Technical Options to Replace HFC-134a in Motor Vehicle Air Conditioning with Opportunity to Reduce Refrigerant Charge and Emissions and for Increased Energy Efficiency

Presented by:

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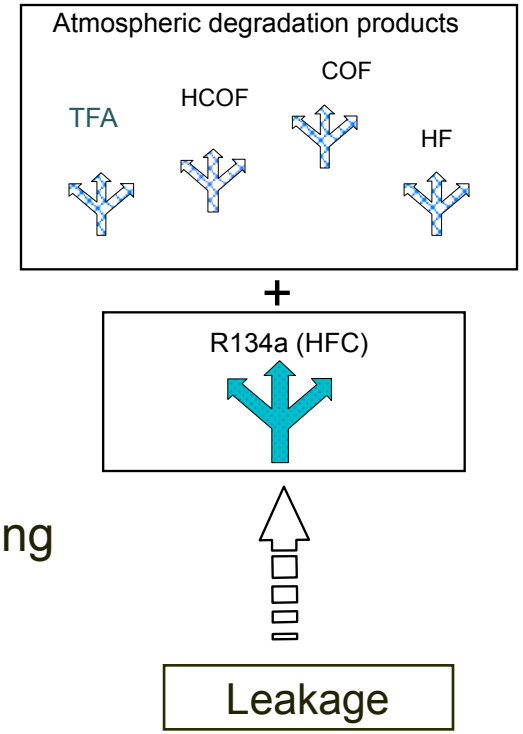
MAC System: Impact on Environment

Direct Greenhouse Gas (GHG) emissions

Leakage of high Global Warming Potential (GWP) refrigerant to the atmosphere (through AC Hoses / Joints / Servicing / Accidents / End-of-Life)



Indirect GHG emissions

CO_2 from exhaust

(About 4% to 20% of fuel use is for air conditioning; depending on climate and traffic congestion)

Atmospheric Degradation Products

COF, HCOF, HF, TFA

Protocol & Market Drivers of HFC-134a Phasedown in MACS

Protocol Drivers

- The Kyoto Protocol already controls HFC *emissions*
- The 2016 Montreal Protocol Amendment will control HFC *production and consumption* and will finance the transition by developing countries to lower GWP refrigerants and higher energy efficiency

Market Drivers

- EU MAC Directive requires GWP <150 after 2016 for new automobiles sold in the European Union
- US EPA offers credit toward fuel mileage standards for low GWP
- US EPA lists HFC-134a as unacceptable in passenger cars and light-duty trucks as of Model Year 2021
- Japan HFC regulations require low GWP MACs after Model Year 2023

Technical Options to Replace HFC-134a in MACs

Three refrigerant replacements approved by the USEPA SNAP also satisfy the EU F-Gas Directive (GWP<150)

SNAP / F-Gas Option	GWP	Efficiency	TFA	Flammable	Application Patent
HFO-1234yf	< 1	Good	Yes	Slightly	Yes
Carbon Dioxide - CO_2	= 1	Poor @ High Ambient	No	No	No
HFC-152a	= 138	Better	No	Moderately	No

*GWP from Intergovernmental Panel on Climate Change Assessment (IPCC) Assessment Report 5 (AR5)

So far, only vehicles with HFO-1234yf have been marketed. Audi and Daimler have announced plans to introduce CO_2 systems in 2017

Status of HFC-134a Replacement

35 Manufacturers, 125 Models so far, 18 Million Vehicles Sold by Year End 2016

- ✓ Every automaker but Audi & Daimler has selected HFO-1234yf
- ✓ Audi and Daimler selected CO_2 based on non-flammability
- ✓ More than 8,000,000 vehicles in Europe and North America have already been sold with HFO-1234yf systems
- ✓ HFO-1234yf models from Alfa Romeo, BMW, Chrysler, Citroën, Ford, Ferrari, Fiat, Fisker Automotive, Ford, General Motors, Great Wall Motor, Honda, Hyundai, Infinity, Jaguar Land Rover, Kia, Lexus, Lotus, Maserati, Mazda, Mia, Mitsubishi, Maruti-Suzuki, Nissan, Pagani Automobili, Peugeot, Renault, SAIC Motor, Subaru, Suzuki, Tesla, Toyota, Suzuki, Volkswagen and Volvo
- ✓ Automobile companies know how to safely use flammable fluids (fuel, hydraulic fluid, motor oil, brake fluid, antifreeze, and windshield cleaning fluid are all flammable)

HFO-1234yf Intellectual Property Overview

A half dozen chemical companies announced ownership of HFO-1234yf *production patents* just weeks after the EU finalized its 2006 MAC F-Gas Directive requiring GWP<150 refrigerants in MACs sold in Europe after 2017; since 2006, more companies have been granted HFO-1234yf production patents

In 2009,15 months before it was realized that Honeywell had an application patent claiming exclusive right to the use of HFO-1234yf in MACs, global automobile manufacturers selected HFO-1234yf to replace HFC-134a

Production patent holders, with the support of automakers, have successfully challenged the Honeywell application patents in several jurisdictions, but Honeywell has appealed and additional Honeywell application patents have recently been granted

Meanwhile, Honeywell has signed a joint marketing agreement with DuPont (now Chemours) and most recently joined with Navin Fluorine in India and Juhua in China to manufacture HFO-1234yf; HFO-1234yf is also manufactured for Honeywell and Chemours by Asahi Glass Chemical (AGC) in Japan and by Shanghai 3F New Material Company (Shanghai 3F) in China

Honeywell profits from application patent pricing of HFO-1234yf, but no publically available analysis has compared actual production costs under various patented production processes to the price charged automakers for bulk purchase or charged technicians for use in MAC service

Resolving HFO-1234yf IP and Pricing

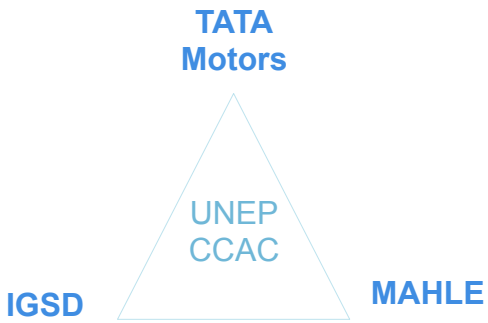
Legal, Licensing, and Timing Solutions to the Honeywell Application Patent

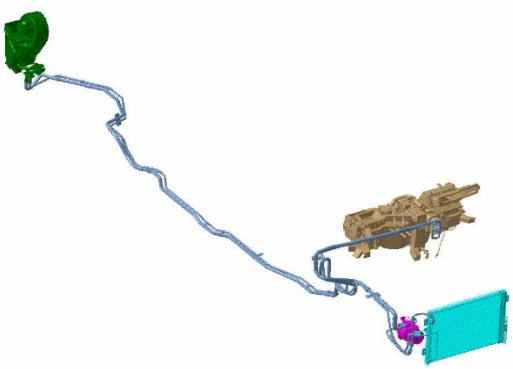
- ✓ **Invalidation of the Honeywell Application Patents**
- ✓ **Agreement by Honeywell to competitively price in Article 5 markets or everywhere**
  - ✓ Voluntary agreement like AIDS vaccine or the Daikin and Trane free access to patented HFC-32 and R-452B refrigerants, respectively, for stationary AC
- ✓ **Phase down other applications until after the MAC application patents expire in most countries in 2023 and India in 2025**
  - ✓ Patent law varies among countries with some aspects internationally harmonized

Technical Solutions to the Honeywell Application Patent

- ✓ **Avoid HFO-1234yf with another low-GWP refrigerant (free from patents)**
  - ✓ CO_2 in direct-expansion MAC systems like Daimler and Audi will introduce in 2017
  - ✓ HFC-152a in direct-expansion MAC systems with active safety systems
  - ✓ HFC-152a in secondary-loop MAC systems that keep the flammable refrigerant out of the occupied space
- ✓ **Apply HFO-1234yf in Secondary-Loop MAC systems**
  - ✓ Lower refrigerant charge and leakage reduces cost impact
- ✓ **Apply HFO-134a in SL-MAC Systems for partial phasedown and later shift to a low-GWP refrigerant**

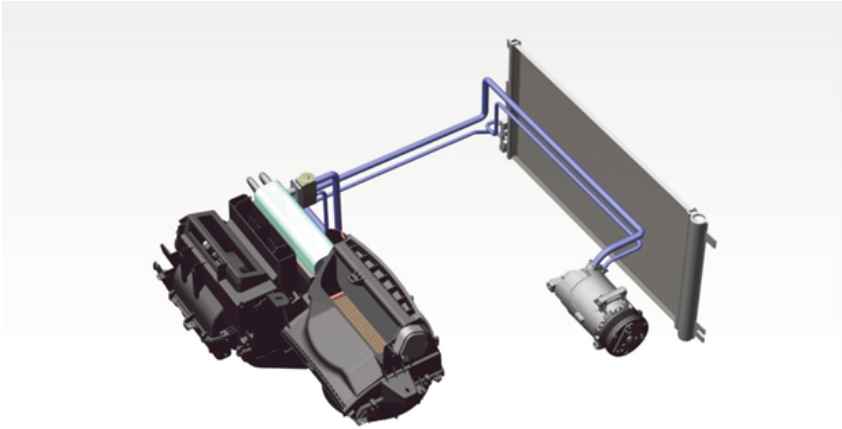
SL-MAC Demonstration Project



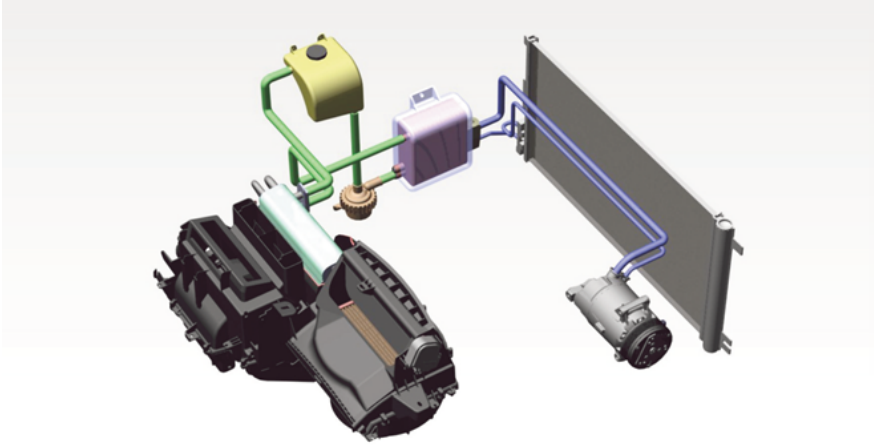


- Financial support by UNEP, as a climate change project of the Climate and Clean Air Coalition to Reduce Short-Lived Climate Pollutants (CCAC)
- TATA Aria 2.2L Dicor is selected vehicle with front and rear A/C system
- Project will demonstrate SL-MAC hardware with improved Power Train Control logic to maximize energy efficiency advantage
- Technical Advisors on board from California Air Resources Board (CARB), Chemours, Chrysler, Fiat, General Motors, Jaguar Land Rover, Neutronics Refrigerant Analysis, HF Consultancy, Natural Resources Defense Council (NRDC), the Mobile Air Conditioning Society Worldwide (MACS), Red Dot AC Corporation, SAE International, Sun Test, TERRE Policy Centre, National Renewable Energy Laboratory (NREL), University of Maryland, and Valeo

Direct Expansion vs. Secondary Loop Systems



Direct expansion system
Andersen et al., 2014



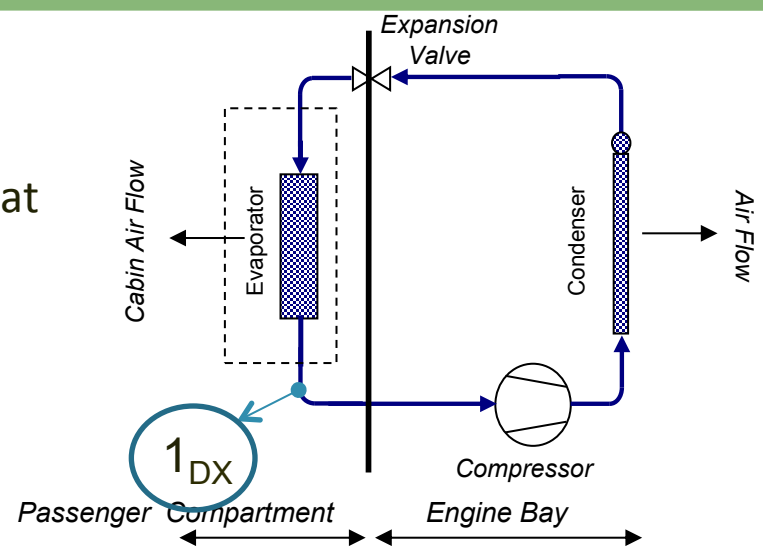
Secondary loop system
Andersen et al., 2014

SL-Loop MACs use refrigerant to chill a fluid (coolant) that is circulated inside the car for comfort; a reduced charge of flammable refrigerants can be used more safely in systems with less emissions from fewer fittings and shorter refrigerant hoses

Comparison of Direction Expansion (DX) and Secondary Loop (SL)

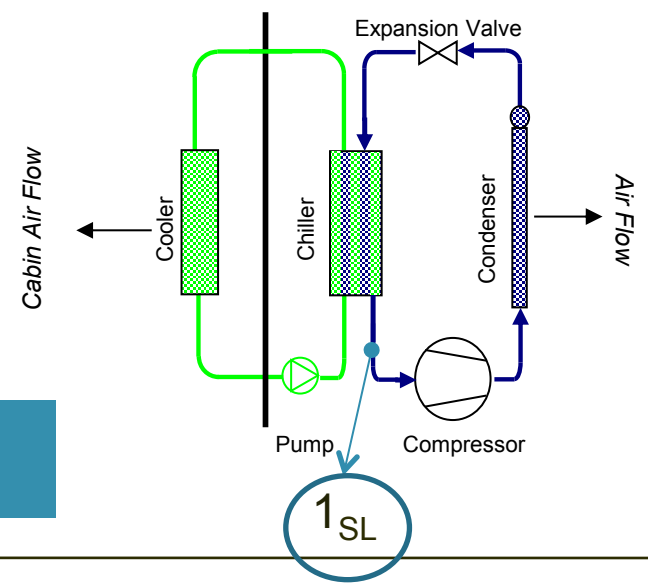
Direct Expansion System

- Most common MAC system
- Air-to-refrigerant passenger compartment heat exchanger - evaporator
- Evaporator is single HX effectiveness: Refrigerant-to-air
- Note evaporator HFC-134a outlet state, 1_{DX}



Secondary Loop System

- Applicable to any refrigerant
- Refrigerant circuit isolated in engine bay
- Air-to-coolant passenger compartment heat-exchanger – cooler
- Refrigerant-to-coolant heat exchanger - chiller
- Note chiller HFC-152a outlet state, 1_{SL}



Systems have Equal Cooling Power but Refrigerant Conditions Differ

Why Secondary Loop?

- Safe use of flammable refrigerants
- Lower refrigerant charge, fewer fittings, and shorter refrigerant hoses reduce refrigerant emissions/costs
- Reduced A/C system noise
- Lower manufacturing and ownership cost, particularly for multiple cooling point systems
- Cold storage comfort, economy & environment
  - ✧ “Regenerative cooling” during deceleration; reduced compressor load during acceleration
  - ✧ A/C comfort during longer stop/start (idle-stop) and engine-off coasting.

Energy Benefits of Secondary Loop Simulated Fuel Economy With Cold Storage

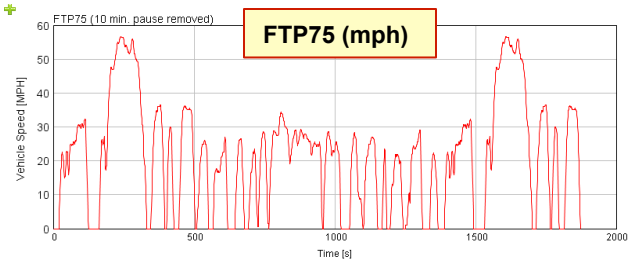
Conditions:

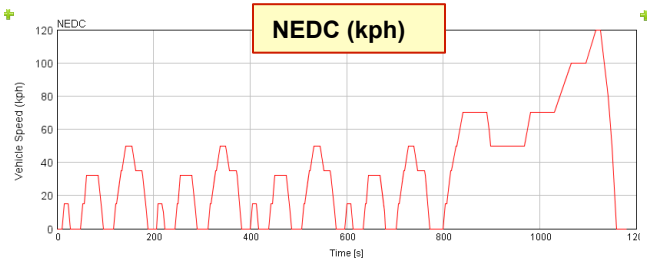
A. No A/C

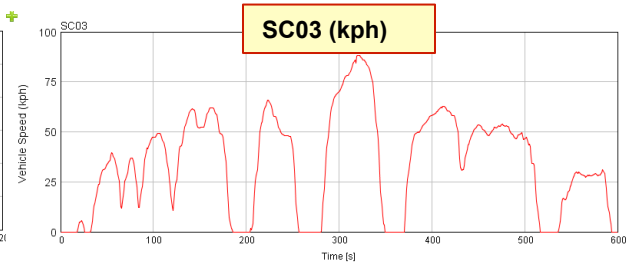
B. Continuous A/C with Cabin Soak to Ambient Condition

C. B + Compressor Disengaged at Speed = 0 (Engine runs at idle)

D. B + Compressor Disengaged at Speed = 0 OR Acceleration >0







	A	B	C	D	
Fuel Econ (mpg)	No A/C	Continuous A/C	Compressor Stop at idle	Compressor Stop at Idle+Accl.	Gain = (D-B)/Bx100 (%)
FTP75@28°C	23.2	19.7	19.8	20.9	6.1%
NEDC@28°C	20.1	17.4	17.5	19.4	11.5%
SC03@35°C	18.1	15.4	15.5	17.3	12.3%

Potential

Chart of Simulated Fuel Economy Improvement, Dr. S. Chowdhury, MAHLE

Project to Demonstrate Fuel Economy Improvement with Stored SL Cold Energy

Key Assumptions in Scenario Examples

Price Paid by Vehicle Manufacturers

- ✓ In June 2016 authorities in India estimated local OEM prices at US$80/kg
- ✓ In July 2016, Honeywell Disclosed in Personal Communication an Estimated Cost of US$50/vehicle; Assuming a 500 Gram Charge this is US$100/kg
- ✓ The Price to Manufactures May Vary by Country and Company
- ✓ ***The example that follows assumes US$80/kg for vehicle manufacture***

Price Charged Owners for HFO-1234yf MAC Service

- ✓ More is Known About the Price Paid for HFO-1234yf for Service
- ✓ Chrysler sets the price at US dealerships at US$360/kg in Mopar 4.5kg (10 lb.) cylinders (Part Number 68224028AA)
- ✓ An informal price survey at vehicle dealers in one US geographical area found prices ranging from US$187/kg to US$280/kg
- ✓ ***The example that follows assumes US$200/kg for service***

How SL-MACs May Resolve the HFO-1234yf Application Patent Price Impact

Uncertain Vehicle *Manufacturing* Cost Advantage

- The manufacturing cost is lower if the net additional cost of SL-MAC components is less than the avoided cost of refrigerant
- SL-MACs require an additional heat exchanger (chiller), coolant pump, and coolant reservoir, but avoids several meters of flexible and rigid tubing as well as fittings and the internal heat exchanger if required for HFO-1234yf systems
- The demonstration project will estimate likely cost differences; in the example below at $80/kg OEM cost net component costs would have to be less than $6 to $16 justify SL-MACs for HFO-1234yf systems or $29 to $75 to justify HFC-152a systems

MAC Design Option	OEM Refrigerant Cost (HFO-1234yf @ $80/kg Per 400-1000 Gram Charge)
DX HFO-1234yf	$32 to $80
SL-MAC HFO-1234yf	$26 to $64 (20% charge reduction)
SL-MAC HFC-152a	$3-$5 (40% charge reduction)

How SL-MACs May Resolve the HFO-1234yf Application Patent Price Impact

Unequivocal SL-MAC *Ownership* Cost Advantage:

The lifetime service cost is substantially lower because the smaller refrigerant charge and lower life-cycle emissions from fewer fittings and shorter hoses avoids routine service (parts and labor); this example assumes $200/kg for service

MAC Design Option	Lifetime Service Cost (US $) Assuming $50 labor charge
DX HFO-1234yf	$260 to $500 (two recharges)
SL-MAC HFO-1234yf	$130 to $250 (one recharge) and 20% less charge
SL-MAC HFC-152a	$56-$60 (one recharge)
SL-MAC Near-Zero Emissions	No routine service cost

The lifetime fuel savings depends on how much more efficient the SL-MAC will be in actual driving conditions:

MACs use 4% to 20% of motor fuel, depending on the climate and traffic congestion

SL-MACs have the potential to provide about half the cooling from deceleration at no net carbon and to prolong the period of idle stop before drivers restart the engine for cooling comfort

Take Home Messages

- HFC-152a and CO_2 Systems will Gain Traction if HFO-1234yf Prices Remain High
- The Current High Price of HFO-1234yf May Price it Out of the MAC Market
- Secondary-Loop MAC Designs are Under Active Investigation for Cost, Cooling and Environmental Performance
- Energy Efficiency Will Dominate Refrigerant Choice Once Low to Near-Zero SL-MAC Emissions Are Routinely Demonstrated in Real World Vehicle Ownership

Backup Slides

Potential Cost Advantages of SL-MACs

Potential Cost Advantages to Vehicle Manufacturers

Savings if the net cost of added SL-MAC components is less than the avoided cost of HFO-1234yf refrigerant for SL-MAC systems providing equal or greater fuel efficiency

Potential Cost Advantages to Vehicle Owners

Savings from less frequent and less costly service from reduced charge and lower refrigerant leakage, potential savings from reduced fuel use for cooling, and lower refrigerant cost if HFC-152a is implemented

Potential Cost Advantages to the Montreal Multilateral Fund (MLF)

Lower agreed incremental costs of HFC phasedown in Article 5 Parties

Technical and Economic Challenges of SL-MACS

Time to comfort in SL-MAC system is demonstrated to be equivalent to DX systems despite the need to cool the intermediate coolant

Added components increase vehicle weight and fuel use (very minor compared to overall fuel economy improvement obtained) and require extra effort to recycle at end of vehicle life

It is always challenging to attribute measured improvements in fuel efficiency to specific design features; some innovations in the demonstration vehicle can also be applied to DX systems

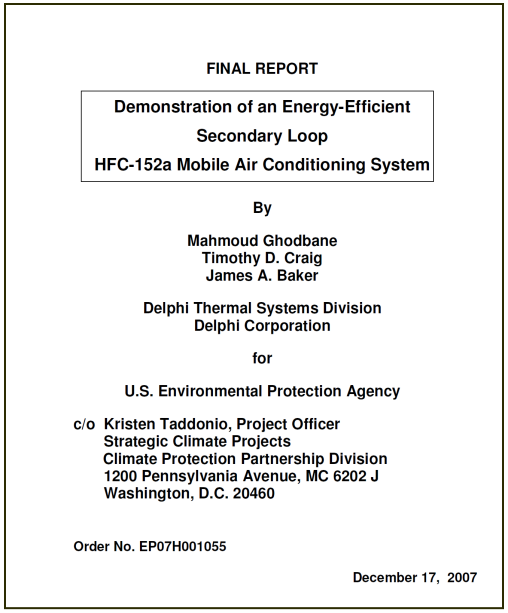
Unique to SL-MACs	Both SL- or DX- MACs
Regenerative cooling, powered cooling controlled for least fuel use, cold storage, low-cost multiple cooling points to reduce the energy use needed for comfort	Alternator preferentially engaged on deceleration, water flow to heater controlled by valve in hot weather, and other enhancements to-be-determined during demonstration

Added SL-MAC Component Cost Offset in Part or in Entirety by Refrigerant Savings

	Baseline HFC-134a	DX HFO-1234yf	SL HFO-1234yf or HFC-152a
Internal heat exchanger		To overcome HFO-1234yf inferior cooling capacity and efficiency compared to HFC-134a	Avoided if HFO-1234yf-to-coolant heat exchanger is more efficient across the heat-transfer surface
Heat exchangers			Chiller (refrigerant-to-coolant) heat exchanger is added. Evaporator is replaced with Cooler.
Refrigerant hose and refrigerant			Half the length of high-pressure hose and refrigerant required for DX HFC or HFO system
Miscellaneous parts added to SL-MAC			Coolant, reservoir, pump, low pressure insulated tubing; systems in cold climate locations need antifreeze in coolant

Selected Past Technical Studies

Timeframe	Objective / Reference	Outcome
2000 – 2002	Various Concept Studies IMAC, Phoenix Forum	Concept demonstration, Multiple Refrigerants
2007	US EPA Funded – Delphi	System Design Guide; No Comfort Lag
2007	CRF-Fiat Demonstration	Comparative study and Life Cycle Climate Performance (LCCP)
2012 – 2013	TATA Motors Ltd.	Concept demonstration (Cooling down rate)



FINAL REPORT

Demonstration of an Energy-Efficient
Secondary Loop
HFC-152a Mobile Air Conditioning System

By

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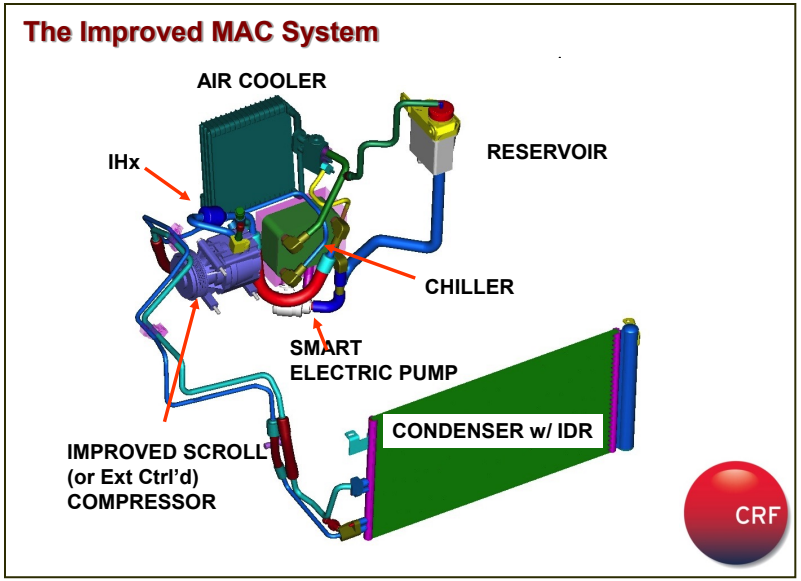


Secondary Loop (SL) vs. Direct Expansion (DX) Perspective

Pluses (+)

- Less Refrigerant Charge/ Emissions
- Deceleration Cooling
- Manage Flammable Refrigerant Risk
- Use Stored Cold Energy
- Coolant Distributed Cooling
- Easy Extension to Heating
- Improved Noise, Vibration, and Harshness (NVH)

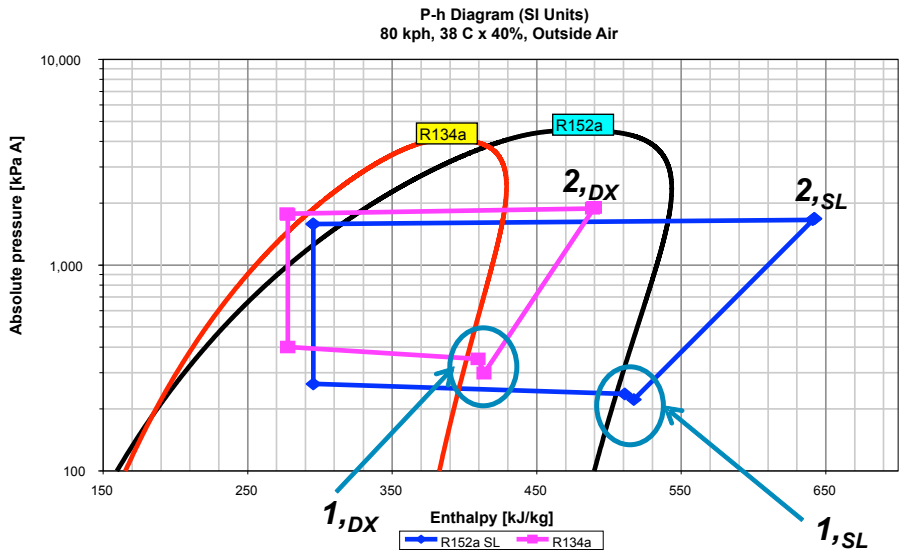
Minuses (-)

- Additional Components and Mass
- Lower Coefficient of Performance (COP) that can be mitigated by SL-MAC engineering choices
- Package Size (parts + volume)

Key Project Objective: Increase the SL-MAC coefficient of performance (COP) and Life-Cycle Climate Performance (LCCP) beyond that of a DX system with Latest Thermal and New Powertrain Technology

Energy Considerations: Direct Expansion (DX) vs. Secondary Loop (SL)

- Refrigerant Cycles for HFC-134a DX vs. HFC-152a SL for the same cooling load
- Lower saturation temperature is required in SL because the cooler/ chiller effectiveness is lower than for a DX evaporator
- Effectiveness for a combined cooler and chiller "sub-system" is Impact of ε and HFC-152a: the compressor power is greater for HFC-152a SL than for HFC-134a DX



B-Segment Vehicle Refrigerant Cycle Data, L. Leitzel, MAHLE

$$\varepsilon = \frac{1}{\left(\frac{1}{\varepsilon_{cooler}}\right) + \left(\frac{C_{air}}{C_{coolant}}\right)\left(\frac{1}{\varepsilon_{chiller}} - 1\right)}$$

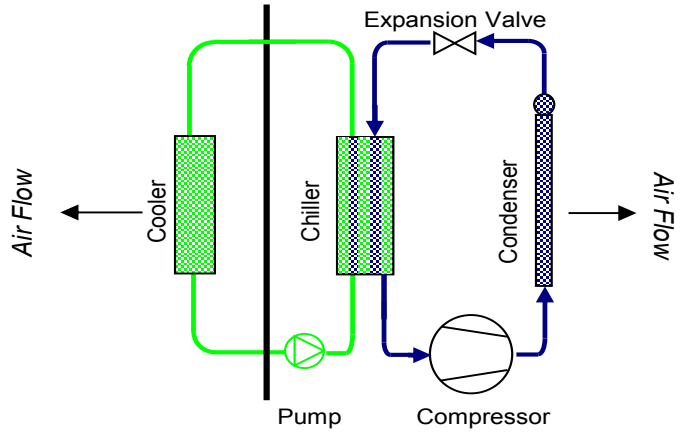
Combined Effectiveness for given Cooler/Chiller

C_x = Air or Coolant heat capacity, respectively

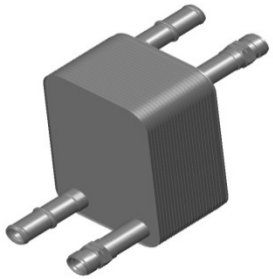
Ref.: 'Compact Heat Exchangers', Kays and London, 3rd Edition

Impact of Lower Effectiveness and HFC-152a is an Increase in Compressor Power

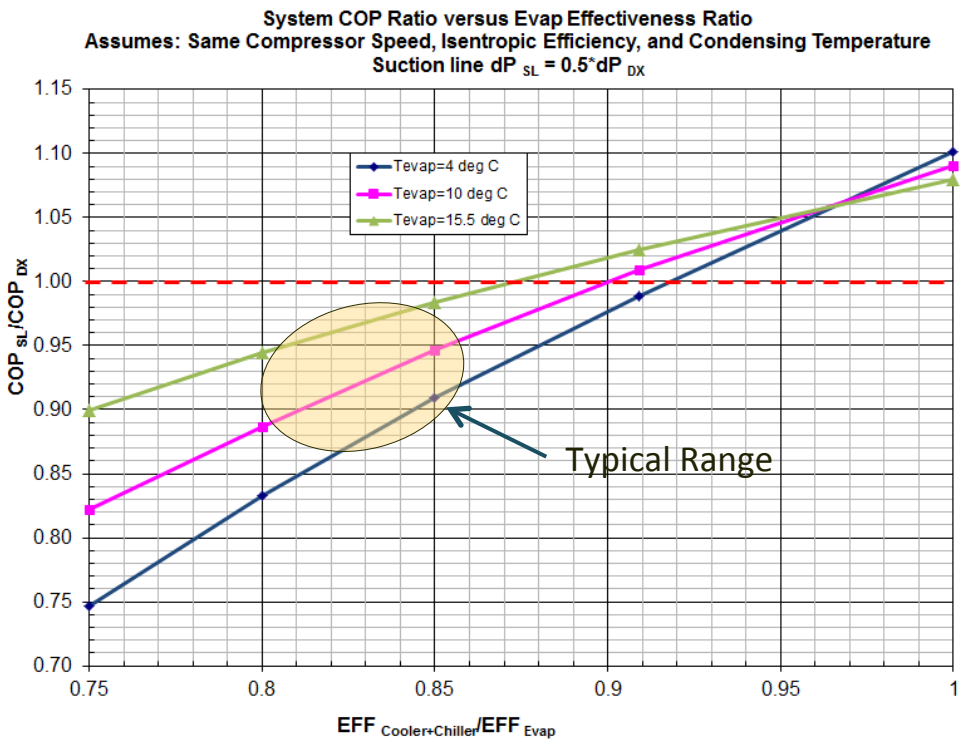
Energy Impact of Typical SL MAC System: Coefficient of Performance (COP)



MAHLE Cooler



MAHLE Chiller



Estimated COP Ratio vs. Effectiveness Ratio for DX vs SL,
L. Leitzel, MAHLE

Past Project COP of SL System Ranges from 85% to 95% of DX

CCAC Technical & Cost Performance Demonstration

Cooling Performance

- Cooling capacity (bench and wind tunnel tests)
- Cooling comfort (ride tests)
- Optimized engine loading by interaction of secondary loop coolant buffer with engine management system

Cost Performance

- Reduced refrigerant charge and refrigerant cost, but added cost of chiller, pump, and reservoir
- Less frequent and lower cost recharge from leaks, accidents or component failure
- Lower cost for additional cooling points

CCAC Environmental Performance Demonstration

Direct Refrigerant GHG Climate Performance

- Reduced refrigerant charge and life-cycle leak rate with shorter hoses, fewer fittings and integrated components (calculated using SAE J-2727)

Indirect Energy GHG Climate Performance

- Higher energy efficiency with EMS integration and cooling on deceleration (regenerative cooling)
- Higher fuel savings from stop/start by reducing the time stop/start is deactivated because it is too hot

Safety & Economy: SL-MAC HFO-1234yf

- Cost of additional secondary loop components offset by savings from reduced system charge and refrigerant for servicing
- Reduced charge encourages proper service using HFO-1234yf rather than improperly with lower cost HFC-134a that is a powerful greenhouse gas
- Lower life-cycle emissions reduce trifluoroacetic acid (TFA) formation from HFO-1234yf refrigerant degradation

Safety & Economy: SL-MAC HFC-152a

- Cost of additional secondary loop components offset by refrigerant cost savings compared to HFO-1234yf
- Proper service using HFC-152a because HFC-134a costs far more
- HFC-152a has no TFA degradation byproducts
- Use of HFC-152a refrigerant in leak-tight secondary loop systems is safe and approved under the US EPA Significant New Alternatives Policy (SNAP) Program and the EU F-Gas Directive (GWP=138)
- HFC-152a also satisfies SNAP and the F-Gas Directive in a direct expansion system with active safety system (leak detection and safe discharge similar to that proposed for HC-290 room ACs)