

Higher content of flammable components → higher flammability of the blend.

Composition of the blends / Flammability

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Some alternatives to R-22 or 134a are flammable. Some others are not.

None of the alternatives to R-123 is flammable.

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R-123	DR-10	514A	1336mzz, 74.7% ; R-1130E, 25.3%						0.00	B1	1.7

Flammability color code:	1	2L	2	3

Higher content of flammable components → higher flammability of the blend. Illustrated above in red « box ».

Methodology for performance comparisons

- Choose a « base line » unit: the mini-split 410A unit tested under AREP / ORNL programs.
- Start from detailed test results at AHRI-A: capacity, evaporation & condensation, liquid subcooling etc.
- Simulate the same unit with different fluids at same capacity and conditions, assuming same air side conditions (air flow and temperatures in/out), heat transfer and constant compressor efficiency (80%).
- In the case of blend with glide, do it with both exchangers being simultaneously counter-flow (« Cf-Cf ») or parallel flow (« Pf-Pf »).
- To simulate the blends, use the “Constant LMTD” method.

The "Constant LMTD" Method (1)

- Basic formula:
  - Q = thermal power (evaporator or condenser):

    Q = K x S x LMTD with:
  - S = heat transfer area
  - K = overall heat transfer coefficient
  - LMTD = Mean Logarithmic Temperature Difference.
- **Assume:**
  - Constant capacity Q
  - Same heat transfer area
  - Same heat transfer coefficients
- Then, **LMTD must be the same**, irrespective of:
  - The fluid (even if blend with glide)
  - The arrangement of the exchangers (Counter or Parallel flow).

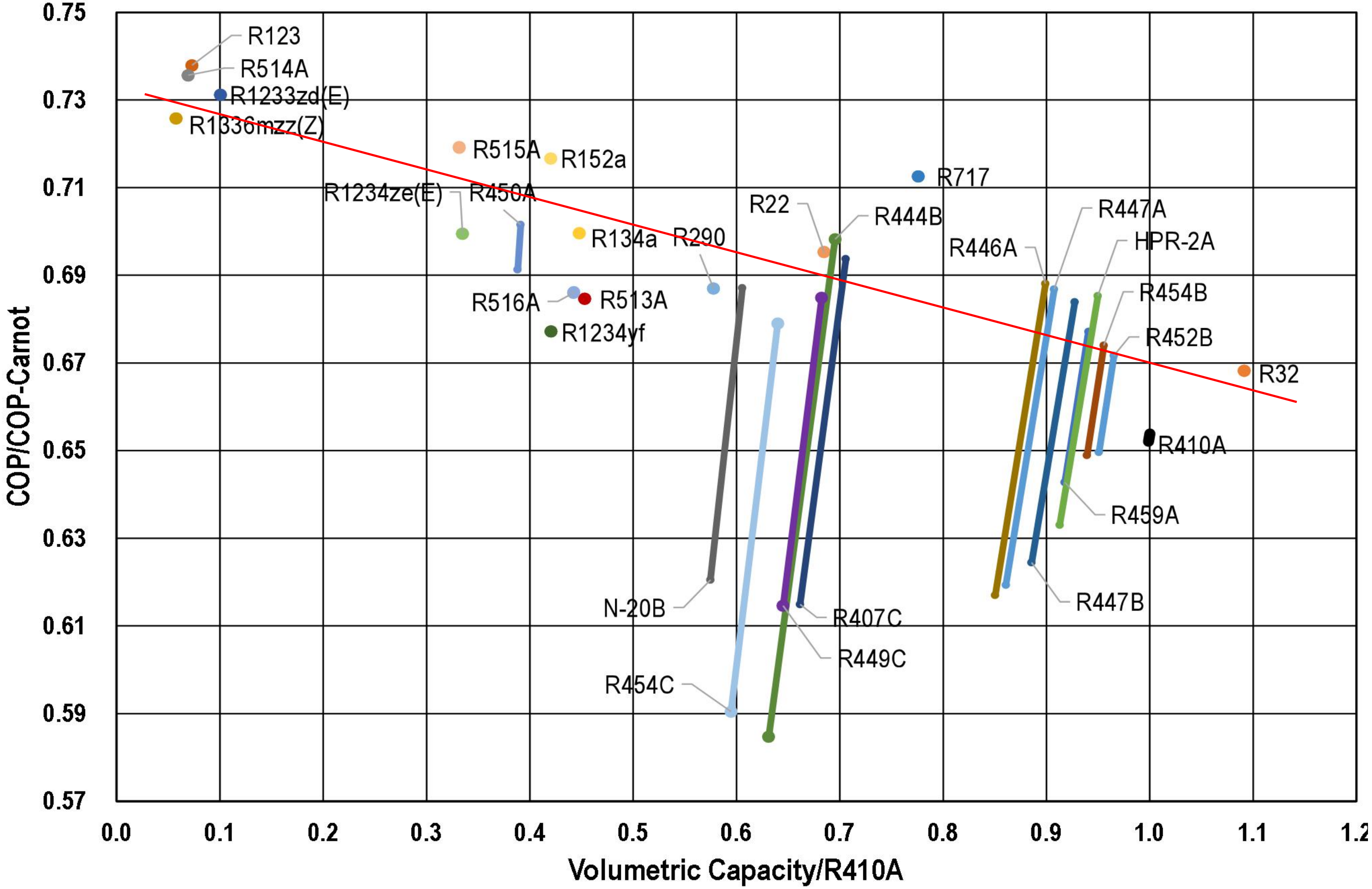
The “Constant LMTD” Method (2)

- For the « base line » unit, calculate the LMTD of each exchanger from R-410A test data:
  - Evaporation and condensation temperatures,
  - Air temperatures in/out of evaporator / condenser
- To identify the evaporation pressure with a blend:
  - Assume a temperature for beginning of evaporation.
  - From the glide, calculate the temperature at end of evaporation.
  - Combining with the air temperatures in a given configuration (parallel or counter-flow), calculate the corresponding LMTD.
  - Iterate until this LMTD = LMTD with 410A
- Do the same for the condenser.
- Proceed with cycle calculation using these data

The "Constant LMTD" Method (3)

- For various fluids, graph shows COP versus volumetric capacity.
- A « Pure » fluid is represented by a single point.
- A zoetropic blend is represented by a segment between the « Cf-Cf » and « Pf-Pf ».

Performance comparisons results



Comments on results (@ AHRI-A)

- In general, fluids with lower Tc / higher pressure have higher capacity but lower COP. General trend, with some variations. Trade-off between Capacity and COP.
- In the optimum configuration, blends with glide can have slightly better COP at equivalent capacity. But the performance can also be much lower in the arrangement of heat exchangers is not optimum.
- Zeotropic blends are generally not recommended for heat exchanger with shell and tube exchangers and out-of-tube evaporation or condensation (e.g. flooded evaporators).
- Real designs should be close to optimum, but optimization is not necessarily simple. Example: most current designs of small split A/C units have cross flow evaporator.

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The context

- A/C in HAT will be critical for successful implementation of the Kigali agreement.
- Several research programs are ongoing: AREP, DOE (ORNL), PRAHA, EGIPRA.
- Wealth of data available, but :
    - Detailed results from PRAHA and EGYPRA are confidential.
    - Details from AREP and ORNL are public. But they are results from retrofits. So, alternatives to R-410A and to R-22 are analyzed in 2 separate « boxes », without cross comparison.
    - Units tested are not the same for R-22 and R-410A: Differences in capacity, size of exchangers, compressors etc.
    - Many of the alternatives are blends with glide, which are complex to model by cycle calculations.

Fluids in the study

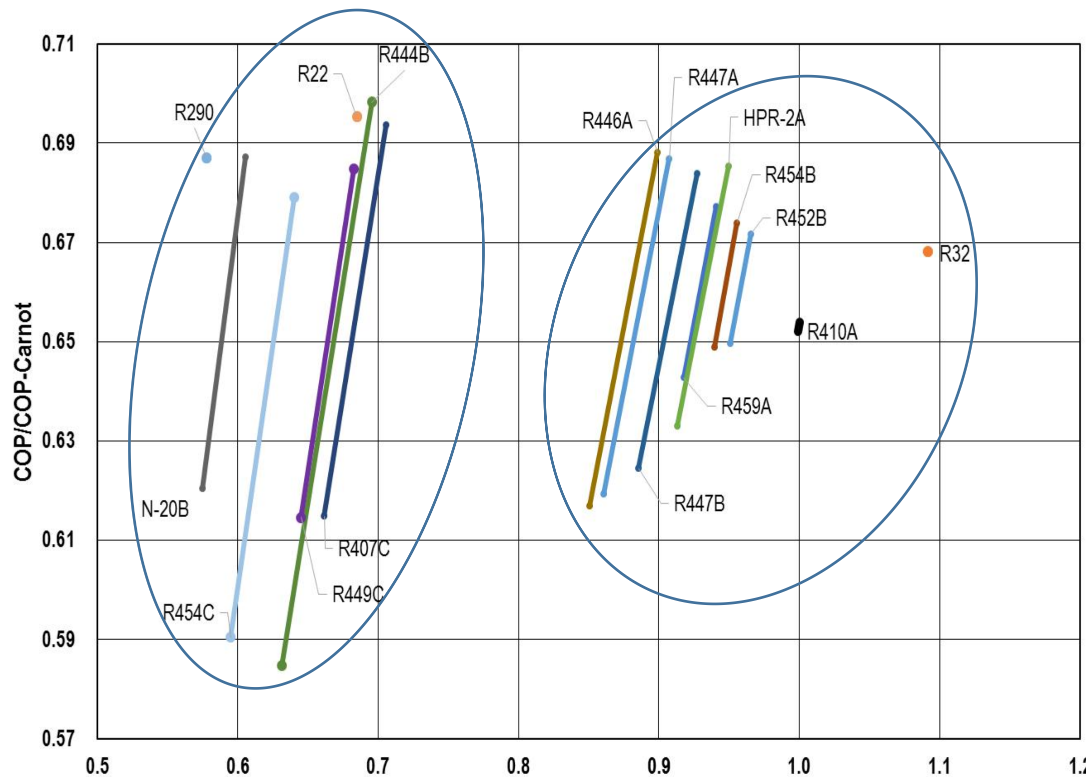
Now restricted to fluids proposed as replacements to R-22 and 410A for A/C D-X systems in the AREP program.

Alternatives to R-410A			
Fluid R-N°	Brand Name	Glide @ 40°C	
		K	°Ra
32	/	/	/
452B	DR-55	1.3	2.4
454B	DR-5A	1.5	2.8
447B	L41z	3.4	6.2
459A	ARM-71A	2.0	3.7
/	HPR-2A	3.0	5.3
447A	L-41-2	3.0	5.3
446A	L-41-1	4.2	7.5

Alternatives to R-22			
Fluid R-N°	Brand Name	Glide @ 40°C	
		K	°Ra
407C	/	5.0	9.0
449C	DR-93	4.6	8.3
454C	DR-3	6.3	11.3
/	N-20B	4.5	8.2
444B	L-20A	7.7	13.9
290	/	/	/

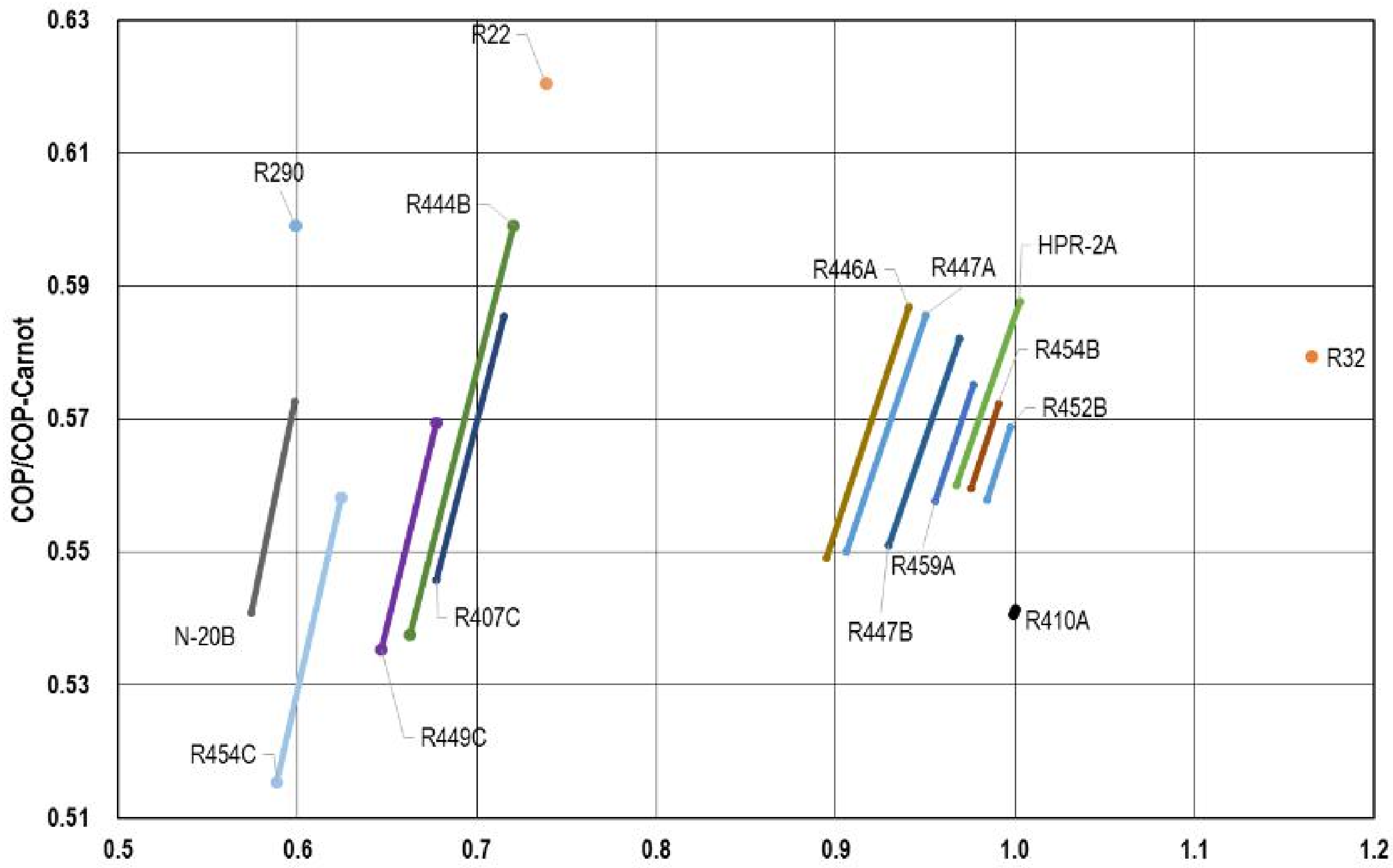
Comments on results (AHRI-A / 35°C)

- In the best configuration (“Cf-Cf”), blends can have same or slightly better COP than “pure” fluids.
- But can be much lower if system is not optimized.
- Real designs should be close to optimum, but optimization is not necessarily simple. Example: most current designs have cross flow evaporator.
- Except R-32, all the alternatives to 410A have lower capacity than 410A. All have a better COP.



- Alternatives to R-22 have equivalent or lower capacity than R-22. None of them matches the COP of R-22.
- Even R-290 has a lower calculated COP than R-22. Paradox to be commented later.

Results at High Ambient Temperature (52°C)



Assumes: Design for same capacity and same indoor conditions as @ AHRI-A

Correction for cooling capacity (1)

- In test data as published (AREP & ORNL reports), capacity and COP are shown "as measured".
- But in retrofits, a lower capacity results in lower temperature differences at the exchangers.
- At the condenser, there is a double effect: at constant ambient temperature:
  - The "SD" is smaller.
  - The leaving air temperature is lower.
- This "artificially" improves the COP.
- Vice-versa, a higher capacity penalizes the COP.
- For "apple to apple" comparisons between fluids, this effect can be corrected.

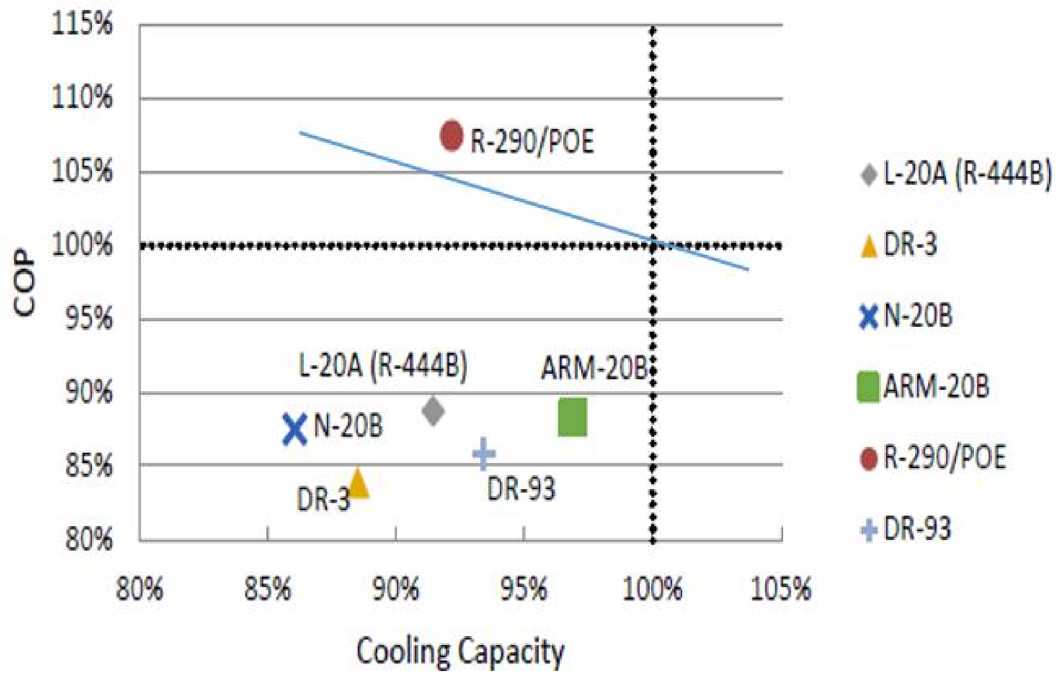
Correction for cooling capacity (2)

- To account for the differences in cooling capacity, start from measured data with a reference fluid (e.g. R-22).
- With a different fluid (e.g. R-290) with lower capacity, evaluate what the evaporation and condensation would be for this R-22 unit at the (lower) capacity of R-290:
  - Correct the leaving air temperature at the condenser (Delta-T proportional to capacity)
  - Correct the LMTD's at evaporator and condenser (proportional to capacity) for the lower capacity.
  - Calculate the Carnot efficiencies at full and reduced capacity: $COP_{Carnot} = Te / (Tc - Te)$
  - Assume the ratio [COP / COP_{Carnot}] is the same at full and reduced capacity.

  → **Calculate the corrected COP at reduced capacity**

Correction for cooling capacity (3)

- Superimposed on results from AREP #62 report.
- The blue line represents what the COP would be with R-22 at variable cooling capacity.
- The blend alternatives to R-22 are even lower than before correction, because their capacity is lower.
- R-290 has slightly better COP than R-22, but not as much as it appears without correction.
- From cycle calculations, R-290 had slightly lower COP than R-22.



Performance Relative to Baseline (R-22) at AHRI A Conditions

- The difference between measured R-290 and corrected R-22 is within measurement uncertainties, but may also come from factors not taken in the model: differences in heat transfer, pressure drops, compressor efficiency etc…

Conclusions

- This study provided methods to:
  - Analyze the cycle efficiency of blends, accounting for variations in system configuration.
  - Cross-compare alternatives to R-22 and R-410A.
  - Correct the measured COP of various fluids according to their cooling capacity.
- Comparisons show (or confirm) that:
  - Blends are highly sensitive to system configuration.
  - Alternatives to R-410A do not match the COP of R-22.
  - R-290 has COP similar to or slightly better than R-22, but not so much better as from uncorrected measured data.

But Caution !

- This is cycle calculation. A model cannot take everything into account.
- Legitimate questions can be raised about some assumptions. Must be kept in mind when looking at the results:
  - Constant in-tube heat transfer coefficients.
  - Extreme" heat exchangers arrangements.
  - Constant compressor efficiency.
  - In HAT, same indoor conditions as AHRI.
- This contribution to analysis cannot replace further testing and optimization with various fluids, taking cost into account.

Bibliography

- Paul de Larminat & Wang Linzhong. 2017. *A/C in High Ambient Temperatures. Comparisons of Alternative Fluids.* Presented at the Second International Conference on Energy and Indoor Environment for Hot Climates, Doha, Qatar, February 26-27, 2017.
- Omar Abdelaziz & Som Shrestha: AHRI-AREP test report # 62 "Soft-Optimized System Test of Alternative Lower GWP Refrigerants in 1.5-ton Mini-Split Air Conditioning Units" / Oak Ridge TN 37831-283 / January 18, 2016.
- Omar Abdelaziz & Al: ORNL test report "Alternative Refrigerant Evaluation for High-Ambient Temperature Environments: R-22 and R-410A Alternatives for Mini-Split Air Conditioners" ORNL/TM-2015/536 / Oct 2015.
- de Larminat, P & Wang, L: "Overview of A2L Fluids for A/C Applications, Chillers and D-X". ASHRAE Journal, Feb. 2017.
- de Larminat, P & Wang, LA: "Performance Analysis of Blends for D-X A/C Applications ». ASHRAE Journal, June 2017.

QUESTIONS?

Paul.delarminat@jci.com