Industry Overview of the Environmental Performance of Non-CO2 [R744] Alternatives

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Acknowledgements:

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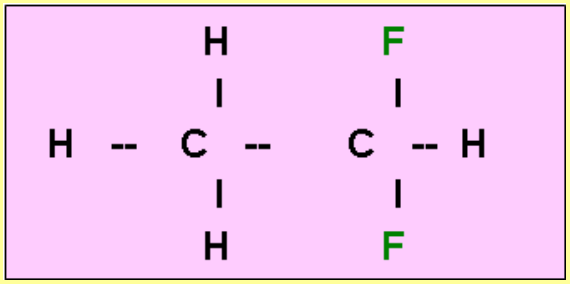
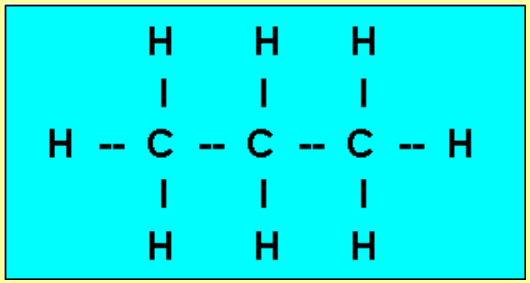
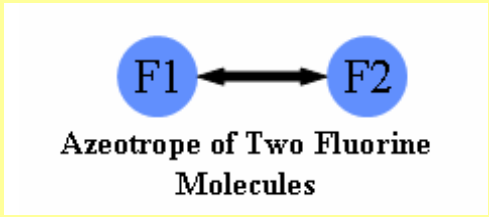
Non-R744 Alternatives



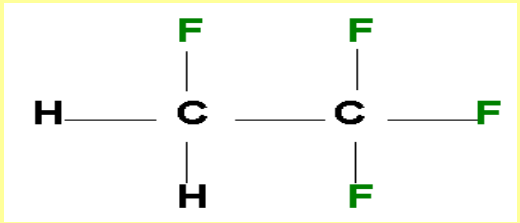
R152a [with Secondary Loop]
ASHRAE A2 [slightly flammable]
Material Compatibility-similar to R134a
GWP=140



R290 [with Secondary Loop]
ASHRAE A3 [flammable]
GWP = 11



Blend "H"
ASHRAE A1 (likely)
Material compatibility similar to R-134a
GWP <<150



R134a
ASHRAE A1 [non-flammable]
GWP = 1300

Refrigerant Properties

Refrigerant	R134a	R744	R290	Blend-H	R152a
Global Warming Potential(GWP)	1300	1	11	<<150	140
Ozone Depletion Potential(ODP)	0	0	0 [VOC]	0	0
Operating Pressures (Max.)	2500 kPa (~400 psig)	13,500 kPa (1950 psig)	2500 kPa (~400 psig)	2500 kPa (~400 psig)	2500 kPa (~400 psig)
Max Discharge Gas Temperatures [ºC]+	125	145	120	115	135
ATEL(PPM)++	50,000	40,000	50,000	TBD	50,000
TWA [ppm]+++	1000	5000	`1000	TBD	1000
Compression Ratio+	5/6	2-3	4.5-5.5	4.5-5.5	4.5-5.5
Refrigerant Flow +	Base	90%	60%	140%	65%

*ODP=Ozone Depletion Potential with R12 as a reference of 1.0
**GWP=Global Warming Potential with R744 as a reference of 1.0

+ Based on ARCRP data

++James Calm report, Sept., 2000
+++OSHA web site
ATEL=Acute Toxicity Exposure Level
TWA=Time weighted average [8 hr. exposure limit]

R152a [secondary loop]

Pros

- Similar components/systems as R134a (direct expansion), i.e. easy to introduce
- GWP < 150
- Reduced refrigerant charge [40%] and emission rate
- Refrigerant cost lower than R134a
- Similar charge, service, and troubleshooting procedures as R134a
- High ignition point (454ºC)
- Improved city traffic and idle performance
- Improvement to interior noise/ refrigerant flow noises
- Opportunity for engine off cooling

Cons

- Flammability – safety concerns related to vehicle accidents
- Increased system mass/cost
  - Additional fluid pump required
  - Additional plumbing required
- Secondary circuit needed
  - EN378/EN7003 standards must be met
- Would still require recycling /recovery
- Training of service personnel
- Industry/Consumer acceptance
- Oil compatibility/durability needs confirmation
- Potential delay in initial cool-down after long soaks
- Increased packaging space
- Contains fluorine (not considered a “natural refrigerant”)

Adapted from 2003 Phoenix Forum Workshop Results

R290 [secondary loop]

Pros

- Low-GWP[11]/natural refrigerant
- Reduced refrigerant charge and emission rate
- Opportunity for engine off cooling
- Improve control of flow to auxiliary cooling coils
- Low refrigerant/oil cost
- Refrigerant already available world wide
- Improvement to interior noise-no refrigerant flow noises
- Established leak testing methods

Cons

- Increased system mass/cost
  - Additional fluid pump required
  - Additional plumbing required
- Flammability – safety concerns
  - Additional safety equipment needed
- Would still require recovery [safety]
- Training of personnel
- Industry/Consumer acceptance
- Potential delay in initial cool-down after long soaks
- VOC
- Increased packaging space
- Two fluids need to be managed/sealed

Adapted from 2003 Phoenix Forum Workshop Results

Fluid H

Pros

- GWP << 150
- Non-flammable
- Performance very close to R-134a
  - May only require minor changes to system
- Uses similar lubricant to R-134a
- Similar discharge pressure/ temperature to R134a
- Higher mass flow – better flow distribution at low loads
  - May need to change heat exchanger pass configuration at high loads
- Service hardware and leak detection same as R-134a
- Will have similar benefits from modifications studied during IMAC project as R-134a.

Cons

- Refrigerant composed of some new molecules
  - New molecule must pass all toxicity testing
  - New manufacturing processes required
  - Material compatibility needs to be confirmed
- Time required to complete toxicity testing and build plants
- Higher cost refrigerant
- Contains fluorine (not considered a “natural refrigerant”)
- Potential VOC
- New proposal with further evaluation required

Refrigerant Leakage

A/C System Choice	Available Options	Potential For Improvement	Comments
R134a Current Production	Baseline	Baseline	
Improved R134a [IMAC]	Compressor Fittings Elastomers	50%	
Secondary loop-R152a	Compressor Fittings Elastomers	50% [~95% environmental]	Additional Coolant joints required
Secondary Loop-R290	Compressor Fittings Elastomers	50% [~99% environmental]	Mineral oil is used Additional Coolant joints required
Blend “H”	Compressor Fittings Elastomers	50% [~99% environmental]	Cost of refrigerant will require better seals
R744	Metal hoses Improved compressor	50% [99.9% environmental]	Smaller molecule

Adapted from 2003 Phoenix Forum Workshop Results

Pro's/Con's-System mass

	Blend "H"	R290	R744	R152a
Evaporator	**Same**	**Same**	**-10%**	**Same**
Compressor	**Same**	**Same**	**+10%**	**Same**
Condenser	**Same**	**-20%**	**+10%**	**Same**
Charge	**+5%**	**-45%**	**-40%**	**-45%**
IHX	**NA**	**+1.1 kg**	**+1.1 kg**	**NA**
Plumbing/lines	**Same**	**Increased due to secondary loop**	**~Same [Diff mat'ls]**	**Increased due to secondary loop**
Safety system	**---**	**+ 0.2/0.4 kg**	**+ 0.2/0.4 kg**	**NA**
Added Components	**---**	**Secondary loop [+5 kg]**	**Accumulator [+1.4 kg]**	**Secondary loop [+5 kg]**

R134a Baseline=Base
Mass Estimates based on ARCRP Phase I data

Indirect Emissions Improvement Potential

A/C System Choice	Improvement from Base
R134a	Baseline
Improved R134a [IMAC]	20-35%
Secondary loop-R152a	5-15%
Secondary Loop-propane	~Same
Blend “H”	10-20%
R744	10-20%

Based on LCCP Analysis

Service Infrastructure

A/C System Choice	Service Investment/equipment Costs	Technician Training Certification	Leak Test
R134a	Baseline	Baseline	Baseline
Improved R134a [IMAC]	Minimal Need to meet new SAE Std	Need to meet new SAE Std	Same
Secondary loop-R152a	More compared to current equipment-flammability	More extensive	Same technology as R134a
Secondary Loop-R290	More compared to current equipment-flammability	Increased diagnostics, training	Technology exists
Blend "H"	Similar to R134a New equipment required	minimal	Same technology as R134a
R744	New, but less compared to current equipment	High pressure, training	Needs to be developed

Adapted from 2003 Phoenix Forum Workshop Results

Risk Assessment

A/C System Choice	Prod./ Shipping	Service areas	Passenger Exposure
R134a	Baseline	Baseline	Baseline
Improved R134a [IMAC]	No change	Reduced-less service	Reduced-less leakage
Secondary loop-R152a	Flammability Concern	Training Recovery/Recycling Sensors Electrical std-safety	Risk slight increase from R134a
Secondary Loop-R290	Safety valve for 2ndary loop	Training Recovery/Recycling Sensors Electrical std-safety	Risk assessment needed if this is to be pursued
Blend "H"	TBD	TBD	TBD
R744	Handling for high pressure refrigerant	Training Venting Sensors	Risk slight increase from R134a

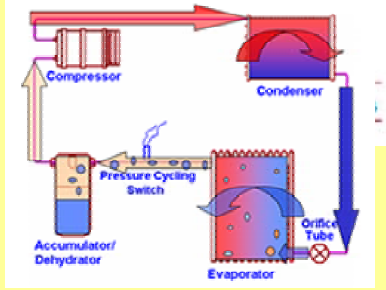
Adapted from 2003 Phoenix Forum Workshop Results

Costs Vs Benefits

AC System Choice	Reduced Direct Emissions	Reduced Indirect Emissions	Added Cost [Euros]	Service Cost	Investment	Time to Market [Years]
R134a	Baseline	Baseline	Baseline	Baseline	Baseline	Current
Improved R134a [IMAC]	50%	20-35%	20	Baseline	+	1-3
Secondary loop R152a	~95%	5-15%	60	110%	++	3-5
Blend "H"	~99%	10-20%	TBD	100%	+	3-5
Secondary Loop R290	~99%	~Equal	60	120%	++	4-6
R744	~99.9%	10-20%	60-150	100%	++++	3-6

Adapted from 2003 Phoenix Forum Workshop Results

Life Cycle Model Assumptions



- **Vehicle Assumptions**
  - Car Size-midsize
  - Engine type-V6 gas

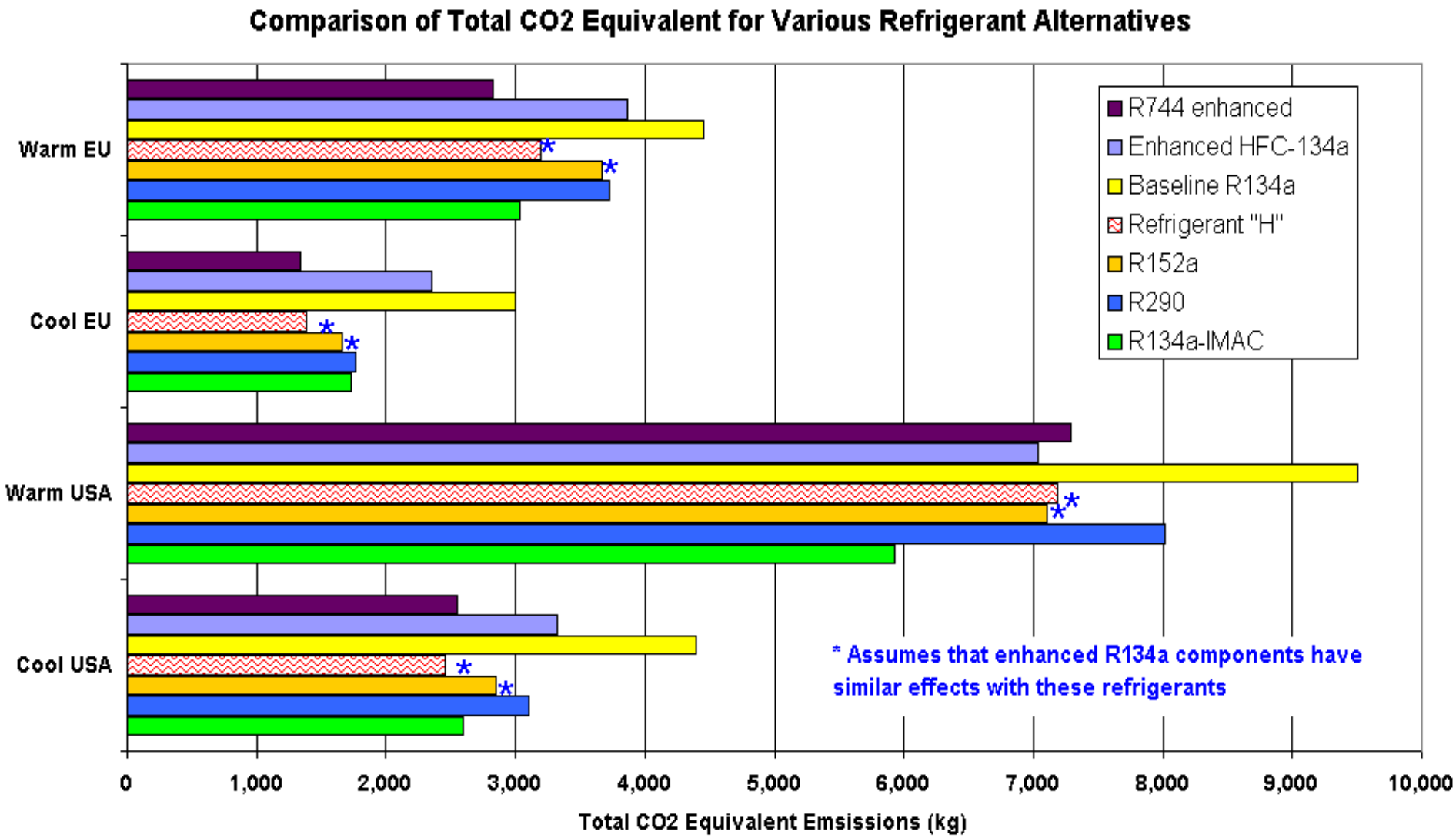
- **Refrigerant System Assumptions:**
  - Production Leakage
  - Total Refrigerant System Mass
  - Blower speeds
  - Temperature at Evaporator Outlet
  - Humidity Effects
  - Evaporator Air Inlet conditions
  - Blower Power
  - Condenser/Gas Cooler Air Inlet air at idle conditions
  - Front End Air Flow

Model

- **Vehicle Usage Assumptions:**
  - Variable Distance
  - Engine Run Time Different for Each City
  - Variable Speed Profiles for Different Cities

- **Environmental Assumptions:**
  - Energy to produce refrigerant
  - Transportation, End-of-Life and By-Product Emissions
  - Ambient Temperature Operation

LCCP-Viable Alternatives



LCCP [kg. of Equivalent CO2]

Impact of More than One Global Refrigerant in MACS

- Multiple Pieces of charge equipment in the plants
- Increased development costs to develop multiple refrigerants
- Vehicle timing to market may be affected
- Mixing of refrigerants needs to be carefully considered
- Addition of suction line heat exchangers require training in assembly plants and service
- If secondary loop is needed, additional coolant fill required and additional training
- Service (technician training, development of service & diagnostics tools)
- Increase complexity of vehicle assemble (flow space if technology requires refrigerant specific HVAC modules)
- Aftermarket problems servicing 2 or more refrigerant systems.

Conclusions

- **Environmental Considerations based on LCCP**
  - **In cool climates, Refrigerant "H" and R744 have similar life cycle performance and are the best choices for life cycle**
    - **Refrigerant "H" is relatively new and more development is required**
  - **The IMAC R134a system is best in very warm climates**
  - **Results are depending on drive cycle and system loading conditions**
- **AC system considerations**
  - **System complexity/cost increases with all alternatives**
  - **Two or more global refrigerant systems will present hardships in industry/service in the future**
- **Relative ease of industry conversion**
  - **Some of these Non-R744 options represent an easier conversion and some require significant further development for optimization**
- **Risk Assessment**
  - **Flammable refrigerants are not considered a viable options without significant development of safety systems [i.e.; secondary loop, relief systems, etc.]**
  - **New refrigerant options will need new risk assessments**

Thank you for your kind attention!