Novel Reduced GWP Refrigerants for Stationary Air Conditioning

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Outline

- Alternatives for Stationary Air Conditioning
  - HFC, HFOs
- Flammability and Refrigerants
  - Options, non Flammable Candidate
- Performance Comparisons – Hot Climates
- Summary

Overview: Air Conditioning Fluid Changes

- CFC — High ODP, Very High GWP
  - R-12
- HCFC — Lower ODP, High GWP
  - R-22
- HFC — No ODP, High GWP
  - R-410A
  - R-407C
  - R-438A
- HFO, CO2 , HC, HFC, NH3, — No ODP, Lower GWP

What are the next best options for AC?

Lowest net carbon footprint

Refrigerant Property Considerations:

- **Environmentally Sustainable** — **Low GWP, Good LCCP**
- **Safe to Manufacture and Use** — **Low Toxicity, Manageable Flammability**
- **High Energy Efficiency / COP** — **Minimize Carbon Impact, Minimize the Cost to Use**
- **Compatible with Existing Lubricants, Compressor and System Materials of Construction**
- **Matching Capacity** — **Match current designs, – minimize equipment physical footprint**

Refrigerant Blends

- **HFO-1234yf can be a replacement for R-134a**
- **It is not a replacement for R-22**
- **By Blending HFO-1234yf with other refrigerants, different properties can be achieved, even approaching R-22 and R-410A performance**
- **However, there are trade-offs**

Leading Reduced GWP Candidates for Air Conditioning

Current AC Refrigerant	GWP AR-5	Lower GWP Candidates* – HFO Based			
		Non Flammable		Mildly Flammable	
		ASHRAE Class 1		ASHRAE Class 2L	
		Name	GWP	Name	GWP
HFC-134a	1300	R-513A	< 580	HFO-1234yf	< 1
HCFC-22	1760	DR-91*	< 880	DR-3*	<150
HFC-410A	1924			DR-5A*	460

* Candidates being evaluated and optimized with input from AC OEMs

Reduced GWP Candidates to Replace R-22 and R-410A

- **DR-91** Nonflammable GWP < 880
  - 48 % lower GWP of R-22. Also non ozone depleting
  - For R-22 type system where nonflammability is required

- **DR-3** 2L Mild Flammability GWP < 150
  - 91% lower GWP than R-22
  - Suitable where not limited by charge size restrictions in codes and standards
  - Useful where regulations restrict GWP to 150, but more capacity needed

- **DR-5A** 2L Mild Flammability GWP ~460
  - 75 % lower GWP than R-22 or 410A
  - For R-410A type systems, where mild flammability can be tolerated and higher capacity is desired.

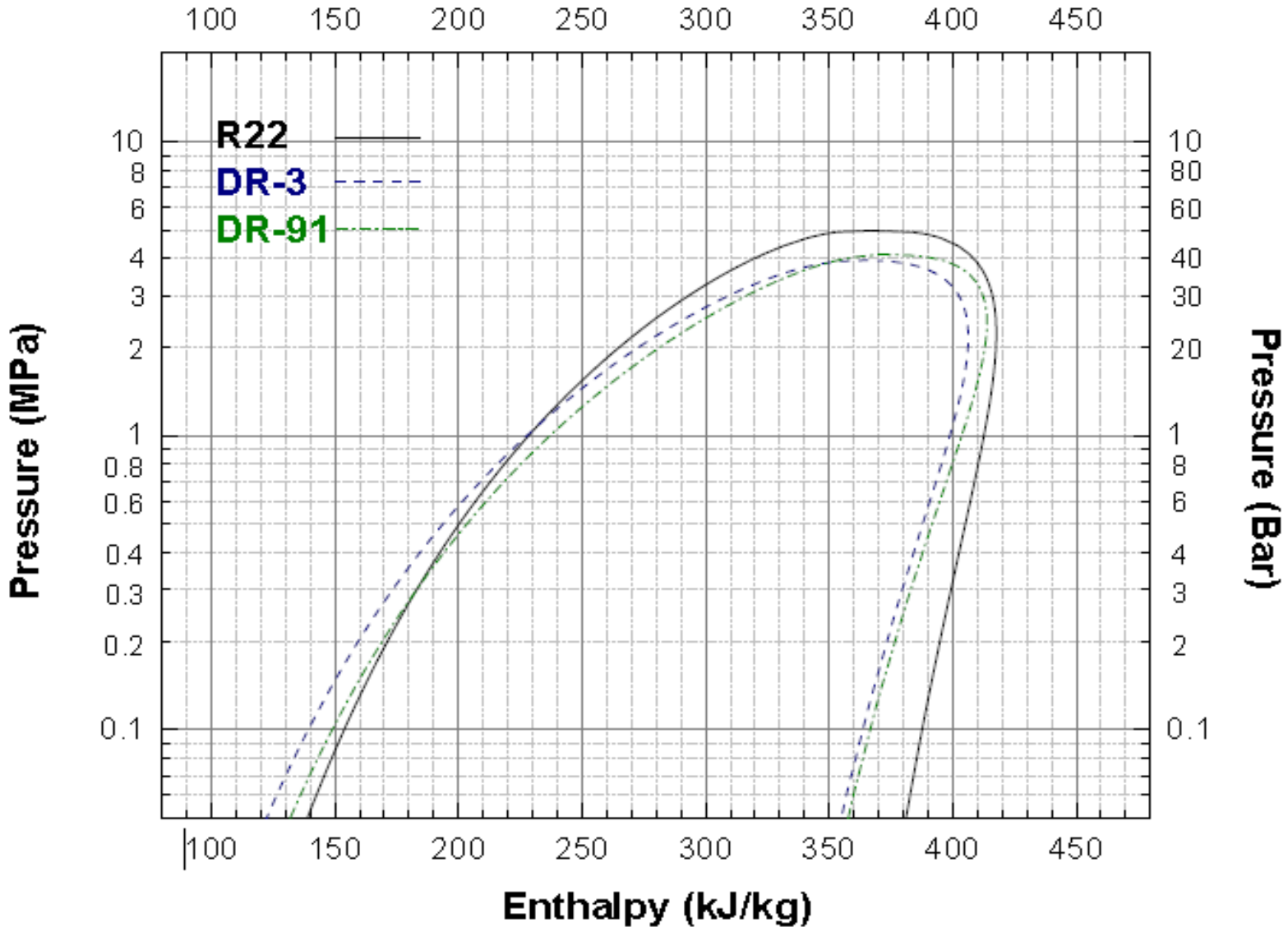
AC Candidate Cycle Comparison vs R-22*

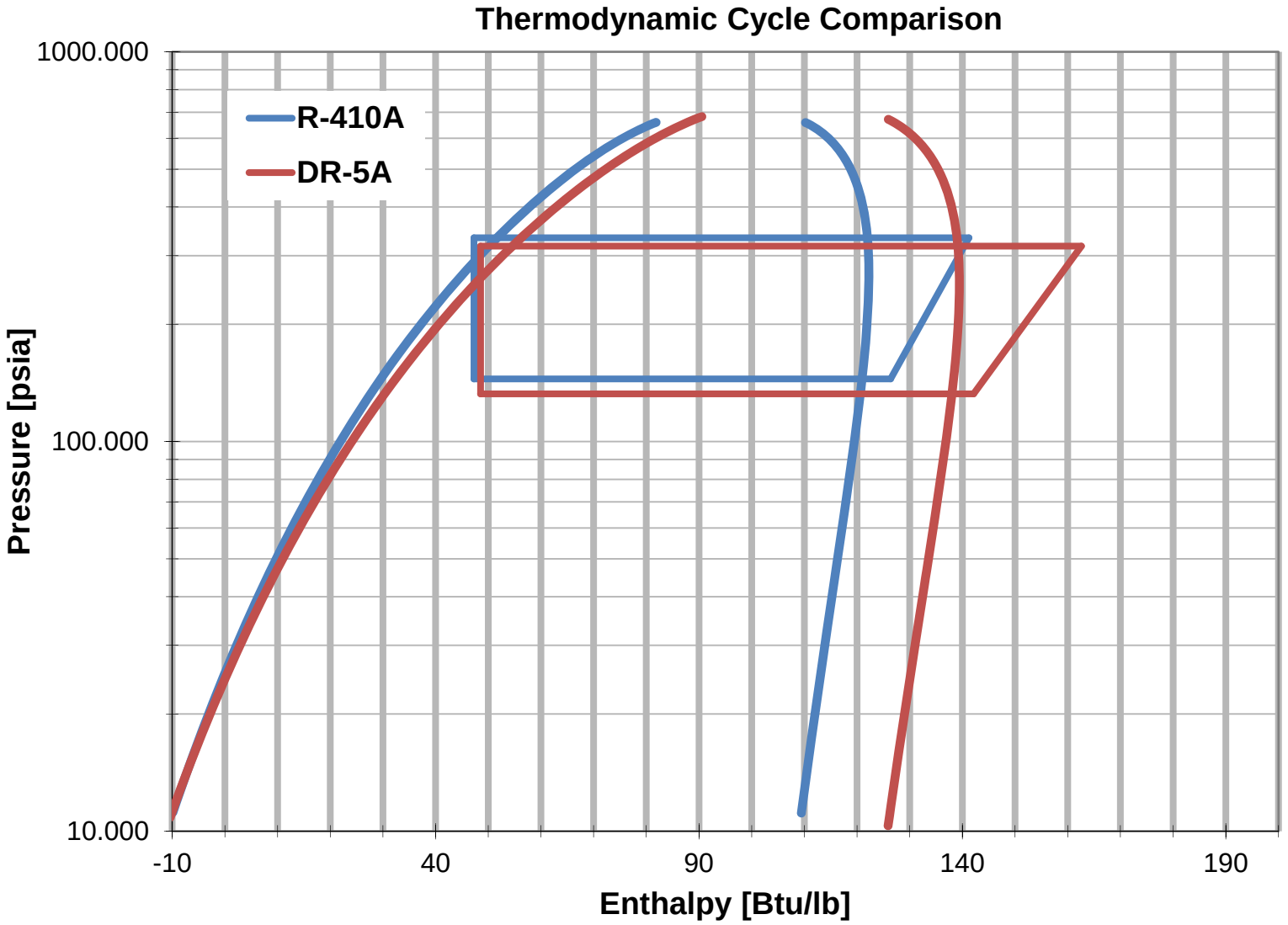
	R-22	R-410A	R-407C	R438A	DR-3	DR-91
GWP AR4	1802	2088	1754	2265	148	940
ASHRAE Class	1	1	1	1	2L**	1**
Capacity vs. R-22	0	+ 45 %	+1.7	-8 %	-4.5 %	-14 %
COP vs. R-22	0	-6 %	-2 %	-3 %	-2 %	-0.6 %
Glide K (°C)	0	<0 .2	4.8	5.8	7	4.7
T Discharge °C	83	81	75	68	69	67
T Critical °C	96.1	71.3	86	85	82.5	86

*Thermodynamic Cycle Model results for T cond = 47 C, T evap = 7 C, Subcool = 12 K, Superheat = 3 C, Compressor efficiency = 70 %. Please recall that heat transfer effects are not included. In cycle calculations.

**Expected ASHRAE Rating

PH Pressure Enthalpy Comparison R-22 and Alternatives




Thermodynamic Cycle Comparison
1000.000
100.000
10.000
Pressure [psia]
R-410A
DR-5A
-10
40
90
140
190
Enthalpy [Btu/lb]

Low GWP AC Candidate Cycle Comparison vs R-410A*

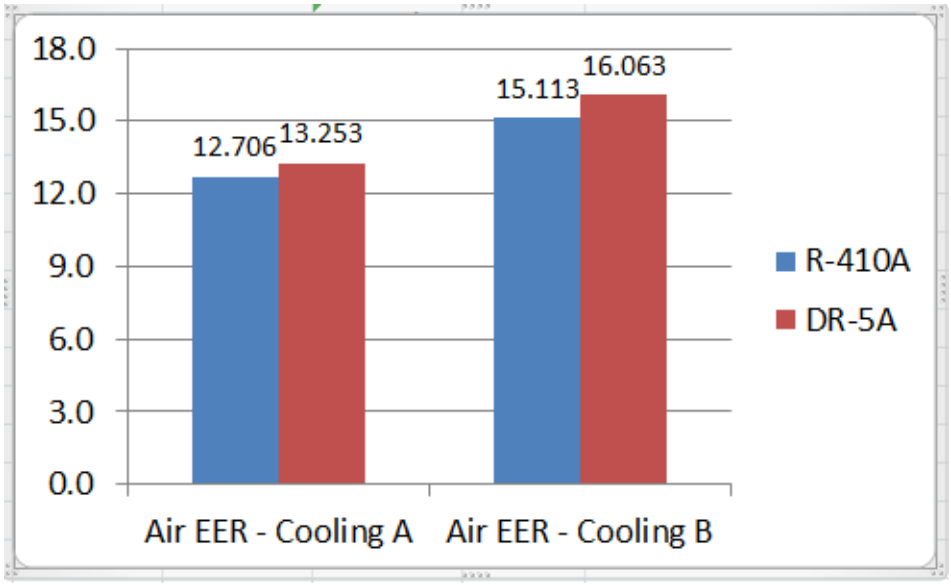
	R-410A	DR-5A
GWP AR4	2088	460
ASHRAE Class	1	2L**
Capacity vs. R-410A	--	-10 %
COP vs. R-410A	--	+1.9 %
Glide °K	0.14	1.5
T Discharge °C	81	93.2
T Critical °C	71.3	77

*Thermodynamic Cycle Model results for T cond = 47 C, T evap = 7 C, Subcool = 12 K, Superheat = 3 C, Compressor efficiency = 70 %. Please recall that heat transfer effects are not included in cycle models.

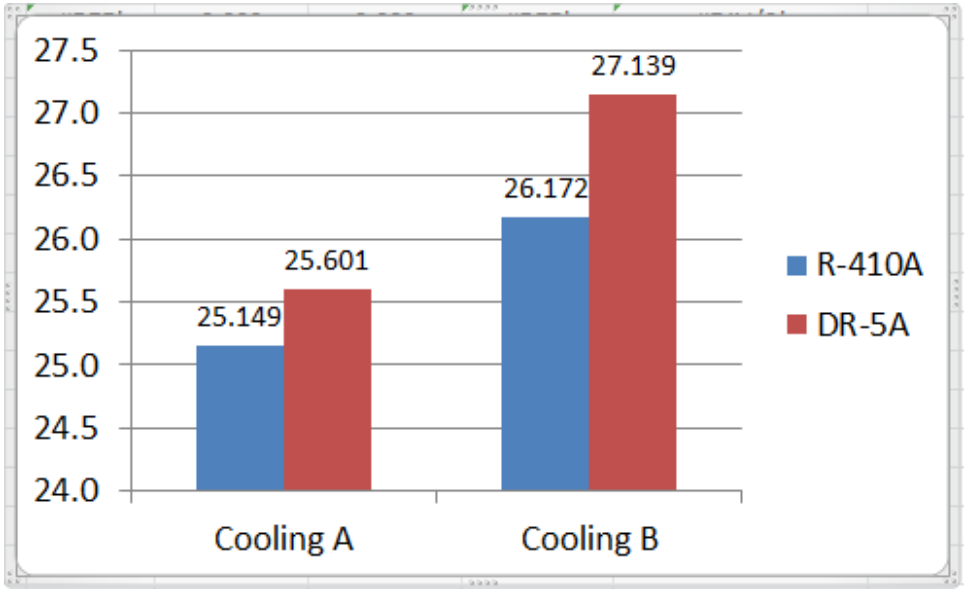
** Expected ASHRAE Rating

System Test Data: DR-5A “Drop In” 30 KW Ducted AC/HP

Air Side EER

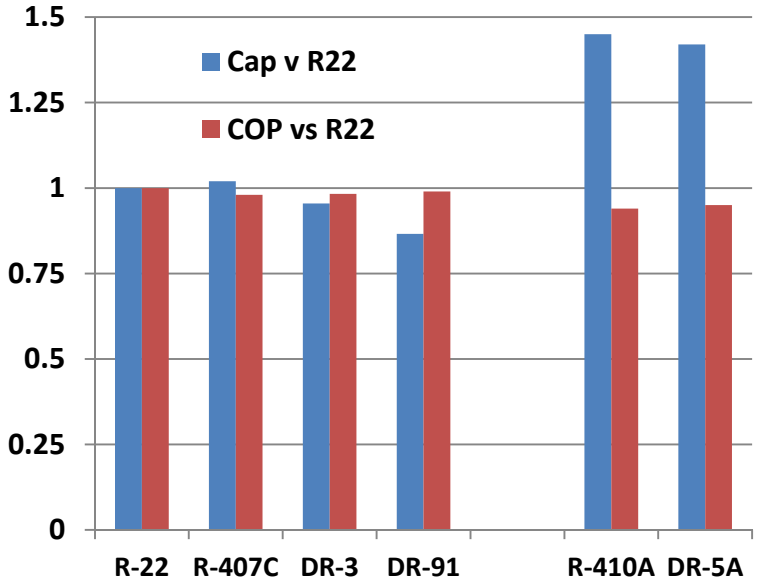


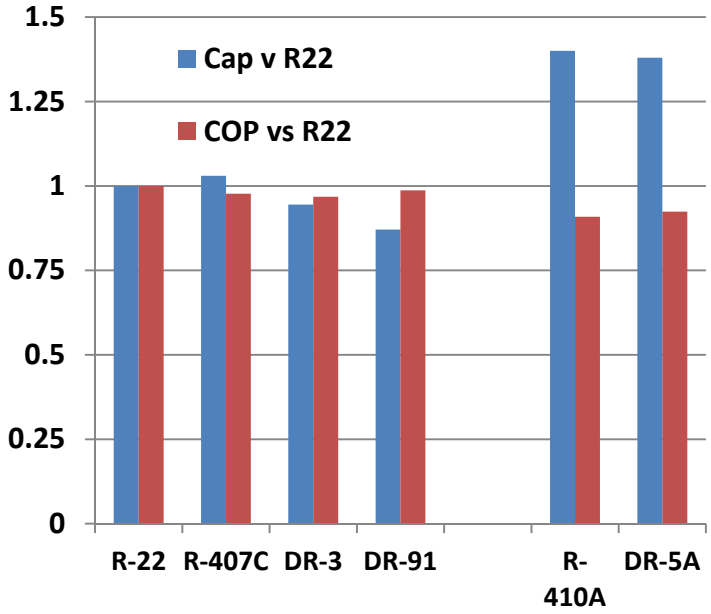
Air Side Capacity – BTU h



AHRI 210-240 AC Test Conditions A and B Cooling Tests

Performance Modeling at Normal and Hot Climate Conditions





<u>Normal</u> climate AC COP and Capacity
Evaporator 7 ° C Condenser 47° C

<u>Hot Climate</u> AC COP and Capacity
Evaporator 19 ° C Condenser 56° C

Refrigerant Miscibility in ISO 32 Mixed Acid POE

R-410A in ISO32 Mixed Acid POE

Temperature (C)

R410A/ POE	-50	-45	-40	-35	-30	-25	-20	-15	-10	-5	0	5	10	15	20	25	30	35	40	45	50	55	60	65	70
95 / 5%	N	N	N	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M		
90 / 10%	N	N	N	N	N	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	N		
85 / 15%	N	N	N	N	N	N	N	M	M	M	M	M	M	M	M	M	M	M	M	M	N	N	N		
80 / 20 %	N	N	N	N	N	N	N	M	M	M	M	M	M	M	M	M	M	M	M	M	N	N	N		
70 / 30%	N	N	N	N	N	N	N	M	M	M	M	M	M	M	M	M	N	N	M	M	N	N	N		
40 / 60%	N	N	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M		
30 / 70%	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M		

R-32 in ISO32 Mixed Acid POE

Temperature (C)

R32/ POE	-50	-45	-40	-35	-30	-25	-20	-15	-10	-5	0	5	10	15	20	25	30	35	40	45	50	55	60
95 / 5%	N	N	N	N	N	N	N	N	N	M	M	M	M	M	M	M	M	M	M	M	M		
90 / 10%	N	N	N	N	N	N	N	N	N	N	N	N	M	M	M	M	M	M	M	M	M		
85 / 15%	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N		
80 / 20 %	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N		
70 / 30%	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N		
40 / 60%	N	N	N	N	N	N	N	N	M	M	M	M	M	M	M	M	M	M	M	M	M		
30 / 70%	N	N	N	N	N	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M		

Refrigerant Miscibility in ISO 32 Mixed Acid POE

DR-5A in ISO 32 Mixed Acid POE

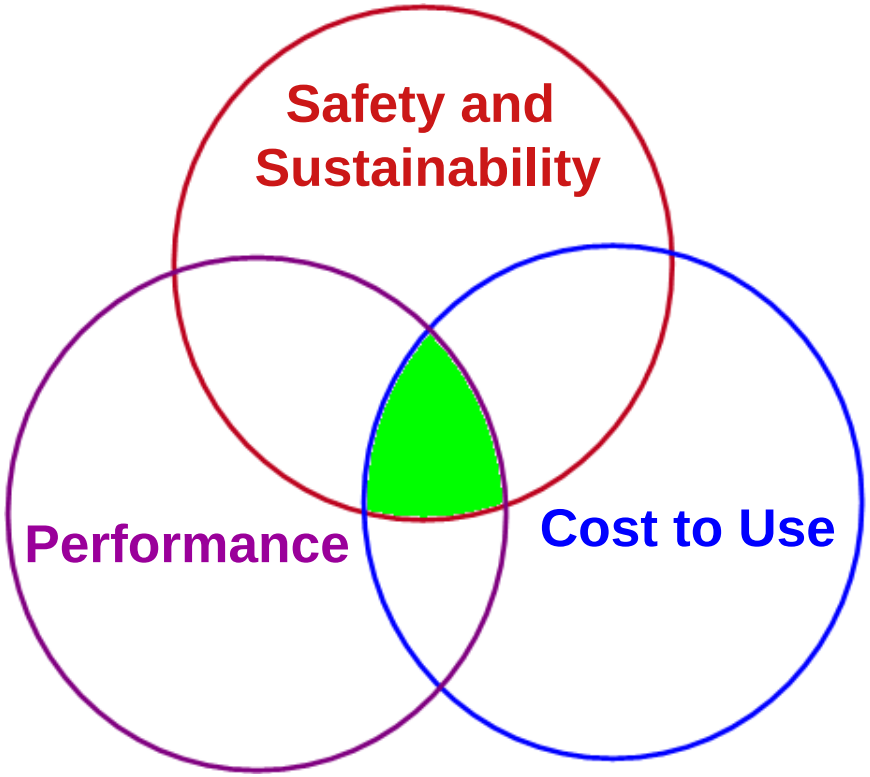
DR-5A/ POE	amt. Oil	Temperature (C) -50	-45	-40	-35	-30	-25	-20	-15	-10	-5	0	5	10	15	20	25	30	35	40	45	50	55	60	65	70
95 / 5%	0.1	N	N	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
90 / 10%	0.2	N	N	N	N	N	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	N
85 / 15%	0.3	N	N	N	N	N	N	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	N
80 / 20 %	0.4	N	N	N	N	N	N	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	N	N
70 / 30%	0.6	N	N	N	N	N	N	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	N	N
40 / 60%	1.2	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
30 / 70%	1.4	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M

DR-91 in ISO 32 Mixed Acid POE

DR-91 / POE	Temperature (C) -50	-45	-40	-35	-30	-25	-20	-15	-10	-5	0	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75
95 / 5%	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
90 / 10%	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
85 / 15%	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
80 / 20 %	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
70 / 30%	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	N	N	M	M	M	M	M
40 / 60%	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
30 / 70%	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M

Refrigerant choice requires a balance of properties for a given application in a given region

Zero-ODP, Low-GWP, Favorable LCCP
Favorable Toxicity
No or Low Flammability
Regulatory Environment



System Energy Efficiency
+
Capacity

Ambient Conditions

First Cost
+ Operating Cost

= Total Cost to Use **

** Impacted by maturity of technology

Balance of Properties

Conclusions

- **There are reduced GWP refrigerants for R-22 type and R-410A type service**
- **None are exact “drop in” replacements**
- **Optimum performance will require some system optimization, otherwise test results will not be meaningful**
- **GWP Regulations and Flammability Regulations continue to impact refrigerant selection**

Thank you!

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Refrigerant Lubricant Miscibility Ranges (ISO32 MA POE)

R-32 in ISO32 Mixed Acid POE

Temperature (C)

R32/ POE	-50	-45	-40	-35	-30	-25	-20	-15	-10	-5	0	5	10	15	20	25	30	35	40	45	50	55	60
95 / 5%	N	N	N	N	N	N	N	N	N	M	M	M	M	M	M	M	M	M	M	M	M		
90 / 10%	N	N	N	N	N	N	N	N	N	N	N	N	M	M	M	M	M	M	M	M	M		
85 / 15%	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N		
80 / 20 %	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N		
70 / 30%	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N		
40 / 60%	N	N	N	N	N	N	N	N	M	M	M	M	M	M	M	M	M	M	M	M	M		
30 / 70%	N	N	N	N	N	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M		

DR-5A in ISO 32 Mixed Acid POE

Temperature (C)

DR-5A/ POE	amt. Oil	-50	-45	-40	-35	-30	-25	-20	-15	-10	-5	0	5	10	15	20	25	30	35	40	45	50	55	60	65	70
95 / 5%	0.1	N	N	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
90 / 10%	0.2	N	N	N	N	N	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	N
85 / 15%	0.3	N	N	N	N	N	N	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	N
80 / 20 %	0.4	N	N	N	N	N	N	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	N	N
70 / 30%	0.6	N	N	N	N	N	N	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	N	N
40 / 60%	1.2	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
30 / 70%	1.4	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M

Containment is Critical

No refrigerant , while sealed in a cylinder, or in a system can cause environmental damage. Or cause fires, or cause other harm.

Proper stewardship of the refrigerant is at least as important as the choice of refrigerant to be used.

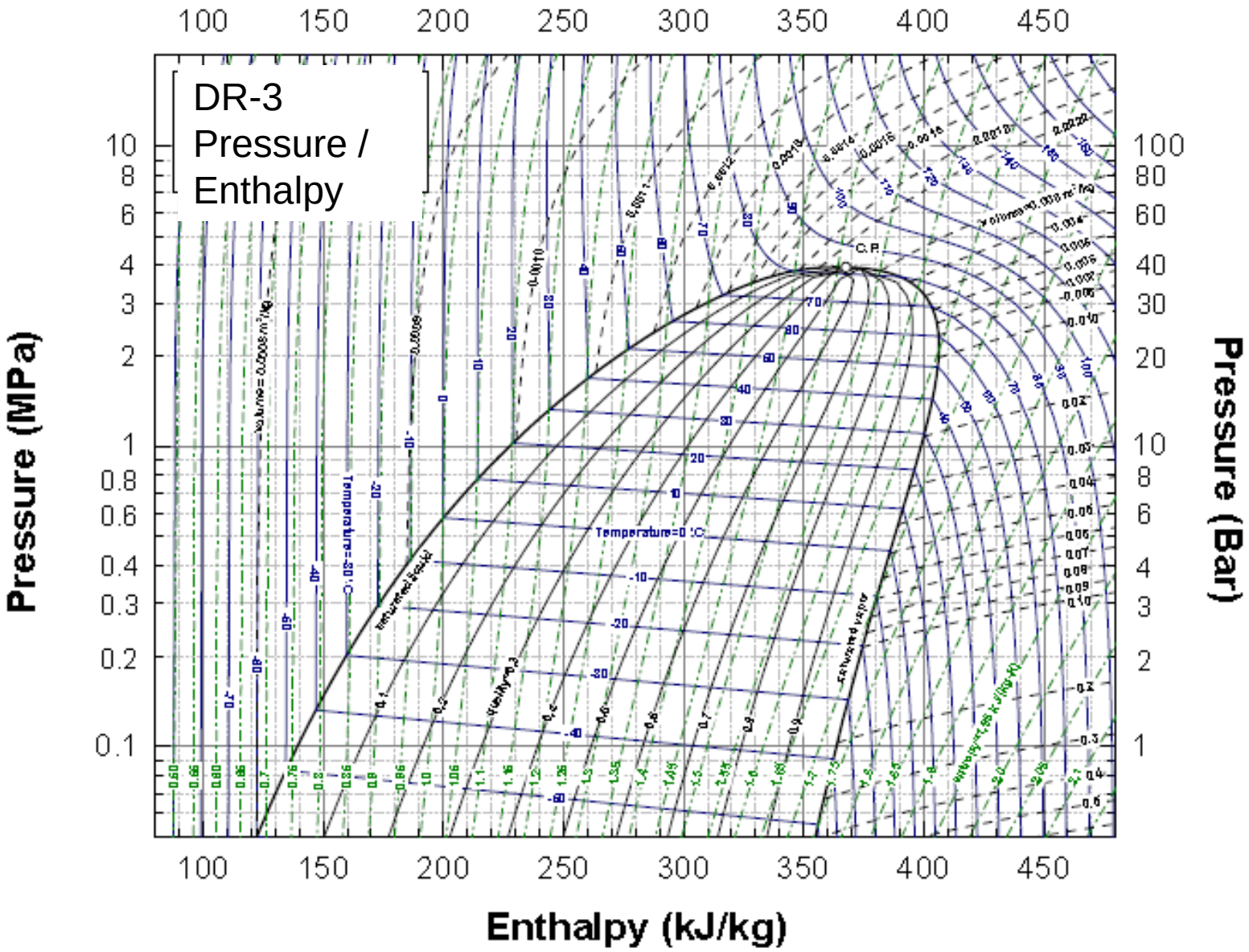
Do we need enforceable protocols, or meaningful incentives for recovery, recycle, and end of life disposition of equipment and refrigerant gases?

Our industry must do much better than it has in the past.

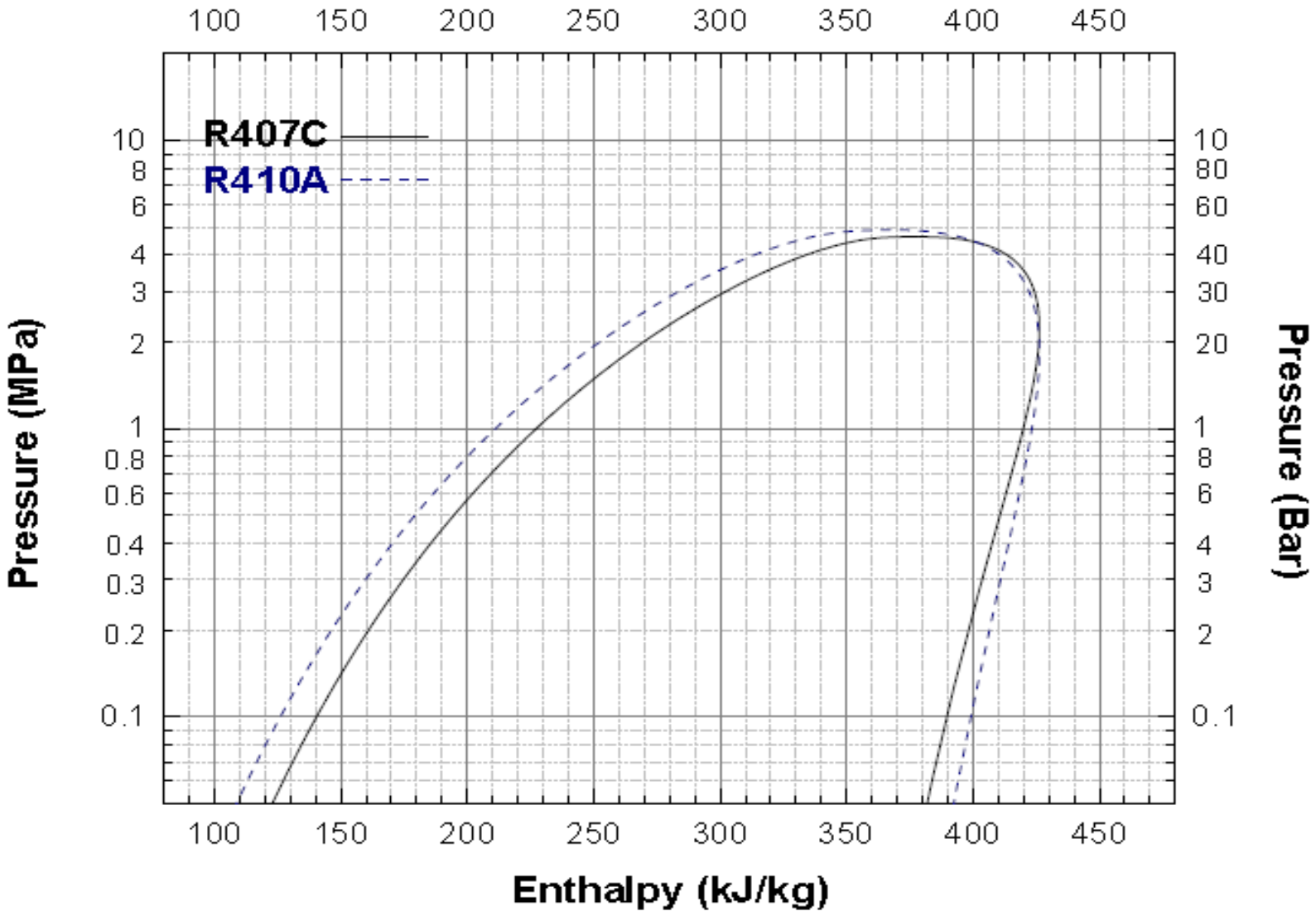
Reduced GWP Candidates for Air Conditioning

Current AC Refrigerant	GWP AR-5	Leading Lower GWP Candidates* – HFO Based			
		Non Flammable		Mildly Flammable	
		ASHRAE Class 1		ASHRAE Class 2L	
		Name	GWP	Name	GWP
HFC-134a	1300	R-513A	< 600	HFO-1234yf	< 1
HCFC-22	1760	DR-91*	< 880	DR-3*	< 150
HFC-410A	1924			DR-5A*	460

* Candidates being evaluated and optimized with input from OEMs


DR-3
Pressure /
Enthalpy
Pressure (MPa)
Pressure (Bar)
Enthalpy (kJ/kg)
100
150
200
250
300
350
400
450
10
8
6
4
3
2
1
0.8
0.6
0.4
0.3
0.2
0.1
100
80
60
40
30
20
10
8
6
4
3
2
1
C.P.
Temperature=0 °C

Pressure Enthalpy (PH) 410A and 407C



HFO-1234yf Flammability: less than other gases,

very much lower than hydrocarbons like propane

	LFL[a] vol%	UFL[a] vol%	(UFL- LFL) vol%	MIE mJ	HOC kJ/g	BV cm/s
Propane	2.2	10.0	7.8	0.25	46.3	46
R152a	3.9	16.9	13.0	0.38	16.5	23
R32	14.4	29.3	14.9	30-100[b]	9.4	6.7
Ammonia	15.0	28.0	13.0	100-300[b]	18.6	7.2
HFO-1234yf	6.2	12.3	6.1	5,000-10,000[b]	10.7	1.5[c]

[a]Flame limits measured at 21 [o]C, ASTM 681-01

[b]Tests run in 12 liter flask to minimize wall quenching effects

[c]HFO-1234yf BV measured by AIST, Japan

Mildly Flammable – “2L”