Industry Leadership in Motor Vehicle Air Conditioning (MACs) and Case Study of MAC Secondary-Loop Architecture Vital to Economic and Environmental Performance of All-Electric Vehicles

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MACS

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In Memory of: Ward Atkinson, Linda Gronlund, Elvis Hoffpauir, Simon Oulouhojian, Mack McFarland, Paul Weissler, and others who are no longer with us.

Acknowledgements: The authors are grateful to the contributors and peer reviewers of this history who, like the authors, were deeply involved in the successful evolution of climate control systems that are now safe for the stratospheric ozone layer, far more friendly to the climate, and well on the way to energy-efficient systems using sustainable refrigerants in all-electric vehicles.

Keywords: Automotive Leadership, Climate Forcing, Environmental Acceptability, Montreal Protocol, Motor Vehicle Air Conditioning, Stratospheric Ozone Depletion.

Guide to Readers

This publication offers the back and front story, the timeline, and the comprehensive bibliography of leadership in the full spectrum of environmentally improved motor vehicle air conditioning, including ozone-safe and climate-friendly refrigerants, leak-tight systems, repair before recharge with recovery and recycle, energy efficiency, and end-of-life recovery and recycle or destruction. It also elaborates on the partnerships that developed secondary-loop motor vehicle air conditioning (SL-MAC), which is a powerful driver of improved performance of all-electric vehicles that are necessary to avoid climate tipping points. The co-authors are insiders to this technical breakthrough.

SL-MAC technology developed through collaboration between government and industry is almost patent-free and is easily adaptable to the special circumstances of passenger and commercial vehicles, small or large, on-road or off-road, and internal combustion, hybrid, or all-electric.

In an appendix, the authors present the extended perspective of Matti Tapani Vainio, the EC regulatory authority who crafted the original MAC Directive limiting the global warming potential (GWP) for MAC refrigerants at 150. This allowed for the use of R-152a, which is an energy efficient refrigerant at high ambient temperatures, does not degrade in the atmosphere to trifluoroacetic acid (TFA), has no active patents on production processes, and can fit within the Kigali Protocol hydrofluorocarbon (HFC) phasedown. Matti does not recall advocating for a lower GWP cap, but Japanese and North American participants clearly recall the aggressive push by Danish, German, Norwegian, and other advocates for a cap at GWP 5 or 10 to exclude all but their speculative choices of R-744 (CO_2) and R-290 (propane). Japanese and North American MAC engineers and equipment manufacturers did not mind stringent limits based on life cycle climate performance (LCCP) but rejected a GWP-only criterion that ignored indirect energy emissions for cooling and embodied emissions from life cycle system manufacture and distribution.

Note that refrigerants are designated by full chemical formula, abbreviated chemical formula, and American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE) refrigerant number as per the following table:

Full Chemical Formula	Abbreviated Chemical Formula in Any Use	ASHRAE Refrigerant Number
CCl_2F_2 (dichlorodifluoromethane)	CFC-12	R-12
$C_2H_2F_4$ (1,1,1,2-tetrafluoroethane)	HFC-134a	R-134a
CH_3CHF_2 (1,1-difluoroethane)	HFC-152a	R-152a
$CH_3CH_2CH_3$ (dimethylmethane; propane)	HC-290	R-290
CO_2 (carbon dioxide)	CO_2	R-744
$CF_3CF{=}CH_2$ (2,3,3,3-tetrafluoro-1-propene)	HFO-1234yf	R-1234yf

Please refer to the help with acronyms and abbreviations and a glossary of specialized vocabulary. Note that each section has web links to further elaboration, and bibliography references are also linked to the web. Readers are encouraged to submit edits and additions to IGSD Technical Editor Sean Dennis (sdennis@igsd.org) for consideration by the authors.

Abstract

In November 2024, Ford Motor Company, on behalf of many automotive original equipment manufacturers (OEMs), petitioned the United States Environmental Protection Agency (US EPA) to list refrigerant R-290 (propane) as an environmentally acceptable refrigerant for secondary-loop heat pumps in all-electric vehicles. This technical breakthrough is the latest triumph in the continuous leadership of the motor vehicle community, working with government and environmental authorities, for continuous progress toward Earth-friendly and sustainable personal transportation. The authors and contributors to this paper were among the drivers of this 40-year market evolution.

This paper recalls and updates the remarkable history of partnership and cooperation in protecting stratospheric ozone and climate by fast actions on motor vehicle air conditioning (MAC) including: 1) refrigerant recovery and recycle empowered by regulations permitting the sale of refrigerant R-12 (chlorofluorocarbon (CFC)-12) only to certified MAC technicians trained to repair before recharge; 2) fast global transition from ozone-depleting R-12 to ozone-safe R-134a (hydrofluorocarbon (HFC)-134a), with an ~85% reduction in climate forcing[1] [2]; 3) pioneering life-cycle refrigerant management including leak detection and reduction; 4) perfecting and agreeing to a computer-assisted Society of Automotive Engineers (SAE) International standard for Life-Cycle Climate Performance (LCCP); 5) engineering support for regulation by the California Air Resources Board (CARB), the European Union (EU), United States Environmental Protection Agency (US EPA), and others; 6) global selection of ozone- and climate-safe R-1234yf (hydrofluoroolefin (HFO)-1234yf)[3]; 7) design, demonstration, and promotion of pathbreaking secondary-loop MAC cooling architecture optimized for lowest carbon footprint using R-152a;[4]8) global interest in R-290 (propane)[5] in energy-efficient, simple unidirectional heat pumps of all-electric vehicles designed and serviced for near-zero life-cycle emissions for safety and to minimize emissions of volatile organic compounds (VOCs)[6] that can contribute to the formation of photochemical smog[7]; and 9) a pending final global agreement to shift from now-obsolete R-134a to alternative low-GWP replacements like R-1234yf in vehicles marketed in developing countries, with sufficient infrastructure for the shift to all-electric vehicles safely using R-290 refrigerant in super-efficient heat pumps providing lowest feasible carbon footprint and highest possible driving range and reliability.

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[1] One-hundred-year global warming potential (GWP_{100}) values used for policy setting are from the International Governmental Panel on Climate Change (IPCC) Assessment Report Four (AR4). Most recent values from the World Meteorological Organization (WMO) can be found in Table A-1. Refrigerants for MAC applications.

[2] CFC-12 $GWP_{100\text{-}yr}$ =~ 10,200; HFC-134a $GWP_{100\text{-}yr}$ = ~1430 with smaller refrigerant charges, lower leak rates, recovery and recycle, and higher energy efficiency.

[3] HFO-1234yf $GWP_{100\text{-}yr}$ <1. However, the increase in trifluoroacetic acid (TFA) atmospheric degradation from ~20% for HFC-134a and ~100 for HFO-1234yf is mitigated by still lower leak rates and recovery recycle.

[4] HFC-152a $GWP_{100\text{-}yr}$ =~ 138; with smaller secondary-loop refrigerant charge, lower leak rates (monobloc, fewer fitting, no flexible hoses), recovery and recycle, and higher energy efficiency.

[5] HC-290 $GWP_{100\text{-}yr}$ <1; no TFA atmospheric degradation.

[6] Volatile organic compounds (VOCs) including AC-290 (propane) have a high vapor pressure and low water solubility. R-290 and its atmospheric degradation contribute to photochemical smog that causes short- and long-term adverse health effects.

[7] Photochemical smog is a mixture of pollutants that are formed when nitrogen oxides and VOCs react to sunlight and create a hazardous brown haze.

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1. Vehicle Air Conditioning is a Significant Fuel Use

In recognition of the indirect emissions resulting from the use of air conditioning to gain its recognized benefits to human health, Table 1 highlights mobile air conditioner (MAC) fuel over-consumption.

Table 1. Estimated motor vehicle fuel use and CO_2 emissions, 2003

Country or Region	Portion of Fuel Use
European Union (EU)*	3.2%
India**	20.0%
Japan*	3.5%
United States (US)**	5.5%

*Source for EU, Japan, and USA: Rugh and Hovland 2003
**Source for India: Rugh, Hovland, and Andersen 2003; 2004

2. The Global Vehicle Market is Growing Fast in a Hot World Getting Hotter from Climate Change

On Earth today there are about 8 billion people owning about 1.3 billion vehicles containing about 1 million tons of refrigerant, with refrigerant emissions of about 125 kilotons/year (Sadamori, Lane, and Scheffer, 2019). Canada, the EU, Japan, the Republic of Korea, Mexico, and the US require that new vehicles with air conditioning or heat pumps use climate-friendly refrigerants with global warming potential (GWP) <150, allowing R-152a, R-290, R-744, and R-1234yf.[8] MAC refrigerants R-134a and R-152a, but not R-1234yf, are controlled substances under the 2016 Kigali Amendment to the Montreal Protocol (listed in Appendix G of UNEP 2020). Pending regulations will likely restrict the use of refrigerants R-134a and R-1234yf due to their trifluoroacetic acid (TFA) atmospheric decomposition, which is considered under some definitions to be a per- and polyfluoroalkyl substance (PFAS); PFASs are referred to as "everywhere and forever" chemicals.

2024 was hottest in recorded history (NASA Online):

- Global temperature is rising fast with the seven most recent years being the warmest and 2016 and 2020 tied for the warmest year on record;
- The oceans are getting warmer, with the top 100 meters (328 feet) about 0.33° Celsius (0.67° Fahrenheit) warmer since 1969;
- The Antarctic and Greenland ice sheets are shrinking, and Arctic Sea ice is declining;
- The glaciers in the Alps, Himalayas, Andes, Rockies, Alaska, and Africa are retreating;
- Snow cover is decreasing;
- Global sea level has increased about 20 centimetres (8 inches) in the last century, with the rate of increase in the last two decades nearly double that of the last century and accelerating every year; and

[8] GWP_{100} values used for policy setting are from the International Governmental Panel on Climate Change (IPCC) Assessment Report Four (AR4). Updated values from the World Meteorological Organization (WMO) can be found in Table A-1. Refrigerants for MAC applications (WMO 2022).

- Extreme weather events such as cold snaps, heatwaves, heavy rainfall, hurricanes, and tornadoes are increasing in frequency and magnitude with corresponding property losses often exceeding insured coverage.

Additionally, the demand for vehicle refrigerant systems, along with energy to support electric vehicles, will continue to grow. Rational sustainable technologies are necessary to offset the potential climate impact.

The challenge is to rapidly penetrate global markets with all-electric vehicles powered by clean energy with an affordably low life-cycle carbon footprint. New technology is needed to cool and heat for passenger comfort and driver alertness, to defrost and defog windows for safety, and for thermal management of batteries and inverters to extend driving range and battery life. Multiple refrigerants have been considered to improve the sustainability of mobile air conditioning. Their attributes are summarized in Table 2**Error! Reference source not found.**.

Initially, R-152a, with a 94% reduction in direct CO_2 emissions, was demonstrated to have better cooling performance and higher energy efficiency for lower fuel use than R-134a systems, but with the challenge of higher flammability (Ghodbane et al. 2003). Furthermore, the improved fuel efficiency compared to R-744 would offset the higher GWP (R-152a: GWP =138; R-744: GWP = 1).

In 2008, the EPA's Significant New Alternatives Policy Program (SNAP) listed R-152a as acceptable for use in motor vehicle air conditioning systems but subject to use conditions. These conditions specified that manufacturers must incorporate safety features to assure that in case of a leak, refrigerant concentrations in the passenger cabin would not pose an undue flammability risk.[9] Engineering solutions such as a squib valve or a secondary loop architecture, which keeps the flammable refrigerant outside of the passenger compartment, can satisfy this requirement.

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[9] Specifically, the EPA stated that "EPA finds R-152a acceptable in new motor vehicle air conditioning systems with the use condition that systems must be designed to avoid occupant exposure to concentrations of R-152a about 3.7% in the passenger cabin free space for more than 15 seconds, in the event of a leak." Source: Federal Register, Volume 73, Number 114, Thursday, June 2, 2008, page 33306. https://www.govinfo.gov/content/pkg/FR-2008-06-12/pdf/E8-13086.pdf.

Table 2. Comparisons of refrigerants for mobile thermal systems

Refrigerant	ASHRAE Class	GWP[10] < 150	Heating	Cooling	TFA	VOC[11]	Recycle[12]	Refrigerant Price	MAC System Cost
R-134a	A1	😡	😟	😊	😡	😊	😊	😊	😊
R-152a	A2	😊	😊	😊	😊	😊	😊	😊	😊
R-290	A3	😊	😊	😊	😊	😟	😊	😊	😊
R-744	A1	😊	😊	😟	😊	😊	😊	😊	😡
R-1234yf	A2L	😊	😟	😊	😡	😊	😊	😟	😊
No-TFA HFC Blends	various	😊	😊	😊	😊	😊	😟	😟	😟

3. From Ventilation to Compressor-Assisted Air Conditioning

The first motor vehicles were only partially enclosed and had little protection from adverse weather but slowly evolved to have enclosed passenger compartments made more comfortable in hot weather by window shades and curtains, roll-up or swing-out windshields (such as the 1925 Chevrolet and 1928 Ford, respectively), air scoops (such as the 1918 Ford and 1923 Buick), swing-out side windows known as "ventipanes" or "wind wings" (such as the 1933 Fisher Body and 1933 Packard), fan-forced ventilation (such as the 1929 Cadillac), interior fans, and ducts to rear seats (such as the 1936 Hudson). Heating evolved from heated iron bars and bricks to air manifolds on exhaust headers, to hot water from engine cooling, and to on-board combustion and electric heaters with and without electric fans (Dickirson 2011).[13]

Those pioneering systems evolved into integrated heating and ventilation in vehicles such as the 1938 Nash, 1939 Studebaker, and eventually all vehicles. In 1939, Packard was the first automobile OEM to introduce a vapor compression mobile air conditioner (MAC) in about 2000 installations using R-22 for the 1940 through 1942 model years, with Cadillac offering about 200 R-22 systems in 1941 until air conditioning for comfort only was banned from new production during World War II (Dickirson 2011; Mitchell and Newton 2024).

These direct expansion (DX) vapor compression systems mostly used R-22 refrigerant, with the evaporator typically in the trunk and air discharge on the rear window package shelf. In 1953, Buick, Cadillac, Lincoln, and Oldsmobile offered vehicles with MAC using R-12, and Chrysler offered vehicles with MAC using R-22. Packard offered MAC in 1954. Pontiac and Nash

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[10] All refrigerants should be responsibly sourced: R-744 from fermentation not fossil fuel; R-290 from landfill and animal biopropane; fluorocarbon refrigerants without process emissions.
[11] VOC emissions of R-290 are mitigated if leak-tight and recovered and recycled or destroyed.
[12] All refrigerants should be recovered to avoid hazardous aerosol lubricant emissions; R-290 should be recovered to avoid hazardous flammable and VOC emissions.
[13] The history of heating and air conditioning of motor vehicles is consolidated from Atkinson 1989; Seidel 1996; Nagengast 1988 and 2002; Andersen and Sarma 2002; Atkinson 2008; Dickirson 2011; Andersen et al. 2013; and Mitchell and Newton 2024. Please report any errors and omissions to the corresponding lead author: sandersen@igsd.org.

introduced the integrated cooling, heating, and ventilating system followed by Chrysler's application of series reheat in the early 1960s. This integrated heating, cooling, and ventilation architecture is used today for all DX belt-driven systems with the compressor and condenser in the engine compartment and the evaporator in the passenger compartment. Auto manufacturers continued to offer R-22 systems in the early 1950s, but these eventually gave way to R-12 systems.

The 1955 Chevrolet offered series reheat as described in Figure 1.

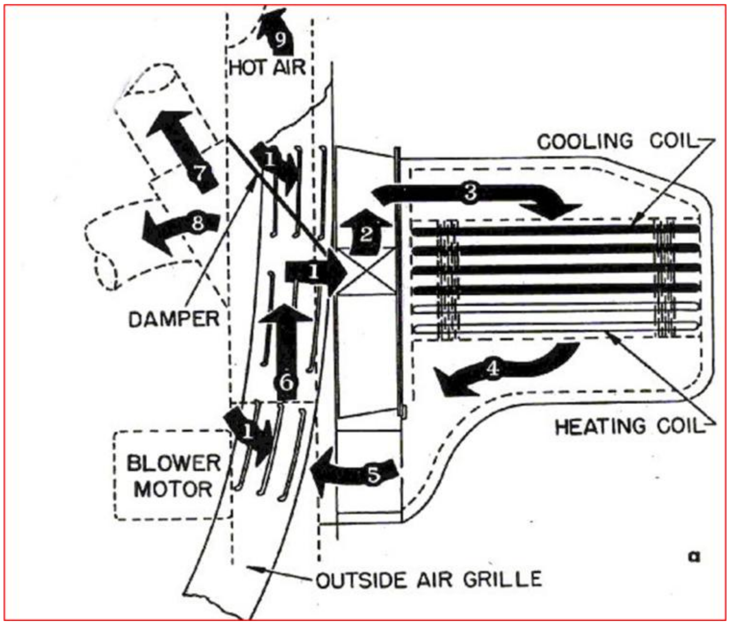

Figure 1. 1955 series reheat

It is notable that in 1964, General Motors (GM) introduced an automatically controlled air conditioning system that utilised low side control via evaporator regulation (EPR) technology and later developed their own POA valve (Pilot Operation at Absolute) devices. The system ran the evaporator coil temperature at just above freezing. Antifreeze warmed by the internal combustion engine then re-heated the cooled and dehumidified air to the selected comfort setting.

When the Montreal Protocol was signed in 1987, about 70% of cars in the US and about 50% of cars in Europe and Japan were equipped with MACs. By 2003, 99% of US cars and about 85% of cars in Europe had MACs. In 2025, almost all four-wheel new cars worldwide have MACs for comfort, resale value, and to fulfil safety standards for demisting windshields.

4. The Story of Secondary Loop MAC Rise to Prominence in Protecting Stratospheric Ozone

The 16 September 1987 signing of the Montreal Protocol on Substances that Deplete the Ozone Layer (Montreal Protocol) was a driver of fast MAC action to reduce R-12 emissions and to transition to R-134a.

The MAC community embraced stratospheric ozone science and welcomed engineering challenges, using the Society of Automotive Engineers (SAE) International standards organization and the Mobile Air Conditioning Society (MACS) service organization to coordinate efforts and actions. The community also partnered with the US EPA and other governmental organizations and environmental non-governmental organizations (NGOs).

SAE International along with governmental and NGO partners embarked on non-competitive Cooperative Researched Projects (CRPs) that combined intellectual, laboratory, and financial assets to rapidly commercialize technologies to protect the ozone layer and climate with minimal duplication and maximum outcome.

Table 3. SAE International Cooperative Research Projects (CRPs)

Time Interval	Topic	Abbreviation	Funding (US $)*
1990–1991	Refrigerant oil compatibility	RO CRP	< $500,000
2001–2004	Alternative refrigerant choice	AR CRP	< $750,000
2004–2007	Improved MAC	IMAC CRP	~ $1,000,000
2006–2008	GWP < 150	150 CRP	~ $3,000,000
2007–2009	Hydrofluoroolefin (HFO)-1234yf	R-1234yf CRP	~ $3,000,000
2011–2013	Refrigerant blends AC5 & AC6	MRB CRP	~ $1,700,000
2012-–2013	Daimler claims R-1234yf unsafe	R1234-4 CRP	
2020–ongoing	Thermal management refrigerant	TMR CRP	~ $8,000,000

*Funding includes cash and in-kind contributions. Estimated by SAE and authors.

Table 4. Indicative participation in SAE CRPs (2001 AR CRP)

Expert	Organization
Stephen O. Andersen	US EPA
Ward Atkinson	SAE Climate Control Technical Standards Committee
Dejan Beatovic	University of Illinois
Jing Che	University of Illinois
Stefan Elbel	University of Illinois
Hans Fernqvist	Volvo Car Corporation
Pega Hrnjak	University of Illinois
William R. Hill	GM Corporation
Xinzhong Li	University of Illinois
Andy Musser	University of Illinois
Andy Pastor	University of Illinois
Rotating Members	Alliance of Automobile Manufacturers (United States)
Rotating Members	Japan Automobile Manufacturers Association (JAMA)
Rotating Members	Verband der Automobilindustrie (VDA) (Germany)
Steve Lepper	Ford Motor Company
Chris Seeton	University of Illinois
Kevin Traeger	University of Illinois
Juergen Wertenbach	Daimler-Chrysler Corporation

Table 5. Indicative scope of SAE Phoenix vehicle performance and comfort testing (2003)

Vehicle	MAC System Supplier	Refrigerant
Alfa Romeo AR147	Delphi	R-744
BMW 3 Series	BMW	R-744
Cadillac CTC	Visteon	Enhanced R-134a
Chrysler Liberty Sport	Modine	R-744
Honda Civic Hybrid	Honda	R-134a
Nissan Cube	Calsonic Kansei	R-744

Jaguar S Type	Visteon	R-744
Pontiac Grand Prix	GM	R-134a
Saturn Ion	Delphi DX	R-152a
Toyota Celsior	Denso	R-744
Volvo S60 (car one)	Delphi SL	R-152a
Volvo S60 (car two)	Volvo	R-134a

Source: Atkinson 2003

Initiated in 1998 by Ward Atkinson, the Phoenix Forums (held in Scottsdale, Arizona) brought together researchers working on alternative refrigerants. Each Phoenix Forum included vehicle demonstrations, ride and drive assessments, and paper presentations on alternative refrigerants and associated system design for MACs. The last forum took place in 2012.

Table 6. Presentations on secondary loop systems

Year	Subject	Presenters
2012	Secondary Loop System for Automotive HVAC Units using phase change materials (PCM) as Thermal Storage	Jürgen Köhler, Julia Lemke, and Nicholas Lemke (Institut für Thermodynamik)
2012	Transient Performance of Alternative Refrigerants in Secondary Loop A/C	Magnus Eisele, Dr. Yunho Hwang, and Dr. Reinhard Radermacher (Center for Environmental Energy Engineering (CEEE), University of Maryland)
2012	An Experimental Comparative Analysis of Mobile Alternative Refrigerant Air Conditioning System	KATECH (Korea Automotive Technology Institute), Doowon Climate Control Co. Ltd., and KB Auto Tech
2011	Virtual Testing of Off-Period Cooling with Secondary Loop System	Dr. Magnus Eisele, Yunho Hwang, and Reinhard Radermacher (CEEE, University of Maryland)
2008	The 4 Opel Astra Experiment and Other Considerations on Refrigerants	US EPA, Delphi, and GM
2003	Secondary Loop R-152a Mobile A/C System	Dr. Mahmoud Ghodbane (Delphi) and Hans Fernqvist (Volvo)

A/C = air conditioner or air conditioning

Four immediate changes reduced the demand for refrigerants in MACs by nearly 50%: 1) recovery and recycling in service, 2) system redesign with smaller refrigerant charge, 3) new hose and seal materials in new systems and in service, and 4) halting the sale of R-12 for do-it-yourself (DIY) service without proper training and tools[14] (Atkinson 2008). Consider also that the new focus on MAC environmental performance motivated simultaneous redesign for energy efficiency including: 1) optimal refrigerant charge by weight, not pressure; 2) micro-channel heat exchangers, variable capacity compressors, and software algorithms to provide higher energy performance with less weight and cost; 3) MAC system controls instantaneously harmonized to engine load; and 4) better thermal insulation, better glazing that cut the infrared heat entering the cabin, and air distribution only to occupied seats.

[14] It is estimated that professional service with leak detection, recover and recycle, and leak repair before recharge uses one-tenth the refrigerant over the life of the vehicle.

In January 1988, US EPA, SAE, and MACS formed a new partnership to simultaneously pursue refrigerant recovery and recycle performance standards, design, testing, technician certification, market commitment by vehicle manufacturers, and promotion by environmental NGOs—delivering significant leak reduction and dramatically reducing service emissions. Global recovery-recycle machine sales were about US $1 billion in 1989 and continue today worldwide.

Refrigerant recovery and reuse and leak reduction in the MAC sector were far more successful than fluorocarbon manufacturers had anticipated, resulting in an immediate oversupply of R-134a with the environmental advantages of stable, low prices. The eventual oversupply of R-12 avoided costly retrofit of legacy systems and allowed the Montreal Protocol to accelerate the phaseout of ozone-depleting substances (ODSs), most of which are also powerful greenhouse gases (GHGs).

In March 1988, DuPont[15] reached agreement with most fluorocarbon producers and large manufacturers of products made with or containing ODSs to cross-license—royalty-free—all replacement technology and know-how as long as those participating enterprises gave reciprocal free use of their intellectual property and know-how and committed to a rapid ODS phaseout (Holliday 2024). Thus, unearned monopoly profits were avoided from CFC and HCFC refrigerant shortages. Most importantly, this technical progress by industry allowed the Montreal Protocol to accelerate the ODS phaseout to put the stratospheric ozone layer on the path to recovery, with climate co-benefits from not-in-kind (NIK) and fluorocarbon replacements with lower GWP.

[15] In 2015, DuPont spun off its performance chemicals business into a separate entity named the Chemours Company. References in this document refer to DuPont before the split.

5. About ODP and GWP Calculations and Values for Setting Policy

Ozone-Depletion Potential (ODP) is the metric that measures the cumulative impact of a refrigerant on stratospheric ozone relative to CFC-11, which has an ODP defined to be 1. A refrigerant with a larger ODP destroys more stratospheric ozone than a gas with a smaller ODP.

GWP is a metric that measures how much a gas contributes to global warming relative to carbon dioxide (CO_2), which is the reference chemical set at GWP = 1. For example, the IPCC AR4 GWP for R-12 is 10,900 times more potent than CO_2. GWP depends on the heat absorption bands of the gas, its lifetime in the atmosphere, its molecular weight, and the time period over which the climate effects are of concern. A number of simplifications are used to derive values for GWP.

For administrative convenience, policy makers typically link published regulations to the IPCC AR4 values while using the latest scientific calculations for estimates, such as the benefits of ongoing technical progress in the MAC sector. However, GWP values can change over time due to: 1) changes in the energy absorption of a ton of one gas versus another as concentrations of GHGs in the atmosphere shift; 2) changes in the estimated atmospheric lifetime of the reference chemical CO_2 as carbon sinks are saturated; and 3) advancements in atmospheric science and monitoring.

Box 1. Total Equivalent Warming Impact and Life Cycle Climate Performance

The pioneering metric for cooling impact was Total Equivalent Warming Impact (TEWI), which was developed under contract by experts at Oak Ridge National Laboratory (Fischer et al. 1991). While TEWI considered the impact on climate of "direct" refrigeration emissions and "indirect" energy impact to supply power for cooling equipment, TEWI did not consider the climate impact of emissions "embodied" in refrigerant, equipment, logistics, and service. For example, TEWI ignored the impact of process emissions of HFC-23, a powerful GHG which alone added about 20% to the GWP of HCFC-22.

The life cycle climate performance metric (LCCP) is a more comprehensive metric for assessing the life cycle carbon footprint of MACs, and as applied by the global MAC community through the SAE J-2766 technical standard, considers factors such as the weight of the air conditioner or heat pump that requires energy to transport, whether operating or not. LCCP includes direct refrigerant emissions calculated from GWP, indirect biomass and fossil fuel emissions to power climate control systems, and embodied emissions of manufacturing and transportation of chemicals, components, and systems (Papasavva and Moomaw 1998; TEAP HFC/PFC TF 1999; Hill and Papasavva 2005; Papasavva, Hill, and Brown 2008; Papasavva, Hill, and Andersen 2010; Papasavva and Andersen 2011; Andersen, Halberstadt, and Borgford-Parnell 2013; Hwang and IIR 2016; Lee et al. 2016; Wan et al. 2021; OTS R&D n.d.).

Table 7. Comparison of refrigerants in MAC applications

Refrigerant	Nomenclature*	ODP**	$GWP_{100\text{-}yr}$***	TFA or VOC?
R-12	CFC	1.0	10,200	Not TFA Not VOC
R-134a	HFC	0	1430	TFA
R-1234yf	HFO	0	4	TFA
R-152a	HFC	0	138	Not TFA Not VOC
R-290	HC	0	<1	VOC

1990 ODP and GWP values from the IPCC Assessment Report Four (AR4).
*Note that chemical nomenclature is the agreed abbreviation to simplify communication of specific refrigerants and is not a reliable indicator of environmental performance or acceptability.
**CFC-11 was the reference chemical in IPCC AR4 for ODP set equal to 1.
***CO_2 is the reference chemical for GWP set equal to 1.

Note: See Appendix C for GWP values as per the *Scientific Assessment of Ozone Depletion: 2022* (WMO 2022).

The automotive industry was fast in the global selection of R-134a to quickly replace R-12 for MACs for compliance with the accelerating Montreal Protocol phaseout schedule and continuing the search for improved mechanical MAC systems using sustainable refrigerants (Will 1999; Andersen, Sarma, and Taddonio 2007; Atkinson 2008; Calm 2012; Andersen, Halberstadt, and Borgford-Parnell 2013). While R-134a has an ODP of zero and about seven times lower GWP than R-12, 20% of R-134a by volume degrades to TFA.

Intrigued by new cooling cycles, European automobile manufacturers persuaded the European Community (EC) Industrial and Materials Technology Program to fund a three-year research and demonstration consortium called the Refrigeration and Automotive Climate under Environmental Aspects (RACE). RACE members quickly embraced Gustav Lorentzen's design for R-744 (carbon dioxide) cooling and demonstrated its impressive technical performance that they hoped to improve enough to be comparable to R-12 and R-134a (Lorentzen and Pettersen 1992; 1993; Andersen and Zaelke 2003; Kim, Pettersen, and Bullard 2004).[16]

At the 1998 SAE Congress, Daimler's Jürgen Wertenbach presented the results of the RACE CO_2 MAC testing to Ward Atkinson, then Chair of the SAE Interior Climate Control Standards Committee (Sun Test Engineering), James A. Baker (GM/Harrison Radiator), and Brian Landsbury of Rover. Shortly after, Wertenbach and Atkinson agreed that the RACE results should be shared globally and agreed to invite anyone with novel MAC technology to conduct head-to-head tests the next summer in Phoenix, Arizona (Andersen and Zaelke 2003; Kim, Pettersen, and Bullard 2004; Atkinson 2008). "If you can cool it in summer in Phoenix, you can cool it anywhere!" Thus, the SAE Automotive Alternate Refrigerants Systems Symposium (Phoenix Forum) was launched, attracting global MAC designers to an annual event for the decade that followed.

German manufacturers from the RACE project brought to Phoenix test vehicles with CO_2 Lorentzen systems, and US manufacturers working with the US EPA brought vehicles with

[16] The OECD has 38 members, 22 of which are EU member states.

secondary loop systems using R-152a refrigerant. Vehicle road testing with data loggers and human judges confirmed R-744 and R-152a cooling capacity performance, but each had conspicuous energy-efficiency and component challenges. For example, a component of one R-744 system exploded loudly from high operating pressure, damaging the headlight and grill but causing no injuries. Simultaneous technical sessions reported a full spectrum of engineering challenges and promising solutions for leak testing, safety, energy efficiency, reliability, affordable service, and compliance with pending MAC regulations in the EU, USA, and elsewhere (Andersen and Zaelke 2003; Atkinson 2008; Andersen et al. 2013).

German automobile manufacturers Audi, BMW, Daimler, and Volkswagen (VW) strengthened and redoubled their efforts to commercialize R-744 MACs and involved a wide range of global systems suppliers, with research and development costs exceeding one billion US dollars (informally estimated).

European, Japanese, and North American vehicle manufacturers and systems suppliers including Delphi, Fiat, Ford, General Motors, Red Dot, Sanden, and Volvo—working with the US EPA—cooperated on secondary loop architecture for vapor compression systems to resolve issues of energy efficiency, bulk and weight, and control systems. A detailed timeline history of the MAC-based secondary loop architecture is included in Appendix F.

US EPA anticipated the success of both R-152a and R-744 with a decision to orchestrate the listing under the EPA SNAP.[17] The EPA also determined that about half of US states had prohibited the use of flammable refrigerants such as R-152a and had restricted the use of high-pressure gases such as R-744. Kristen Taddonio and Stephen O. Andersen, in an extracurricular partnership with two US motor vehicle manufacturing associations and outside the authority and remit of US EPA, took on a five-year project for removal of state barriers (Taddonio et al. 2023). This forethought proved essential when R-1234yf, which is considered mildly flammable under ASHRAE classification procedures, was selected as a low-GWP replacement for R-134a (as described later in this paper).

In parallel with the RACE project and Phoenix Form work, the EU was working toward a regulation to limit the GWP of refrigerants via what is now known as the F-gas regulation. Initial reports were that GWP =1 would be the new limit. In response, Stephen O. Andersen, James A. Baker, Ward Atkinson, Matti Tapani Vainio, and others worked successfully with the EC to set the cap on MAC $GWP_{100\text{-}yr}$ at 150 as published by Intergovernmental Panel on Climate Change (IPCC) AR4, which explicitly and intentionally allowed R-152a (IPCC AR4 $GWP_{100\text{-}yr}$ =138), R-744 (IPCC AR4 $GWP_{100\text{-}yr}$ =1) and R-1234yf (IPCC AR4 $GWP_{100\text{-}yr}$ = 4 but now revised down to <<1 in WMO et al. 2022).

Within weeks of the 2006 EC F-gas Directive, international chemical manufacturers Asahi, Arkema, DuPont, Honeywell, Ineos, and Sinochem announced refrigerants suitable for MACS with $GWP_{100\text{-}yr} < 150$, including HFO-1234yf (IPCC AR4 $GWP_{100\text{-}yr}$ = 4). R-1234yf was attractive to automakers because an industry cooperative development project demonstrated that the energy

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[17] R-152a and R-744 are the only replacements for ODS SNAP-listed from inside EPA without named corporate applicants. Arguably, EPA could have taken this approach on a wide range of unpatented solutions where commercialization costs cannot be recovered in competitive markets.

and cooling capacity of R-1234yf in systems incorporating an internal heat exchanger (IHX) is comparable to R-134a. Auto manufacturers also expected, albeit falsely, that the six R-1234yf suppliers would offer competitive pricing from geographically distributed chemical processing facilities with very low probability of supply disruption.

R-744 commercialization stalled over poor cooling performance in high ambient temperatures, unresolved methods of leak detection in 400+ ppm CO_2 in ambient air, and the incremental system cost estimated by Harry Eustice from GM of about US $300 per system, which was at least US $250 more expensive than the estimate for the incremental cost of a Secondary Loop MAC (SL-MAC) using SNAP approved R-152a (Andersen et al. 2017).

6. The Seminal Tata Motors Demonstration Sponsored by the Climate and Clean Air Coalition

In 2014, the Climate and Clean Air Coalition (CCAC) funded a demonstration project with MAHLE, Tata Motors Limited (TML), and IGSD to determine the economic, environmental, and technical performance of R-152a in an SL-MAC.[18]

The demonstration vehicle was a production Tata sport utility vehicle with dual front and rear cooling points.

Figure 2. Technical Review Committee, Lockport, New York, September 2017

MAHLE's Advanced Engineering team in Lockport, New York received the vehicle from TML India and refit it with the new single primary loop refrigerant-to-coolant heat exchanger and dual coolant to air secondary loop heat exchangers. As part of the vehicle build, a coolant pump and reservoir were also added along with a thermostatic expansion valve (TXV) matched to R-152a. MAHLE test chamber results confirmed acceptable cooling performance and the prolonged ability to maintain passenger comfort with the A/C compressor off by only using the cold energy stored in the circulating coolant. Data showed off-time versus coolant quantity as a metric to take advantage of the cold storage.

[18] The IGSD project team led by Dr. Stephen O. Andersen included Kristen N. Taddonio, Dr. Nancy J. Sherman, and Melinda Soffer. The MAHLE Advanced Engineering team led by Timothy Craig included Dr. Sourav Chowdhury, Dr. Prasad Kadle, and Lindsey Leitzel. The Tata Motors team led by Sangeet H. Kapoor included Maneesh Arora, Jagvendra Meena, and Prasanna Nagarhalli.

The vehicle with the updated R-152a single secondary loop (SSL), dual cooling point system was then returned to India for further comfort and energy efficiency evaluations by TML and then road testing. Further development at the Tata test facility matched with new control software algorithms improved the vehicle's fuel economy by up to 4%. This cost effectiveness of fuel efficiency improvement is almost unprecedented as compared to other applications of cold storage in today's production vehicles that typically achieve just a fraction of the fuel economy improvement demonstrated in the CCAC demonstration project.

Figure 3. MAC testing at Tata Climate Control Laboratory, Pune, India, February 2018

Because of the CCAC project's success, TML requested that the SAE Interior Climate Control Committee (ICCC) standards be updated to outline the safe application of R-152a in an SSL configuration. In response, a workshop was organized in Phoenix that developed a detailed list of all the ICCC standards and the content that required revision to enable SSL R-152a. Updates to the standards were completed over the next two years.

Although the introduction of R-1234yf, regulatory changes in India, and the evolution of the heat pump in EVs combined to stall its implementation, R-152a remains a viable, low cost, unpatented, TFA-free, super-efficient low-GWP candidate, alone or as part of a blend, for replacement of both R-134a and R-1234yf.

Following this SSL system demonstration, both the OPTEMUS and UTEMPRA projects noted in Appendix F. MAC Timeline with Indicative Firsts and Seminal Associated Events applied dual secondary loop (DSL) systems for cooling and general thermal management of EVs. Moreover, current work to apply refrigerant R-290 in a DSL has been proposed by vehicle OEMs as the next generation, sustainable, non-PFAS option for EV thermal management.

7. Timing is Everything

With the benefit of hindsight, it is useful to examine what key stakeholders knew at each important decision point in the evolution of refrigerants for MACs and how these refrigerants satisfied economic and environmental criteria.

Table 8. Refrigerants and market transitions

Refrigerant	Period of Use in New Vehicles	Years of Use	Overview of Transition Market Drivers
R-22	1940s and 1950s	20	The first MACs were fabricated from the components of stationary ACs that used R-22, creating the first market in light duty vehicles (LDVs).
R-12	1960s to 2003	50	R-12 systems proved lighter, smaller, more energy-efficient, and less expensive than R-22 systems; the unanticipated pitfall is stratospheric ozone depletion and climate forcing; global market demand rapidly increases worldwide.
R-134	1990 to ?	35+	An ozone-safe replacement for R-12 with no incremental equipment cost at scale, refrigerant costing only about US $5 more per system, and with ~7x lower GWP and comparable energy efficiency; the unanticipated pitfall is an estimated 20% atmospheric degradation leading to life cycle TFA and PFAS pollution.
R-1234yf	2013 to ?	25?	Ozone- and climate-safe but with an estimated 100% atmospheric degradation to TFA and PFAS pollution.
R-744	Limited availability currently		Premiered in 2002 in the Toyota fuel-cell hybrid vehicle (FCHV) using a Denso system and was offered in the mid-2000s as an option in Mercedes S and E-Class, but S and E offerings were then reverted to R-1234yf. Introduced by VW around 2019 for use in VW all-electric vehicles sold in temperate climates; VW now sells ID4 vehicles in Canada with heat-pump systems that use R-744; Audi offers one model with R-744 in select markets.
R-152a	Experimental only so far		Successful demonstration by Red Dot in rooftop overland commercial trucks for selected off-road applications such as agriculture, construction, forestry, and mining (Hartley and Hansen 2005). Successful on-road demonstration of an internal combustion engine SUV with a secondary loop architecture dual-cooling system (CCAC-IGSD-TML-MAHLE 2016–2019).
R-290	Pending for dual SL-MACs in all-electric vehicles and possibly in any electrically driven DX or SL system		Announced by Ford Motor Company on behalf of many OEMs for MAC heat-pump systems in all-electric vehicles that heat and cool occupants, batteries, and inverters; and defrost and demist.

8. List of Notable wins and losses on the path to environmentally friendly MACs

- **Technology WIN: R-12 and R-22 First Choice MAC Refrigerant Environmental LOSS: energy inefficient and an ozone-depleting GHG**

  The pioneering choices of R-12 and R-22 for the first MACs was made entirely to take advantage of components available from stationary A/C, where space and weight are not barriers.

- **Technology WIN: Efficient, non-toxic, non-flammable R-12 replacing inferior LCCP R-22**
  Environmental LOSS: both are ozone-depleting GHGs

The selection of R-12 occurred once the market was large enough to justify custom component designs matched to R-12.

- **Technology and Environment WIN**: GM's William Kume discovered that all the refrigerant was not captured by recovery equipment meeting the EPA and SAE vacuum/duration specifications. This failure was promptly reported to EPA, SAE, and other partners who immediately resolved it with a new standard requiring higher vacuum and longer recovery time.[19]

- **Technology WIN: Efficient, non-toxic, non-flammable R-134a rapidly replacing R-12 worldwide**
  Environmental WIN: Protected stratospheric ozone and reduced climate forcing
  Environmental LOSS: 20% atmospheric degradation of R-134a to TFA and still unsustainable climate forcing

  The shift from ozone-depleting R-12 with GWP 10,900 to ozone-safe R-134a with GWP 1,430 was the only available choice that could be implemented quickly to put the ozone layer on the path to recovery. The significance of R-134a degrading to TFA was not understood until the global industry had already made the shift. The incremental cost of MAC systems with R-134a was only about US $5, which was unnoticed by vehicle buyers who ultimately benefitted from improvements in leak tightness and refrigerant recovery and recycle that reduced life-cycle ownership costs.

- **Technology WIN: R-744 research for MACs supported success in supermarket and industrial refrigeration and domestic water heating**

  Global MAC sector enterprises and European public financing contributed up to US $2 billion in research and development that helped R-744 penetrate supermarket and industrial refrigeration with efficient compressors and controls and containment of refrigerant gases at very high pressure. Many of these technical breakthroughs were adapted to refrigeration, air conditioning, and heat pumps in every application.

- **Technology WIN: Global collaboration simultaneously improved economic, environmental, and technical performance**

  Policy makers and the public persuaded engineers at all levels to optimize systems for cooling and energy performance and for minimizing leaks in normal operation and service. System optimisation has driven enhanced component design and refrigerant charge levels. Electrically driven cooling and heat-pump systems take advantage of compressor speed control and smart controls that constantly rebalance mass flow of refrigerant as a performance parameter to keep vapour temperatures under control. Engineers and system integrators increasingly focus on all design parameters for system enhancement of cooling capacity and energy efficiency. (Atkinson 2008; Andersen, Halberstadt, and Borgford-Parnell 2013; Mitchell 2023)

- **Technology WIN: Development and commercialization of on-site refrigerant recycling and reuse at service for MAC systems**

[19] Ironically, US EPA was unwilling to admit the failure and strengthen the standard, so SAE implemented its own superseding workaround by declaring that new equipment must satisfy the new standard in order to be listed under the old standard.

Environmental WIN: **Contributing to the protection of the Earth's Ozone Layer and slowing climate change**

Recycling and reuse prevented hundreds of millions of tons of CFC-12 from being emitted to the atmosphere.

- **Environmental WIN: EU MAC F-GAS rule limiting MAC refrigerant GWP <150**

  The original EU proposal was to cap MAC GWP at 1, with R-744 the only disclosed refrigerant meeting that criteria. Now, three decades and a billion US dollars of investment later, CO_2 has still not demonstrated cost, reliability, and cooling performance suitable for hot and humid climates that are getting hotter from fossil-fuel and other GHG emissions.

- **Technology WIN: Introduction and successful development of Secondary Loop technology** and the accompanying Risk Assessment guidelines to assure the safety of selected refrigerants.

- **Environmental WIN: Ability to use refrigerants rejected in the past, notably R-290**, that promise to provide the lowest possible adverse effects on the global climate.

- **Fluorocarbon Monopoly WIN; R-1234yf selected to replace R-134a**

  In retrospect, the choice of R-1234yf to replace R-134a was economically, environmentally, and technically an inferior choice to R-152a in SL-MACs; misinformation from the fluorocarbon industry drove this decision. MAC and environmental authorities did not know at that time that 100% of R-1234yf would atmospherically degrade to TFA and that TFA is considered under some definitions as an "everywhere and forever" perfluoroalkyl and polyfluoroalkyl substance (PFAS) that is subject to prohibition and possible recall or penalty. MAC and environmental authorities—and the half dozen fluorocarbon producers with process patents to produce and competitively market R-1234yf—did not know that DuPont and Honeywell had "application patents" that would extract unearned monopoly profits reflected in pricing at about twice the cost of production (Seidel and Ye 2015; Seidel and Ethridge 2016; Sherry et al. 2016; Deo and Callahan 2022; Taddonio et al. 2022). Due to the monopoly-based pricing, R-1234yf only penetrated markets where required by regulation or rewarded by incentives, with most automobile manufacturers fitting MACs with R-134a for markets, such as developing countries, where R-134a is not yet prohibited.

  Looking back, the authors can see the situation as it unfolded:

  - MAC global industry and environmental authorities identified R-152a and R-744 as top runners in low-GWP MAC refrigerants (R-290 was determined to be far too flammable for the refrigerant charge necessary in a DX MAC to cool an automobile at high ambient temperatures, humidity, and clear sky sun).
  - The EC sets the cap for GWP < 150 as recommended by Stephen O. Andersen, Ward Atkinson, James A. Baker, William R. Hill, Matti Tapani Vainio, and other experts to allow for consideration and development of refrigerants other than R-744, which ultimately failed to satisfy cooling-capacity, energy-efficiency, and economic-performance criteria.
  - A half dozen fluorocarbon companies disclose chemical process patents and plans to supply R-1234yf at a competitive commodity price of about US $77.00/kg (US $35.00/lb.)

- Honeywell and DuPont keep secret from automobile and environmental authorities their application patent[20] for MACs and do not report R-1234yf and feedstock degradation to TFA with environmental toxicity and ecosystem concerns.
- SAE technical standards committee undertakes an R-1234yf review that would not have occurred for a technology with just one supplier (violation of SAE ethics and charter), and US EPA undertakes an accelerated SNAP review unaware of TFA/PFAS degradation. Automobile manufacturers might not have taken the risk of DuPont and Honeywell setting the refrigerant price for a DX MAC with no other GWP <150 option. Moreover, the antitrust investigation of R-1234yf essentially put a stop to the global MAC industry's non-competitive cooperative research for more than a decade.
- The added cost of a DX system with competitively priced R-1234yf was estimated at about US $35 (mostly added refrigerant cost); the cost of an R-152a SL system at about $50.00 (mostly cost of added components not yet at economy of scale); and the added cost of a R-744 system up to about $300 (mostly cost of added components and upgrade of all parts for high operating pressures). It is noteworthy that the added internal combustion engine (ICE) vehicle fuel efficiency of the R-152a SL system more than offsets the higher GWP of R-152a compared to R-744.
- OEMs falsely believing that R-1234yf DX systems would cost less than R-152a SL systems and not knowing the TFA/PFAS environmental consequences announced their selection of R-1234yf as a climate-friendly MAC refrigerant and suspended work on R-152 SL-MACs and associated chiller development.
- Meanwhile, a coalition of automotive OEMs and fluorocarbon refrigerant suppliers successfully persuaded the US EPA to offer credits toward tailpipe carbon emissions. Vehicle manufacturers calculate that the cost of credits by measures other than low-GWP MACs is at least US $200 per vehicle and in some cases US $300.
- SAE stumbled onto application patents and confronted Honeywell and DuPont. Honeywell and DuPont admit not disclosing the patents but do not admit guilt or accountability. Automobile OEMs had passed the point of no return, having suspended development of the R-152a SL-MAC and having contracts and work underway to implement R-1234yf by the time of the tailpipe rule. Honeywell and DuPont realize that at double the cost, R-1234yf is still the least-cost choice for automakers to satisfy CO_2 tailpipe limits (interviews – Andersen and Craig 2025).

- **Economic, Environmental, and Technical WIN-WIN-WIN: Selection of LCCP Superior, TFA/PFAS-free R-290 SL heat-pump systems for all-electric vehicles**

  In 2021, an SAE CRP titled Thermal Management Refrigerant (TMR)—driven by automotive corporate leadership and not by regulation—was initiated by Angelo Patti with SAE's Mark Klavon as project manager and communicator.[21] The goal was to identify refrigerants and thermal system designs that provide benefits to all-electric vehicles. Most of the effort was focused on enhancing thermal operation in heat-pump mode to augment occupant, inverter, and battery heating in the absence of sufficient waste heat abundant in ICE vehicles. The CRP team quickly incorporated into the project the discovery that the low-quality waste heat of EV

[20] US Patent Nos. 7,534,366 filed 27 October 2003 and 7,279,451 filed 29 April 2004.

[21] SAE TMR CRP Project Manager Mr. Mark Klavon; mark.klavon@sae.org.

batteries, inverters, and motor/generators can be recovered and pumped up to the temperature level required for passenger comfort.

Several teams were formed, termed Sub-CRPs, to investigate newly formulated blend refrigerants along with a team to study applying R-290 in a DSL system and another to study only system design changes using R-1234yf to improve performance.

As the project progressed, the spectre of regulation of TFA as a PFAS arose under the proposed EU definitions. This new possibility of regulation placed more urgency on the non-PFAS options available to vehicle OEMs, particularly for DSL system use of R-290 or new refrigerant blends that do not atmospherically degrade to chemical substances defined now or in the future as PFAS.

After nearly four years of work on the DSL R-290 option under a team dubbed "*Team Entropy*" and chaired by Dr. Chris Seeton, Ford Motor Company summarized the work on behalf of global automobile manufacturers in a SNAP submission to the US EPA to request this thermal system option be listed as acceptable under the US Clean Air Act. Much of the work was focused on assessing the flammability risk of R-290 in a DSL for all-electric vehicles. An increasing number of global vehicle and MAC system OEMs are signing onto and supporting Ford's SNAP submission.

Testing of a concept bench system at Creative Thermal Solutions (CTS) in Urbana, Illinois, USA also identified performance deficits when existing automotive thermal system components are applied in an R-290 DSL. This has spurred a new round of component development by the automotive thermal Tier 1 industry to enhance the performance and energy efficiency of the DSL R-290 system. As this follow-on work is considered competitive, it is outside the scope of the SAE TMR CRP.

In recognition of the potential environmental benefits of the DSL R-290 system, the CCAC has funded a vehicle-level demonstration project via the United Nations Industrial Development Organization (UNIDO) to be implemented in the 2025–27 timeframe by TML in India. This project's aim is to design, build, test, evaluate, and document the performance of two all-electric vehicles, one each in the light duty car and light truck vehicle segments (Kapoor 2025). A significant focus will be the evaluation of safety risks associated with R-290's mild flammability. TML will conduct a detailed risk analysis and develop safety guidelines and standard operating procedures to mitigate potential hazards.

Beyond technical innovation, the project seeks to enable conditions for widespread adoption through the development of design standards and safety guidelines. These outputs are intended to be disseminated through platforms such as the Society of Indian Automobile Manufacturers (SIAM) and regional stakeholder networks.

The knowledge generated will also contribute to regional replication, particularly in South and Southeast Asian countries with similar climatic and regulatory contexts (Kapoor 2025)

9. Lessons Learned

Government, industry, and NGO MAC partners learned how to combine market, regulatory, and public-interest forces to protect stratospheric ozone and climate faster, better, and with less cost and more satisfaction.

Collaboration of industry, government, and public-interest organizations proved vital to rapid protection of the stratospheric ozone layer and additionally to climate protection by reducing the emissions of MAC refrigerants that are GHGs.

Topics where no single company had the expertise to find the way forward were resolved faster, better, and with more confidence by experts working cooperatively on problem solving. For example, the US Army enhanced the flammability risk analysis for R-152a by providing computational fluid dynamics (CFD) calculations of refrigerant leak dispersion. These calculations were generated by supercomputers with sophisticated modelling originally developed for mitigating fire and explosion risk in armoured vehicles during normal operations and in combat.

The unimpeachable results proved that the small R-152a charge was safe in secondary-loop systems as was a larger charge in direct expansion systems with active leak detection and discharge outside the occupied space. The CFD modelling informed the risk analysis for both the far less flammable R-1234yf and then far more flammable R-290.

Without this partnership, the MAC community would not have appreciated how the US Army's expertise could be applied to MACs and would not have had access. And without the collaboration, the MAC community could not have so confidently designed the systems proven safe in operating circumstances.

Unlike stationary cooling, MAC development had the advantage of expert engineers routinely mitigating risks of flammable fluids and gases that include antifreeze, gasoline, hydraulic fluid, lubricants, and even windshield wiper fluids. While stationary cooling engineers focus on flame spread as the basis of ASHRAE standards, automotive engineers considered the full range of flammability risk metrics including autoignition, burning velocity, coefficient of expansion, flame spread, flaming duration, flash point, heat of combustion, lower and upper flammability limits (LFL & UFL), mass consumed, and time to ignition. Furthermore, automotive engineers had working experience in tried-and-true passive and active safety measures proven effective in automotive applications.

MAC partners used their combined know-how to increase energy-efficiency design during the transition to new refrigerants with breakthroughs such as: 1) enhancing sound insulation to thermally insulate and also deploying glazing technologies to reduce infrared heat entering the cabin; 2) relocating MAC components to reduce refrigerant leaks through fewer joints, new sealing technology (seal washers) and shorter hoses; 3) developing micro-channel heat exchangers and other advanced components; 4) reducing series reheat with electronic control of variable displacement compressors; 5) controlling electric motor compressor speeds for higher cooling and energy performance independent of speed; 6) using thermal ballast to shift MAC power demand for greater motive power with lower fuel use; 7) capturing waste heat and cascading cooling of batteries, inverters, occupants, and windows for defrosting; and 8) integrating control of humidity to achieve comfort at the lowest carbon footprint.

MAC partners learned how to look far into the future with new engineering and inventions to reduce hazardous refrigerant emissions and increase energy efficiency and driving satisfaction. Conspicuously, SL-MACs conceived in the late 1990s were continuously improved to the state-of-the-art today as the superior and necessary architecture for all-electric vehicles and other motor-driven MACs.

SL-MAC system architecture proved to be the platform that enables all-electric comfort plus increases driving range, battery life, and affordability, which speeds market penetration. Versatility of refrigerant choice allows refrigerants to be matched to the application, enables competitive prices in supply, and removes worries and regulatory risks of everywhere-and-forever TFA and PFAS chemicals. Containment and recovery-recycle service mitigate the concern of VOC emissions if R-290 is implemented worldwide at scale. Responsible and natural R-744 from fermentation and R-290 from landfill and animal waste mitigates dependence on vulnerable fossil fuel sources.

Automobile OEMs learned to be more vigilant in guarding against unfair business practices in refrigerant supply, including SAE doubling up on development of new standards for alternate low-GWP refrigerants and enforcement of patent disclosure and fair pricing of technical solutions guided and commercialized in both the public and private interest.

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Appendix A: About the Authors

All the authors have decades of experience in automotive technology and in strengthening and implementing the Montreal Protocol. They are key members of the ongoing search for an environmentally superior MAC refrigerant and systems with superior environmental performance.

Dr. Stephen O. Andersen is the longest-serving stratospheric ozone activist, having coauthored a 1974 assessment of the impact of ozone depletion and climate change on northern latitude grain yields. In high school, he pursued both the academic track to qualify for college and the trade track to qualify as an automobile technician. With another student, Stephen placed second in the Utah State Chrysler Troubleshooting Competition. He is the founding pioneer of the Montreal Protocol TEAP where he served as Co-Chair for 23 years from 1989–2012. He was Deputy Director of the US EPA Stratospheric Protection Division, Liaison to the US Department of Defense on Stratospheric Ozone and Climate, and Director of EPA Strategic Climate Projects. Stephen with EPA colleagues created the first EPA voluntary partnerships and created and managed the US EPA Stratospheric Ozone and Climate Protection Awards. His Ph.D. is from the University of California, Berkeley, and he has earned awards from the governments of Brazil, Iraq, Japan, Russia and the Union of Soviet Socialist Republics, Thailand, the US, and Vietnam. He has also won awards from the Future of Life Institute, Industry Cooperative for Ozone Layer Protection, Mobile Air Climate Systems Association, Planetary Guardians, Service to America, and the UN. Stephen is certified by MACS to repair motor vehicle air conditioners under Section 609 of the Clean Air Act since 2004.

James A. Baker has focused throughout his career on developing and championing new refrigerants, lubricants, components, and systems to eliminate/minimize the impact of motor vehicle air conditioning on the Earth's Ozone Layer and the global climate. He retired as Senior Staff Research Scientist for Delphi Corporation (34+ years) after which he served as an industry consultant. In 1988, Jim was a pioneer in developing and commercializing equipment that allows the MAC industry to recycle refrigerants on site, leading to a very successful outcome and a decades-long collegial partnership with Stephen O. Andersen (US EPA), Simon Oulouhojian (Mobile Air Conditioning Society Worldwide or MACSW), and Ward Atkinson (SAE). Jim received the US EPA Ozone Protection Awards for "Engineering Excellence and Corporate Leadership" in 1990 and for the "Best-of-the-Best" in 1997 for Global Leadership and Technical Innovation, the latter award for pioneering the technology to recycle and reuse refrigerants and the conversion to climate-friendly refrigerants. He received GM's 1993 "Most Valuable Colleague" Award for developing lubricants that allow the use of R-134a in GM vehicles. SAE honoured Jim with election to SAE Fellow status in 2008 and SAE Emeritus status in 2016. For his work with MACSW, he was recipient of the MACS International Award (2000) and the MACS Industry Pioneer Award (2006). Jim was inducted into the Delphi Corporation's Innovation Hall of Fame in 2004 for his many patents, trade secrets, and other technical achievements.

Internationally, Jim was part of a US Department of State delegation to Hungary and the Union of Soviet Socialist Republics in 1990, advocating for their participation in the Montreal Protocol. He served 19 years on the UN Refrigeration, Air-Conditioning and Heat Pumps Technology Options Committee as Lead Author for vehicle air conditioning in support of the Montreal Protocol's ozone layer protection objectives. Additionally, he served for eight years as a MAC expert for the World Bank's Ozone Operations Resource Group (OORG), assisting the Multilateral Fund for the

Implementation of the Montreal Protocol (Multilateral Fund or MLF) in distributing resources to developing countries to reduce their reliance on CFCs and other ODSs. Klaus Topfer, Executive Director of the United Nations Environment Programme (UNEP), awarded Jim a Citation of Excellence in "Recognition of an Outstanding Contribution to the Protection of the Earth's Ozone Layer." Jim was further honoured to be recognized by the IPCC for "Contributing to the Award of the Nobel Peace Prize for 2007 to the IPCC."

Jim holds a Bachelor of Arts in Chemistry and a Master of Science in Physical Chemistry with a research thesis on gas phase chemical reaction mechanisms, both from Wright State University in Dayton, Ohio.

Timothy Craig crafted a career in automotive thermal systems that successfully incorporated prudent and progressive environmental stewardship. His work in engineering development, invention, commercialization, and communication included over 30 years in the design, development and implementation of OEM thermal systems as part of the business evolution of GM, Delphi and Mahle. Early involvement with the readiness of GM trucks to adopt R-134a evolved into additional engineering and regulatory development work during the transition to low-GWP R-1234yf refrigerant. With colleagues including Ward Atkinson, William "Bill" Hill, James A. Baker, Hans Fernqvist, Stephen O. Andersen, and many others, Tim helped set the stage for R-152a by proving equal or better cooling capacity and passenger comfort, and he worked on the team that persuaded US EPA to approve R-152a upon on proof of safety.

Tim led a CCAC-sponsored team with Tata Motors and Institute for Governance & Sustainable Development (IGSD) members that demonstrated a production vehicle with a secondary loop system achieving lower carbon footprint and lower cost of manufacture and ownership as compared to R-134a direct expansion systems. Tim continues to innovate in MAC sustainability, SAE technical standards development, education, and publication initiatives via his consulting firm, Melrose Technologies LLC.

Tim holds both bachelor's and master's degrees in mechanical engineering from Purdue University in West Lafayette, Indiana, with his master's research documented in a 1982 thesis titled "Radiative Transfer Process in Scattering Absorbing Media."

Sangeet Hari Kapoor is currently an Advisor on Mobile Air Conditioning and Automotive Thermal Management Systems. Prior to retirement in 2025, Sangeet was a General Manager and Head of Climate Control at the Engineering Research Centre, Tata Motors Passenger Vehicles, in Pune, India. In the mid-1990s, he oversaw the migration from CFC-12 refrigerant to R-134a on Tata Motors range of passenger vehicles and light trucks. He is an official observer at the Montreal Protocol Open-Ended Working Group (OEWG) and Meeting of the Parties (MOP) and frequent expert at Side Events sponsored by CCAC and IGSD. He partners with UNEP and IGSD on projects to help reduce impacts of global warming and climate tipping points. Sangeet is an active member of SAE International and other professional and engineering societies and is a founding member and mentor of the SAE Think Tank in India on Thermal Management Systems. He has authored and coauthored 22 research papers on simulation methodologies for thermal management, low-GWP refrigerant alternatives, and MACs, including over 20 SAE International publications.

Sangeet H. Kapoor is recipient of the 2010 SAE International, Excellence in Oral Presentation Award and a recipient of the 2019 SAE Environmental Excellence in Transportation (E2T) Award "… for pioneering research work done in the field of low-GWP environmentally friendly refrigerants and secondary loop MAC engineering architecture."

He is actively involved in formulation of Indian Standards pertaining to MACs in internal combustion vehicles and all-electric vehicles. He has 25 patents in the automotive domain, which include 13 international filings. Sangeet graduated as a Mechanical Engineer from the Delhi College of Engineering in 1987 and has a master's degree in management sciences from Symbiosis Institute of Business Management. Sangeet's motto in life is "Never Give In."

Steven G. Schaeber, Jr. is Director of Training and Regulatory Affairs and Editor-in-Chief of *ACtion Magazine* for MACS, the Mobile Air Climate Systems Association. Steve engages with industry and government stakeholders, provides technical support to MACS members, teaches mobile A/C training classes, and writes air conditioning related technical content. He is also involved in the greater automotive industry on behalf of MACS members through SAE Human Factors Technical Committee 6 (SAE-HFTC6) and Technology and Maintenance Council of the American Trucking Association (TMC). Steve Schaeber has worked as a technician, manager, instructor, and author in the automotive, HD trucks, off-road, packaging, and education sectors since 1989.

Steve holds a Bachelor of Science degree in Automotive Technology Management and an Associate of Applied Science degree in Automotive Service Management from the Pennsylvania College of Technology, along with an Associate of Arts degree from Bucks County Community College. He received his first MACS Section 609 certification in 1995 (for R-12 and R-134a refrigerants) and started teaching US EPA Clean Air Act Section 609 classes in 2007 when he became a MACS proctor. In 2015, he updated his Section 609 certification to include HFC-152a, R-744 and HFO-1234yf refrigerant. Steve is also a vehicle Safety and Emissions Inspection instructor in the Commonwealth of Pennsylvania.

During his time at MACS, Steve has authored, edited, and updated countless blogs, columns, articles, books, newsletters, and magazine issues for the association, and has written dozens of training classes (books and slide presentations) focused on MAC service and repair. In 2014, following US EPA update requirements, he updated the MACS Section 609 Certification Training Manual and associated testing materials to include (then new) information about R-152a, R-744, and R-1234yf refrigerants.

Steve's focus is on refrigerant lifecycle management in the MAC and thermal management sectors through training and best service practices, including the use of proper tools and equipment for refrigerant recovery and recycle and minimizing refrigerant release into the atmosphere. Steve serves as vice chair of the SAE Interior Climate Control Service Committee and secretary of SAE HFTC6 (Human Factors Technical Committee).

Appendix B. About IGSD, MACS, and SAE International

IGSD

The mission of the Institute for Governance & Sustainable Development (IGSD) is to promote fast climate mitigation to slow near-term warming and self-propagating climate feedbacks, avoid catastrophic climate and societal tipping points, and limit global temperatures to 1.5 °C—or at least keep this temperature guardrail in sight and limit overshoot.

IGSD approaches to fast mitigation includes finance, law, policy, science, and technology. IGSD works at the global, regional, national, and subnational levels, including in partnership with industries with shared environmental ambition.

MACS

The Mobile Air Climate Systems Association (MACS) was founded in 1981 by Simon Oulouhojian to bring information and training from the motor vehicle OEMs to automotive technicians and mechanics so they could better serve their customers. When the Montreal Protocol was signed in September 1987, Simon and assistant director Elvis Hoffpauir grasped the opportunity to professionalize car air conditioning by requiring leak-tight systems repaired without intentional emissions. In January 1988, Simon and Elvis teamed up with US EPA, SAE, Underwriters Laboratories, and OEMs to commercialize and implement (without patents) refrigerant recovery and recycling equipment. A year later, the technology was agreed by OEMs for new car warrantee service and endorsed by a dozen environmental NGOs urging repair before recharge and recovery recycle. MACS and the NGOs secured under the US Clean Air Act certified training as a requirement to purchase R-12 and a ban to the sales of R-12 in small cans notorious for careless do-it-yourself MAC service. Through economy of scale, they offered training approved by US EPA and used the extra revenue to promote green car service to protect the stratospheric ozone layer and climate. Now MACS is at the forefront of the shift to R-290 (propane) for heat pumps in all-electric vehicles, by working front and centre with the industry on the steering committee for the SAE Thermal Management Refrigerant Cooperative Research Project.

MACS also continues to work with the UN and the Montreal Protocol through its programs to promote professional service and best practices during the service, maintenance and repair of mobile air conditioning and thermal management systems. By using the right tools and procedures to recover and recycle refrigerant on site, technicians can help to avoid the release of harmful CFCs, HFCs and HFOs into the atmosphere. The MACS global network includes MAC Partners Europe (MAC Partners) and Automotive Air Conditioning, Electrical, and Cooling Technicians of Australia (VASA).

SAE International

Founded in 1915, SAE International has members in about 65 countries and has a mission to advance mobility knowledge and solutions for the benefit of humanity; to connect mobility professions; and to build networks in aerospace, automotive, and commercial vehicle industries. SAE champions collaboration across companies and borders, including life-long learning and development of voluntary consensus standards. In the case of stratospheric ozone depletion, these standards are referenced by the US EPA in implementing the Clean Air Act and the Montreal

Protocol. The SAE Foundation supports many programs, including A World in Motion® and the Collegiate Design Series.

Appendix C. Comparison of Refrigerants in Motor Vehicle Air-Conditioning Applications and Updated 2022 ODP and GWP Values

The table that follows presents an overview of MAC refrigerants, with the most recent ODP and GWP values from the World Meteorological Association report, *Scientific Assessment of Ozone Depletion 2022* (WMO 2022).

Table A-1. Refrigerants for MAC applications

Refrigerant ASHRAE #	Nomenclature	$ODP_{WMO\ 2022}$	Formula	$GWP_{WMO\ 2022\ 100\text{-}yr}$ / $GWP_{20\text{-}yr}$	LCCP cooling	LCCP heat pump	Affordable?	TFA or VOC?
R-12	CFC	0.75	CCl_2F_2	12,500 / 12,760	Superior	Inferior	Phased Out	Not TFA Not VOC
R-134a	HFC	0	CF_3CH_2F	4,060 / 6,790	Inferior	Inferior	Phasing Down	7–20% TFA
R-1234yf	HFO	0	$CF_3CF{=}CH_2$	<<1 / <<1	Inferior	Inferior	Monopoly*	~100% TFA
R-152a	HFC	0	$C_2H_4F_2$	153 / 550	Superior	Inferior	Affordable	Not TFA Not VOC
R-290	HC	0	C_3H_8 $CH_3CH_2CH_3$	0.02 / 0.072	Superior	Superior	Affordable	VOC
R-744	CO_2	0	CO_2	1 (reference chemical)	Inferior	Inferior	Affordable**	Not TFA Not VOC

Source ASHRAE #: ASHRAE 2022.

Source latest relative ODP and GWP values by the Montreal Protocol Scientific Assessment Panel (SAP): WMO 2022: Table A5, pp. 448–492

Source TFA Yield: UNEP EEAP 2022: p. 279 and Table 10, p. 280, Chapter 6: Trifluoroacetic Acid in the Global Environment with Relevance to the Montreal Protocol. See also Hodnebrog, Dalsøren, and Myhre 2018 and Hodnebrog et al. 2020.

CFC = chlorofluorocarbon; HC =hydrocarbon; HCFC = hydrochlorofluorocarbon; HFC = hydrofluorocarbon; HFO =hydrofluoroolefin

*Despite court rulings of invalid patents, the price of R-1234yf is about twice the cost of estimated production (Sherry et al. 2016; see also Seidel and Ye 2015; Seidel and Ethridge 2016; Deo and Callahan 2022; Taddonio et al. 2022).

** R-744 is affordable as a refrigerant, but the cost of the MAC system itself, the energy to power the system, and the service costs are very high.

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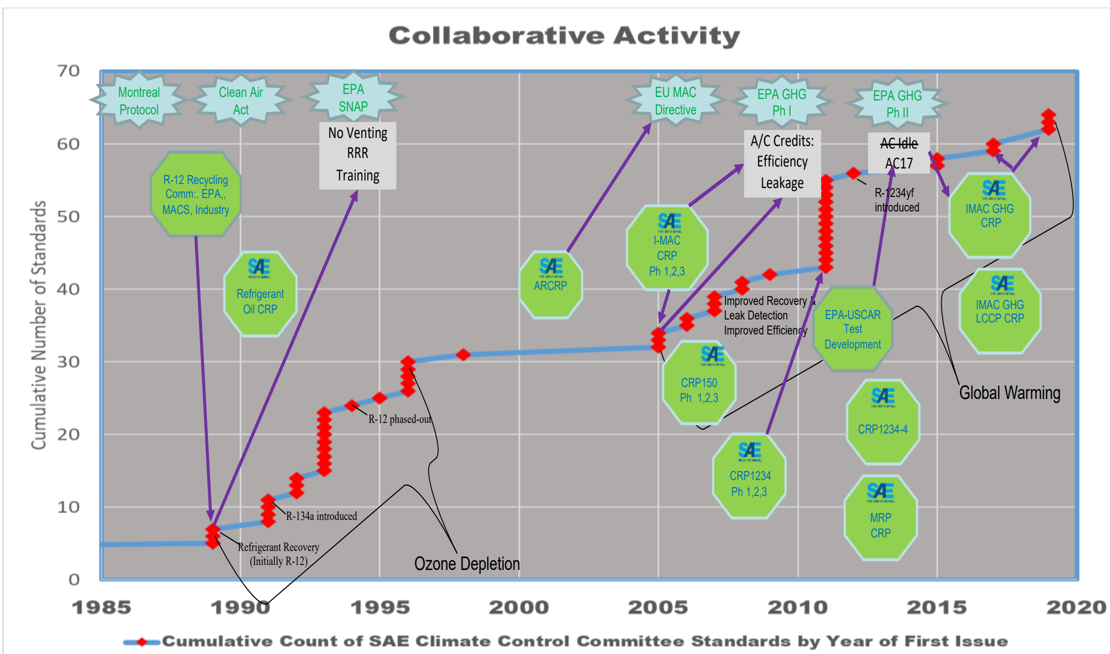
Appendix D. Natural Refrigerants from Responsible Sources: R-290 Can Be Sourced as "Biopropane" from Landfill, Animal, and other Non-Fossil Fuel Sources

Natural refrigerants[22] are chemical compounds occurring "naturally" on Earth that can be responsibly sourced from what otherwise would be an emission and without generation from fossil fuel processes. Specifically, if CO_2 is captured at breweries and used as refrigerant R-744, any leakage will not be a net atmospheric contribution if the electricity for purification is from clean net-zero sources such as solar and wind. Similarly, propane can be captured and purified as "biopropane" from landfill, compost, or animal waste operations for use as natural refrigerant R-290 (Fischer et al. 1991; Campbell and McCulloch 1999; Johnson 2004; Lysova et al. 2023). Sources of biopropane include vegetable oils, animal fats, forestry residues, and microorganisms. Because propane is a small fraction of biogas, the costs to use as an energy source have been prohibitive but can be affordable as a refrigerant because the quantity per vehicle is so small.

Appendix E. Graphic Presentation of the Remarkable Scope of MAC Community Cooperation 1985–2020



Source: Angelo Patti 2019. Opening Remarks Thermal Management Systems Symposium (TMSS) Regulatory Panel, October 11.

Appendix F. MAC Timeline with Indicative Firsts and Seminal Associated Events

Adapted, merged, and updated from CMA FPP 1986; Smith 1998; Andersen and Sarma 2002; Andersen, Sarma, and Taddonio 2007; Atkinson 2008; Dickirson 2011; Andersen, Halberstadt and Borgford-Parnell 2013; and Mitchell and Newton 2024.

1883 Karl Benz founds Benz & Cie and builds the first mass produced automobile.

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[22] The American Society of Heating, Refrigeration and Air-conditioning Engineers (ASHRAE), which is the official registry of refrigerant nomenclature, suggests this definition: "Natural refrigerants occur in nature's biological and chemical cycles without human intervention" (Zahid et al. 2011).

1884 William N. Whiteley demonstrates the first vehicle A/C for horse-drawn carriages using a wheel-driven fan to blow air across ice.

1890s Belgian scientist Frederic Swarts pioneers the synthesis of CFCs by a chemical reaction later known as the "Swarts reaction."

1928 Working alongside Charles Franklin Kettering, the vice president of the GM Research Corporation, Thomas Midgley, Jr., Albert Henne, and Robert McNary invent CFC refrigerants that are non-flammable, non-toxic, odourless, colourless, and energy efficient. It was not until 1974 that CFCs were identified as ozone-depleting and 1975 when identified as climate-forcing. Frigidaire Division of GM receives first CFC patent.

1929 Per its research notes, the Midgley team identifies other promising refrigerant candidates including R-134a (1,1,1,2-tetrafluoroethane), which was shelved because it cost more to produce than CFC-12. At that time, stratospheric ozone depletion and climate forcing were not yet appreciated.

1930 GM and DuPont form a joint stock company, the Kinetic Chemical Company, to manufacture and market CFCs.

C&C Kelvinator air conditions first automobile for John Hamman, Jr. of Houston, Texas (Nagengast 1988).

1936 Ralph Peo patent 2,115,785 filed for a MAC system.

1938 Nash applies for a patent (granted in 1942 as No. 2295750) for the first complete description of a modern integrated vehicle air conditioning system with the evaporator heat exchangers inside the cabin using non-flammable and low-toxicity CFC.

1939 Packard offers the first motor vehicle with CFC A/C in the 1940 Senior 160 and 180 models using a system designed and installed by Bishop & Babcock, Cleveland, Ohio.

1955 GM offers the first air-conditioned vehicle with all components mounted up front under the hood or in the dash and integrated with the heating system. Ward Atkinson is on the design team.

1971 James Lovelock warns that CFCs were detected in every analysed global air sample and that there may be consequences of these long-lived manufactured gases.

1972 Dupont secretly warns global CFC producers that: "Fluorocarbons are intentionally or accidentally vented to the atmosphere worldwide at a rate approaching one billion pounds per year. These compounds may be either accumulating in the atmosphere or returning to the surface, land or sea, in the pure form or as decomposition products. Under any of these alternatives, it is prudent that we investigate any effects which the compounds may produce on plants or animals now or in the future."

Nineteen CFC manufacturers from Australia, Europe, Japan, and North America organize the Fluorocarbon Program Panel (FPP), administered by the United States Chemical Manufacturers Association (CMA), to investigate the-effects of CFCs on the environment.

The CMA sponsors a confidential study of the potential for CFCs to create smog. The study finds that CFCs are very stable in the atmosphere and are only destroyed in the stratosphere by solar ultraviolet radiation.

1974 In June, Mario J. Molina and F. Sherwood Rowland warn that CFCs destroy the stratospheric ozone layer that protects life on earth from harmful ultraviolet radiation. In September, Rowland and Molina call for a boycott of cosmetic and convenience CFC aerosol products such as hairspray, deodorant, and household pesticides. In December, DuPont pledges to halt CFC production *"…if credible scientific data…show that any chlorofluorocarbons cannot be used without a threat to health.*"

James Lovelock, working for DuPont and other CFC stakeholders, measures CFCs at 45,000 feet altitude and an absence of ozone, which he views as proof CFCs destroy ozone, but he does not publicly disclose the findings because he believes the ozone layer is less important than CFC uses.

1985 Vienna Convention for the Protection of the Ozone Layer is signed on 22 March.

Joseph S. Farman, Brian G. Gardiner, and Jonathan D. Shanklin on 16 May warn of drastic stratospheric ozone depletion over Antarctica and without proof attribute it to CFCs. F. Sherwood Rowland brands it "The Antarctic Ozone Hole," and the NASA image goes viral.

Allied Signal, DuPont, and Imperial Chemical Corporation (ICI) disclose that between 1975 and 1980 chemical substitutes for CFCs were invented but shelved in the absence of regulation.

1987 John S. Hoffman and Stephen O. Andersen at US EPA assemble a panel of global fluorocarbon chemists from Germany, France, Japan, the UK and the US, chaired by Richard J. Lagow. In 1988, the panel finds that R-134a has the greatest potential for replacing CFC-12 in refrigerant applications with an estimated cost of production of just three to five times the 1988 market price of CFC-12 (US $1.30–1.75 per kilogram). This translates into a price increase of only about US $5 per MAC for vehicles selling for US$ 18,000 or more.

1987 The Antarctic Airborne Ozone Expedition flies ER-2 and DC-8 research aircraft from Punta Arenas, Chile, into the Antarctic Vortex to simultaneously measure ozone and chlorine monoxide (ClO) concentrations. The flight's measured data shows that higher the concentrations of ClO correlate to lower concentrations of ozone. This produced the "smoking gun" linking CFC-derived chlorine to the Ozone Hole.

Montreal Protocol on Substances that Deplete the Ozone Layer is signed on 16 September by 24 nations and the European Economic Community (EEC).

Motor Vehicle Manufacturers Association (MVMA) and US EPA partner on materials and lubricants testing with proposed refrigerants.

1988 At a UNEP technology workshop in the Haag, Netherlands; General Electric, Sanden, and US EPA propose an electrically driven hermetically sealed MAC system suitable for use with R-152a or R-22.

MACS and the MVMA on 15 January form an *ad hoc* committee, chaired by Simon Oulouhojian (MACS) and co-chaired by James A. Baker (GM) and Stephen O. Andersen (US EPA), to pursue CFC-12 recycling. The committee had a head start because Baker had already brainstormed the process that ultimately led to proving the efficacy of on-site refrigerant recycling in service shops. The combined clout of the chairs, technical prowess of the committee, and confidence in Underwriters Laboratories (UL) test supervision of satisfying the agreed standard of purity of recycled refrigerant persuaded vehicle OEMs to endorse and implement in their own service facilities refrigerant reuse under warranty.

The findings released on 15 March by the UN World Meteorological Organization (WMO) Report of the International Ozone Trends Panel persuades DuPont on 24 March to announce an orderly phase out of production of fully halogenated CFCs. This action prompts a half dozen other fluorocarbon companies to phase out CFCs (Brysse and McFarland 2009). DuPont also pledges to customers to release patents on chemical substitutes to CFCs (Holliday 2024).

Fourteen global manufacturers of ODSs form the Program for Alternative Fluorocarbon Testing (PAFT) for substitutes that include R-134a.

1989 CFC recycling is commercialized with SAE International standard, UL performance testing, automobile manufacturers agreement to allow use of recycled refrigerant under warranty repair, and with endorsement of environmental NGOs and government authorities; by August, GM implements recovery-recycle at all its dealerships worldwide and by December Toyota implements at all its dealerships.

Friends of the Earth (FOE) calls for a national ban on the sale of small cans of CFC-12 refrigerant that can be used by car owners for DIY recharging of leaking systems on a continuous basis.

Nissan pledges to be CFC-free by 1993, including refrigerants, solvents, and foam blowing agents used in seats, steering wheels and bumpers.

Norwegian Professor Gustav Lorentzen and colleagues apply for an international patent application for a "transcritical" CO_2 cycle system, where the high-side pressure is controlled by the throttling valve (Lorentzen 1994; Lorentzen 1995; Andersen and Zaelke 2003; Kim, Pettersen, and Bullard 2004).

SAE (now rebranded SAE International) with US EPA organizes its first Cooperative Research Program (CRP) under terms of The National Cooperative Research Act of 1984 (NCRA) that exempts from antitrust restrictions any research intended for public benefit and pledges to public disclosure within a reasonable time after completion (Wright 1986; Mahler and LaMont 1988; Scott 1989; Klavon and Pollak 2025).

1990 Mercedes, Chevrolet, and Volvo are first to introduce vehicles with CFC-free A/C.

The US Clean Air Act of 1990 requires that technicians be trained and certified to standards as least as stringent as specified in SAE J-1989 under certification programs of the National Institute for Automotive Service Excellence (ASE) or the MACS and that recycling equipment satisfying SAE and UL standards be used on any repair of MACs.

US EPA presents the first Stratospheric Protection Awards to MACS, Ward Atkinson (SAE MAC Standards Chair and Sun Test), James A. Baker (Delphi), James Beyreis (UL), Don Grob (UL), and Simon Oulouhojian (MACS).

1991 Refrigerant recycling is mandated in Connecticut, Hawaii, Oregon and Vermont.

Recycling equipment is made mandatory in Ford, GM and Volvo dealerships.

Daikin, DuPont, and Showa Denko are first to commercialize production of R-134a.

Nissan, Mercedez Benz, and Saab are first to produce vehicles with R-134a MACs.

Nissan earns corporate US EPA Stratospheric Ozone Protection Award.

Elisabeth Cook (FOE) earns individual US EPA Stratospheric Ozone Protection Award.

1992 United Nations Framework Convention on Climate Change (UNFCCC) is signed by countries at the Rio Earth Summit.

Acra, BMW, Chrysler, Ford, GM, and Volvo introduce the first vehicles with R-134 MACs, with Chrysler first to implement full-scale production at its Jeep Grand Cherokee plant.

Chrysler, Ford, and Mercedes-Benz earn corporate US EPA Stratospheric Ozone Protection Awards.

US EPA requires containment and recycling of CFC-12 (1 January 1992).

US EPA restricts the sale of containers less than 20-pounds of CFC-12 to only Section 609[23] certified technicians (15 November 1992).

1993 Patent for transcritical CO_2 vapor compression cycle: "Method and Device for High-Side Pressure Regulation in Transcritical Vapor Compress Cycle" issued to Gustav Lorentzen, Jostein Pettersen, and Roar R. Bang who promote for both MAC and stationary cooling (Andersen and Zaelke 2003; Kim, Pettersen, and Bullard 2004; Lorentzen 1994 and 1995).

Honda, Jaguar, Mitsubishi, Infinity, Porche, Toyota, and Volkswagen introduce first vehicles with R-134a.

Audi, BMW, Porche, and Volvo are first to fit all new vehicles with R-134a.

Nippon Denso and Volvo earn corporate US EPA Stratospheric Ozone Protection Awards.

Arthur Hobbs (Four Seasons) and Kenneth Manz (Robinair) earn individual US EPA Stratospheric Ozone Protection Awards.

[23] https://www.epa.gov/mvac/section-609-technician-training-and-certification-programs

1994 Global production of vehicles is almost CFC-free (with exceptions of some developing countries)

Ford, GM, and Saab Scania earn corporate US EPA Stratospheric Ozone Protection Awards.

US EPA restricts the sale of all ODS refrigerants in any size container to only certified technicians (14 November 1994).

1994–97 EU sponsors RACE (Refrigeration and Automotive Climate under Environmental Aspects) industry consortium to develop and demonstrate carbon dioxide (CO_2) vehicle A/C.

US EPA prohibits individuals from knowingly venting substitutes for CFC refrigerants during the maintenance, service, repair, and disposal of air conditioning and refrigeration equipment (15 Nov 1997).

1996 Shared Mercedes/BMW patent is granted for CO_2 automotive heat pump.

1997 Kyoto Protocol to the UNFCCC is signed in Japan.

When favourable results of the three-year EU RACE program on R-744 were presented at the Earth Technologies Forum in Washington DC, SAE's Ward Atkinson and Daimler's Jürgen Wertenbach agree to road test a prototype vehicle in Phoenix the next summer because "If you can cool them there, you can cool them anywhere" (Andersen and Zaelke 2003).

Nissan earns corporate US EPA Best-of-the-Best Stratospheric Ozone Protection Award.

Ward Atkinson (Suntest), James A. Baker (Delphi), and Simon Oulouhojian (MACS) earn individual US EPA Best-of-the-Best Stratospheric Ozone Protection Awards.

1998 First Phoenix Forum on Alternatives to HFC A/C (Phoenix Forum) attracts 65 participants with discussion focused on CO_2 (R-744) critical-cycle MAC systems and HFC-152a (R-152a) secondary loop MAC systems.

1999 Second Phoenix Forum decides by consensus to create the Mobile Air Conditioning Climate Protection Partnership (MACCPP) and appoints Stephen O. Andersen (US EPA), Ward Atkinson (SAE), and Simon Oulouhojian (Mobile Air Conditioning Society Worldwide) as Co-Chairs.

Nissan earns corporate US EPA Climate Protection Award.

2000 Third Phoenix Forum is held.

The European Council on 10 October requests the EC to study and prepare measures in reduction of all GHGs and prepare measures in reduction of all GHG emissions from air conditioning in vehicles.

2001 SAE creates new project on benchmarking R-134a vehicle A/C for energy efficiency and emissions and testing of alternatives under its CRP.

US EPA and Environment Canada become first of 25 stakeholder partners financially contributing to the SAE Alternative Refrigerant CRP (SAE ARCRP for vehicle A/C, considering enhanced R-134a DX systems, R-152a and R-290 in SL-MACs, and R-744 in new MAC architecture).

2002 Fourth Phoenix Forum on energy-efficient alternatives to R-134a A/C is held.

China stops production of vehicles with CFC-12 A/C (31 December 2002).

First VDA Alternative Refrigerant Winter Meeting is held in Saalfelden, Austria (Saalfelden Winter Forum).

Toyota's FCHV includes the world's first commercially produced vehicle with CO_2 air conditioner—a Denso electrically driven, hermetically sealed heat pump using natural CO_2 refrigerant.

EC environmental authority Matti Tapani Vainio proposes a wide range of MAC economic and command-and-control drivers to reduce the indirect emissions of GHGs from powering MACs and to reduce the direct emissions of HFC GHG refrigerants. Proposals include a cap of 1 on MAC refrigerant GWP, with the only disclosed choice being R-744.

2003 India is the final country to phaseout production of vehicles with CFC-12 A/C (31 December 2003).

January EC Conference on the Options to Reduce Greenhouse Gas Emissions Due to Mobile Air Conditioning: EC executives declare R-134a "unsustainable" and urge strong measures to reduce direct and indirect MAC GHG emissions.

Second Saalfelden Winter Forum is held.

MAC Summit Brussels is held on 10–11 February.

Minister Margot Wallström, Matti Tapani Vainio, Philip Callaghan, Peter Gammeltoft, and colleagues agreed "Performance, Not Prescription" and welcomed R-152a, R-290, and R-744 if satisfying safety as certified by EU authorities of jurisdiction.

Fifth Phoenix Forum on energy-efficient alternatives to R-134a A/C is held on 15–17 July.

Matti Tapani Vainio (EC DG Environment) confirms R-152a with IPCC AR2 GWP = 140 will be allowed by the EC MAC F-gas Directive (Vainio 2003).

2004 Sixth Phoenix Forum is held.

Third Saalfelden Winter Forum is held.

SAE International launches the Improved Mobile Air Conditioner (IMAC) CRP, with a three-year budget of over $5 million dollars to reduce refrigerant leakage by at least 50 percent and to increase A/C system energy efficiency by at least 30 percent (Atkinson 2008).

2005 Fourth Saalfelden Winter Forum is held.

Red Dot proves higher cooling capacity and energy efficiency of R-152a versus R-134a in DX vehicle rooftop AC.

SAE International publishes Standard J-2727: R134a Mobile Air Conditioning System Leakage Chart (J2727_200506) used to estimate annual and life-cycle refrigerant emissions. J-2727 is frequently updated to include R-1234yf and is used by OEMs to demonstrate compliance with refrigerant emission regulations, such as California and the US EPA rules for new vehicles.

The Improved Mobile Air Conditioning Team earns a team US EPA Stratospheric Ozone Protection Award.

2006 Seventh Phoenix Forum hosts 264 MAC authorities.

The Mobile Air Conditioning Society Worldwide earns the association US EPA Climate Protection Awards.

EC, US, and Japan environmental authorities agree to work cooperatively and swiftly to remove global barriers to the adoption of refrigerants to replace R-134a, with EPA's Kristen Taddonio appointed to lead the US effort.

Fifth Saalfelden Winter Forum is held.

On 17 May, the EC passes the mobile A/C directive "MAC Directive" (Directive 2006/40/EC of the European Parliament and the Council) requiring that air conditioners sold on new "type" vehicles in the EU after 2010 and all vehicles sold in the EU after 2017 use refrigerants with GWP<150. At the time of the announcement, the only publicly disclosed refrigerants satisfying this criterion were hydrocarbons (then considered GWP=~5), CO_2 (GWP=1), and R-152a (IPCC AR-4 $GWP_{100\text{-}yr}$ ~124). On 4 July 2006, the EC F-gas regulation 842/2006, 2006/40/EG MAC Directive, and amendments to directive 70/156/EWG enter into force.

Within weeks of the EC F-gas Directive, international chemical manufacturers Asahi, Arkema, DuPont, Honeywell, Ineos, and Sinochem announce refrigerants suitable for motor vehicle A/C with GWP<150 including HFO-1234yf with $GWP_{100\text{-}yr}$ ~<1.

2007 Eighth Phoenix Forum is held.

Sixth Saalfelden Winter Forum is held.

DuPont and Honeywell promoted HFO-1234yf as "a new low-GWP, market-ready refrigerant satisfying the EC MAC Directive."

EU implements Registration, Restriction, Evaluation, and Authorisation of Chemicals (REACH) requiring industry to demonstrate to the satisfaction of authorities that chemicals are safe both for human health and the environment.

2008 Seventh Saalfelden Winter Forum is held.

William R. Hill (GM) and Stella Papasavva (GM) earn team US EPA Climate Protection Award for Life-Cycle Analysis.

MACCPP chairs present an elaborate plan for commercialization of R-1234yf at the 4 February meeting of MACS Worldwide, including standards development by SAE, agreement on safety standards to replace US state and other barriers to flammable refrigerants, and cooperation to speed US EPA SNAP and EC REACH approval.

Japan SAE Meeting 4–5 March in Tokyo confirms the choice of R1234yf and organizes working groups to rapidly implement necessary technical standards.

In March, the Association of International Auto Manufacturers (AIAM) and the Alliance of Auto Manufacturers (AAM) ask the White House Office of Management and Budget (OMB) and US EPA for permission to commercialize R-152a and R-744 (Dinnage 2008)

The Minnesota legislature requires OEMs to report estimated refrigerant emissions calculated according to SAE J-2727 for any vehicle sold in Minnesota and publishes that information. Because most vehicles sold worldwide might be offered in Minnesota, the disclosure becomes de facto source. OEMs with high emissions react quickly to reduce emissions using the leakages documented in SAE J-2727 (Minnesota Legislature 2008; MPCA 2011; SAE International 2005).

Ninth Phoenix Forum and SAE Climate Control Standards Meeting is held on 14–16 July in Scottsdale, Arizona.

Vehicle Thermal Management Systems Conference & Exhibition is held in Phoenix, Arizona.

At a 9 December meeting chaired by Stephen O. Andersen of automobile manufacturers, mobile A/C system and component suppliers, mobile A/C service associations, environmental authorities, and public interest organizations, all but four of more than 70 participants agree that R-1234yf is the refrigerant-of-choice to replace R-134a in motor vehicle A/Cs.

2009 Eighth VDA Alternative Refrigerant Winter Meeting is held on 11–12 February in Saalfelden, Austria.

2010 Tenth Phoenix Forum is held.

Ninth VDA Alternative Refrigerant Winter Meeting is held in Saalfelden, Austria.

GM announces that it will adopt R-1234yf on its US Buick, Cadillac, Chevrolet, and GMC models from 2013 (GM 2010).

Stephen O. Andersen and Kristen N. Taddonio (US EPA) and DuPont atmospheric modelers raise concerns over atmospheric degradation of R-134a and R-1234yf to TFA, which is a naturally occurring plant growth inhibitor (Luecken et al. 2010).

2011 Eleventh Phoenix Forum is held.

The Great East Japan earthquake and tsunami on 11 March destroys the Asahi chemical plant supplying refrigerant under contract to DuPont and Honeywell.

2012 Informally in February and officially in May, the EC suspends enforcement of the mobile A/C F-gas Directive due to shortages in supply of R-1234yf resulting from the destruction of the Asahi plant.

In September, Daimler issues a press release stating that R-1234yf is unsafe and that it intends to revert to HFC-134a, in violation of the F-gas Directive.

In December, the EC rejects Daimler's claim and warns that the F-gas Directive will be strictly enforced.

As a part of the European Thermal Systems Integration for Fuel Economy (TIFFE) project, a secondary loop is modelled for a delivery van including consideration of PCM for heat and cold storage (Lemke, Lemke, and Koehler 2012).

2015 Audi, BMW, Daimler, Porsche, and VW signal plans to introduce vehicles with CO_2 systems.

SAE International publishes Test Procedure for Determining Refrigerant Emissions from Mobile Air Conditioning Systems (J2763_201502), which covers the mini-SHED testing methodology to measure the rate of refrigerant loss from a MAC system (SAE International 2015).

2016 The Kigali Amendment to the Montreal Protocol is ratified to phase down HFC GHGs and urges simultaneous increases in energy efficiency for lowest life-cycle carbon footprint.

Tata Motors and Mahle with IGSD are awarded a CCAC-UNEP sponsored project to develop a SL-MAC system on an SUV with a dual-cooling point system.

2017 CCAC funds a project with Mahle, Tata Motors, and IGSD to demonstrate an R-152a Secondary Loop system in a dual-cooling point Tata sport utility vehicle (SUV).

Mercedes-Benz offers CO_2 MACs as an option on its E-class model but later discontinues the system.

2018 IGSD defines environmental dumping as offering in export markets products not satisfying domestic standards for safety, energy efficiency, and/or refrigerant acceptability, such as vehicles compliant domestically with a MAC GWP cap of 150 sold in export markets with R-134a (GWP = 1430) (Andersen et al. 2018).

US EPA permits the sale of ODS and substitute refrigerants (such as R-134a and R-1234yf) only to certified technicians (1 January 2018).

2019 VW equips its all-electric vehicles sold in cold and temperate climates with CO_2 MACS.

SAE International and US EPA CRP release IMAC LCCP model for public use.

The Tata Motors-Mahle-IGSD SL-MAC project titled "A Green Air Conditioner to Save the World" is awarded the prestigious 2019 SAE International Environment Excellence in Transportation (E2T) Award.

2020 OPTEMUS project undertaken over four years by Fiat, three TIER 1 suppliers, an academy, and research and development institutes (15 partners from five European countries) demonstrates the benefits of integrated engineering in a MAC compact secondary loop refrigeration unit using R-290.

SAE International forms the Thermal Management Refrigerant Cooperative Research Project (MRC CRP) of 13 OEMs, 35 system/component suppliers, 3 university partners, 3 regulatory partners, 10 MAC consulting companies, and one environmental non-government organization. The CRP focus is to identify and test the technical and environmental performance of refrigerants for battery electric vehicles (BEVs). The work quickly evolves into a multi-year, multi-phased project with sub-teams performing research specific to each refrigerant candidate and each optimized for application in secondary loop MAC architecture.

2022 SAE LCCP Phase 2 model is perfected with more data points and functionality and expanded to evaluate the cooling and carbon footprint performance of secondary loop heat-pump systems. Sponsors include IGSD.

2023 Audi introduces CO_2 MACs on all-electric vehicle sold in cold and temperate climates.

2024 Ford Motor Company on behalf of many automobile OEMs petitions US EPA SNAP to list R-290 (propane) for use in secondary loop heat pumps for all-all-electric vehicles.

The CCAC engages again with Tata Motors by supporting the UNIDO project that aims to develop and implement prototype systems for passenger all-electric vehicles and small commercial vehicles that use R-290 in SL-MAC systems. The project aligns with global climate goals and supports the Kigali Amendment, which aims to phase down high-GWP HFC based refrigerants.

2025 Toyota Miria FCHV with CO_2 heat pump is sold only in California where hydrogen fuel is available. VW markets all-electric vehicles with CO_2 heat pumps on all-electric vehicles sold in Canada or as an optional accessory in temperate climates.

Tata/CCAC conduct an R-290 secondary loop MAC demonstration.

Seminal Events in R-152/Secondary Loop

1999 (Delphi out of the fluorocarbon box)
Delphi describes simulated performance of R-152a and hydrocarbon refrigerants and their potential as alternative refrigerants to R-134a in mobile air conditioning systems. A comparative assessment of the performance of a secondary loop system using these refrigerants is provided. (Ghodbane 1999)

2002 Delphi and Volvo demonstrate a two evaporator R-152a SL-MAC system in a Volvo XC90 SUV.

2004–5 (Australia field test, Robert Gardiner supervising)
Red Dot proves higher cooling capacity and energy efficiency of R-152a versus R-134a in DX rooftop A/C for mining equipment operating in extreme high temperatures.

2005 (Seattle laboratory test)
Red Dot proves higher cooling capacity and energy efficiency of R-152a versus R-134a in DX vehicle rooftop A/C (Hartley and Hansen 2006).

2007 Delphi proves higher cooling capacity and energy efficiency with measurable but unnoticed longer cooldown from hot soak but faster and noticed cooldown from brief stops of R-152a versus R-134a in SL system in modified production vehicle (Ghodbane, Craig, and Baker 2007).

2014–19 With CCAC funding support approved in 2014, Tata Motors and partners create a prototype air-conditioning system in 2017 that significantly reduces HFC emissions. In 2019, the project team creates the first commercially viable, safe, and cost-saving MAC system to use R-152a, demonstrated in a pilot project in a Tata Motors SUV with a dual A/C system. The project demonstrates a system that provides both lowered emissions and improved vehicle energy efficiency and is awarded the prestigious SAE International 2019 Environment Excellence in Transportation (E2T) Award.

Appendix G. Acronyms, Abbreviations, and Glossary

A/C	Air conditioner or air conditioning
A5 Parties	Parties covered under Article V (Article 5) of the Montreal Protocol (typically developing countries)
AR4	IPCC Assessment Report Number 4 (2007)
ASHRAE	American Society of Heating Refrigeration and Air Conditioning Engineers
BEV	battery electric vehicle
C	Celsius
CCAC	Climate and Clean Air Coalition to Reduce Short-Lived Climate Pollutants
C2ES	Center for Climate Change and Energy Solutions
CFC	Chlorofluorocarbon
CO_2	carbon dioxide
COP	coefficient of performance
CTS	Creative Thermal Solutions
DOE	Department of Energy (DOE)
DX	direct expansion
EPA	Environmental Protection Agency (US)
EU	European Union
EV	electric vehicle
F	Fahrenheit
FCA	Fiat Chrysler Automobiles
GHG	greenhouse gas
GWP	global warming potential
HCFC	hydrochlorofluorocarbon
HFC	hydrofluorocarbon
HFO	hydrofluoroolefin
ICEL	International Cooperative for Environmental Leadership (was ICOLP)
ICOLP	International Cooperative for Ozone Layer Protection (now ICEL)
IGSD	Institute for Governance & Sustainable Development
IMAC	Improved Mobile Air Conditioning
IPCC	Intergovernmental Panel on Climate Change
ISO	International Standards Organization
LCCP	Life-Cycle Climate Performance

MAC	Mobile Air Conditioner or Motor Vehicle Air Conditioner
MACCPP	Mobile Air Conditioning Climate Protection Partnership
MACS	Mobile Air Conditioning Society Worldwide (rebranded as Mobile Air Climate Systems Association)
MAC Partners	European MAC Association
NGO	non-governmental organization
NHTSA	National Highway Traffic Safety Administration (US)
NIT	Norwegian Institute of Technology
NOAA	National Oceanographic and Space Administration (US)
NREL	National Renewable Energy Laboratory (US DOE)
ODP	ozone depletion potential
ODS	ozone-depleting substance
OEM	original equipment manufacturer
PCM	phase change materials
PFAS	per- and polyfluoroalkyl substances
PFC	perfluorocarbon
RACE	Refrigeration and Automotive Climate under Environmental Aspects
REACH	Registration, Restriction, Evaluation and Authorisation of Chemicals (EU)
RTP	Research Triangle Park (US EPA)
SAE	Society of Automotive Engineers International
SAP	Scientific Assessment Panel (of the UNEP Montreal Protocol)
SINTEF	Stiftelsen for Industriell og Teknisk Forskning (The Foundation for Industrial and Technical Research)
SL	secondary loop
SL-MAC	secondary loop motor vehicle air conditioner
SNAP	Significant New Alternatives Policy Program (US EPA)
TEAP	Technology and Economic Assessment Panel (of the UNEP Montreal Protocol)
TERI	The Energy and Resources Institute (India)
TES	thermal energy storage
TFA	trifluoroacetic acid
UN	United Nations
UNEP	United Nations Environment Programme
US or USA	United States
VASA	Vehicle Air-conditioning Specialists of Australasia, Rebranded Mobile AC, Electrical and Cooling Technicians of Australia
VDA	Verband der Automobilindustrie (German Association of Automobile Industry)

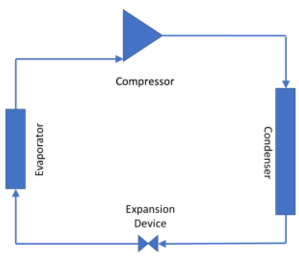
Glossary of Terms

Coolant (heat transfer fluid)

A coolant in a SL-MAC is the fluid that circulates through the primary heat exchanger to the secondary heat exchanger. It is typically an antifreeze with additives to prevent corrosion and to lubricate pumps and valves.

Direct Expansion (DX) MAC

A DX MAC directly cools the vehicle cabin by circulating a refrigerant through an evaporator coil, absorbing heat from the air. DX components include a compressor, condenser, expansion device, and evaporator.



Global Warming Potential (GWP)

GWP is the metric to compare the GHG climate-warming impact of a chemical compared to carbon dioxide (CO_2) over a specified time period (typically 100 years), with CO_2 assigned a GWP of 1. A chemical with a higher GWP is more destructive to climate than a chemical with a lower GWP. GWPs allow the comparison of the carbon footprints using methods such as life-cycle climate performance.

Life-Cycle Climate Performance (LCCP)

LCCP is a comprehensive metric used to estimate the total direct refrigerant emissions, indirect energy emissions, and embodied emissions of an air conditioning or refrigerating system throughout its entire lifespan, from manufacturing to recycle disposal. For MACs LCCP is calculated using SAE Technical Standard J-2766 using software managed by Optimized Thermal Solutions.

Original Equipment Manufacturers (OEMs)

An OEM is a company that in its own facilities assemble of parts and components into a product offered for sale with its own brand name or names.

Ozone Depletion Potential (ODP)

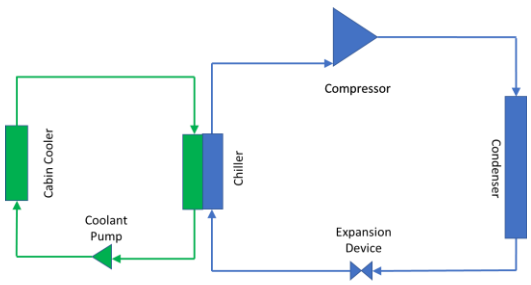
ODP is the metric to compare a chemical's stratospheric ozone impact over the entire atmospheric lifetime of that chemical to the impact of CFC-11 serving as a benchmark with an ODP of 1.0. For example, halons have higher ODPs, while HCFCs and HFCs have lower or zero ODPs, respectively. A chemical with a higher ODP is more destructive to the ozone layer than a chemical with a lower ODP.

SAE Automotive Alternate Refrigerants Systems Symposium (Phoenix Forum)

The SAE Phoenix Forum was initiated by Ward Atkinson in 1998 to bring together engineers and environmental authorities working on more environmentally acceptable refrigerants to replace R-134. Each Phoenix Forum included vehicle demonstrations and paper presentations on alternative refrigerants and associated system design for automotive air conditioning. The last Phoenix Forum was held in 2012.

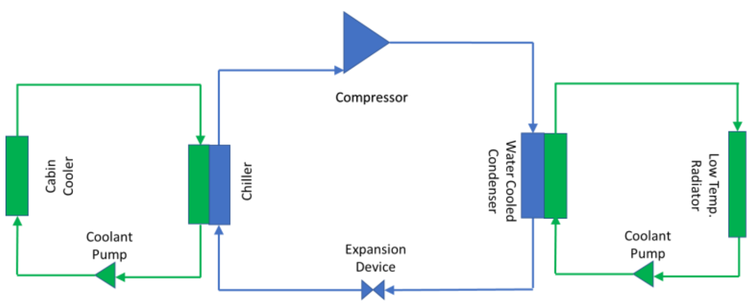
Single Secondary Loop (SSL)-MAC (one cooling point)

A basic SL-MAC with one cooling point indirectly cools the vehicle cabin by first using the *primary* refrigerant cycle evaporator/heat exchanger to cool a liquid coolant circulating to a *secondary* heat exchanger moving the cold from the coolant to the air that is conventionally circulated in the vehicle. SL-MAC components include a compressor, condenser, expansion device, evaporator, refrigerant-to-coolant heat exchanger, coolant pump, coolant-to-air heat exchanger, and fan.



Dual Secondary Loop (DSL) Heat Pump MACs (two or more cooling or heating points)

A SL Hat Pump MAC has two or more cooling or heating points supplied from the primary refrigerant.



i VDA Winter Meeting

The Saalfelden Austria Winter Meeting was initiated in 2002 by VDA to demonstrate the heating performance of alternative refrigerants in various DX heat pump configurations. The last Saalfelden Winter Meeting was in 2010.

Tier 1 Suppliers

Automotive Tier 1 MAC suppliers are companies that produce and deliver complete AC and heat-pump systems, and subsystems directly to OEMs, who then install them into vehicles for sale.

Tier 2 Suppliers

Automotive Tier 2 MAC suppliers are companies that produce and deliver raw materials and components to Tier 1 MAC suppliers who manufacture and assemble complete MAC systems and subsystems for OEMs.

Appendix H. Intense Networking and Workshops to Continuously Improve MACs

Winter

MACS Worldwide Convention, Tradeshow, and Training Event
VDA Alternative Refrigerant Winter Meeting, Saalfelden, Austria

Spring

SAE International Congress & Exposition

Summer

SAE MACs Phoenix Forum

Fall

Earth Technologies Forum

Appendix I. Who's Who of Continuously Improved MACs

Nacer Achaichen, Delphi
Yash P. Abbi, TERI
Baroto Adipasito, Volkswagen
Samuel Alber, Modine
Frank Allison, IMACA
Jay Amin, Visteon
Stephen O. Andersen, US EPA/IGSD
Michael Arnemann, Zexel-Valeo
Alberto Ayala, CARB
Ward Atkinson, Suntest
James A. Baker, GM/Delphi
David Bateman, DuPont
Carlo Burkhardt, Witzenmann
Pat Bassett, Denso
Dave Bateman, DuPont
Jacob Bayyouk, Sanden
Andreas Bergami, Delphi
Erin Birgfeld, US EPA
Bob Bishop, GM
Neil Blackwell, US Army
John Bresnahan, ICI
Roland Caesar, Daimler
Ralph Cadman, Unicla
Larry Chaney, NREL
Jiangping Chen, Shanghai Jiao Tong University
Shidar Chidambaram, TERI
Sourav Chowdhury, Mahle
Steve Church, GI ARB
Kevin Cleary, CARB
Peter Coll, Neutronics/MACS Worldwide
Sam Collier, Modine
Steve Colmery, ICI
Elizabeth Cook, FOE/WRI
Richard Corey, CARB
Timothy D. Craig, Delphi/Mahle
Tom Crandall, RTI
Satyavrat Dahiya, Tata Motors
John Danaher, UDP
Barwin David, Nissan
Paul DeGuiseppi, MACS Worldwide
Paul DeWitt, Eaton
Gene Dianetti, Parker
Gerardo Diaz, Modine
John Dingell, US House, Michigan
David Doniger, NRDC
Gary Douglas, Goodyear
Karsten Drewes, RISA Sicherheitsanalysen
John Duerr, Tracer Products
Alan Edwards, Unicla
Frank Fruehauf, Daimler-Chrysler
Christine R. Ethridge,
Harry Eustis, GM
Robert Farrington, NREL
Walter Ferraris, Centro Ricerche FIAT
Hans Fernqvist, Volvo
Richard "Tad" Ferris, IGSD
Wayne Forest, Delphi
Mahmoud Ghodbane, Delphi/Mahle
Stefan Glober, Delphi
David Godwin, US EPA
Craig Govekar, Snap-on
Murali Govindarajalu, FCA
Mark Gunter, Modine
Joern Froehling, Visteon
Don Grob, UL
Linda Gronlund, BMW
Peg Gutman, Ford
Armin Hafner, SINTEF
Brad Haines, Goodyear Tire & Rubber
Hans Hammer, Audi
Bob Hall, Clore Automotive
Icheol Han, Halla
Gary Hansen, Red Dot
Dale Harmon, US EPA RTP
Wayne Herndon, MJ Research Ice 32
Dieter Heinle, Behr
Peter Hellmann, Volkswagen
Anne Karin T. Hemmingsen, SINTEF
Mike Hettrick, ICI
William R. Hill, GM
Art Hobbs, MACS Worldwide
Elvis Hoffpauir, MACS Worldwide
Kathleen Hogan, US EPA CPPD
Kurt Hollasch, Delphi
Mike Hope, Jaguar Land Rover
Hiroyuki Hotta, Toyota
Valerie Hovland, NREL
Predrag "Pega" Hrnjak, UI/CTS
Werner Huenemoerder, Denso
Drusilla Hufford, US EPA
Ulrich Hussels, RISA Sicherheitsanalysen
Masahiro Iguchi, Calsonic Kansei
Kenji Iijima, Zexel
Kiwamu Inui, Toyota
Mashide Ishikawa, Toyota
James Irvine, Jaguar/Land Rover
Osamu Ishida, Honda
Hajime Ito, Denso
Virender Jain, Parker
Bill Jamo, Service Engineer
Caley Johnson, US EPA
Prasad S. Kadle, Delphi
Sangeet H. Kapoor, Tata Motors
Larry Kettwich, UL
Aamir Khawaja, FCA
Mark Klaven, SAE International
Mary Koban, Dupont/Chemours

Nubuo Kobayashi, Toyota
Juergen Koehler, Technical University Braunschweig
Rich Koldewey, CPS Products
William Kume, GM
Lindsay Leitzel, Mahle
Steve Lepper, Ford
Jeffrey Levy, US EPA
Thomas Lewandowski, Gradient
Gustaf Lorentzen, NIT/SINTEF
Deborah Luecken, US EPA RTP
Jason Lustbader, NREL
Greg Major, GM
GD Mathur, Calsonic
Koch Matthias, Eaton
Mack McFarland, DuPont/Chemours
Robert Mager, BMW
John Maggiioncalda, Zexel
Carloandrea Malvicino, Stellantis Italia
Ari Meder, Corus
Jagvendra Meena, Tata Motors
Robert Mager, BMW
Steve Memory, Modine
Paul Meurillon, Valeo
John Meyer, Visteon
Alan S. Miller, Center for Climate Change
Mark Mitchell, VASA
Christoph Muererr, Solvay
Gary Murray, Robinair
Prasanna Nagarhalli, Tata Motors
Arthur Naujock, Calsonic
Peter Nekså, SINTEF
Keneth Newton, VASA
Kakehashi Nobuharu, Denso
Frank Obrist, Obrist Engineering
Simon Oulouhojian, MACS
Stella Papasavva, GM
Angelo Patti, Chrysler/Ford Chrysler/DaimlerChrysler/Ford
Christophe Petijean, Valeo
Jostein Pettersen, Norwegian University of Science and Technology
Gwendolyn Peyton, US EPA
Jill Phillips, US EPA
Gary Pollak, SAE
Tom Potter, Denso
Rick Reddington, GTM
Al Reginaldo, Toyota
Jim Resutek, OTB Consultants
William Rhodes, US EPA
Bob Rinkel, Gates
Frank Rinne, Sanden
Frank Rogers, GM
David Rudyk, Parker Hannifin
John Rugh, NREL
Michael Sailer, Honda
Mark Santacesaria, Mahle
Jeff Santer, GM
Stephen Schaeber, MACS
Sachin Shendge, Tata Motors
Lawrence P. Scherer, Delphi
Rusty Scott, ATCO
Bernie Serriani, Delphi
Christopher Seeton, Honeywell
Frederick S. Sciance, GM
Stephen Seidel, US EPA/C2ES
Jeong-Hun Seo, Halla
Doris Showalter, Eaton
Carlos Silva, US EPA
N. Dean Smith, US EPA
Mark Smith, Goodyear
Melinda Soffer, IGSD
Mark Spatz, Honeywell
Kjell Stenstadvold, Hydro
Maneesh Arora, Tata Motors
Xiaopu Sun, IGSD
Mark Sundberg, MJ Research
Kristen Taddonio, US EPA/US DOE/IGSD
Jim Taylor, MACS Worldwide
Charles Thrift, TI Auto Systems
Karen Thundiyil, US EPA
Pravin Tilekar, Tata Motors
Gene Titov, NREL
Phil Trigiani, Uview
Matti Tapani Vainio, EC
Denise San Valentin, CCAC
Frank Vetter, Modine
Curt Vincent, GM/Honeywell
Richard Vincent, CARB
Jerry Wander, Inficon
Paul Weissler, MACS Worldwide
Karl-Heinz Weller, Daimler-Chrysler
Jürgen Wertenbach, Daimler
Flonan Wieschdiec, Visteon
Bill Williams, Twin Rivers Engineering
Jon Winkler, NREL
Frank Wolf, Obrist Engineering
Naoya Yokomachi, Toyota
Yasushi Yamanaka, Denso
Jason Yi, CCES
Jianmin Yin, Modine
James Young, Skye International
Durwood Zaelke, IGSD
Jie Zeng, Denso
Mark Zima, Mahle

Appendix J. Selected Bibliography for Elaboration of the Importance of the MAC Community in Protecting the Stratospheric Ozone Layer Under the Montreal Protocol

Montreal Protocol Core Reading

Mario J. Molina and F. Sherwood Rowland (1974)
Stephen O. Andersen and K. Madhava Sarma (2002)
Stephen O. Andersen, K. Madhava Sarma, and Kristen N. Taddonio (2007)
Stephen O. Andersen and Marco Gonzalez (2023)

MACs History of Stratospheric Ozone and Climate Leadership

Ward A. Atkinson (2008)
Gene D. Dickirson (2011)
Stephen O. Andersen, Marcel L. Halberstadt, and Nathan Borgford-Parnell (2013)
Mark Mitchell and Ken Newton (2024)

Secondary Loop Patents Publications

Stephen O. Andersen et al. (2014)
Stephen O. Andersen et al. (2015)
Stephen O. Andersen et al. (2016)
Stephen O. Andersen et al. (2018)
James A. Baker and Mahmoud Ghodbane (2000) (Patent)
Timothy S. Craig, Sourav Chowdhury, and Nancy J. Sherman (2019)
Timothy S. Craig et al. (2020)
Magnus Eisele, Yunho Hwang, and Reinhard Radermacher (2013)
Mahmoud Ghodbane (1999)
Mahmoud Ghodbane (2000)
Mahmoud Ghodbane and Hans Fernqvist (2003)
Mahmoud Ghodbane, James A. Baker, and Prasad S. Kadle (2004)
Mahmoud Ghodbane, Timothy D. Craig, and James A. Baker (2007)
Inguk Hwang et al. (2021)
Mei, Hwang and Kim (2018)
Wanyong Li et al. (2021)
Guidan Liu et al. (2025)
Jan Christoph Menken et al. (2014)
Carrie Kowsky et al. (2012)
Anurag Maurya, Santosh Venu, and Sangeet H Kapoor (2024)
Kristen N. Taddonio, Nancy J. Sherman, and Stephen O. Andersen (2019)
Lawrence J. Scherer et al. (2003)
US EPA (2007a)
Wang, et al. (2010)
Paul Weissler (2016)

Appendix K. Authors of Publications Featuring SL-MACs

Radhey S. Agarwal
Stephen O. Andersen
James A. Baker
Wei Chang
Jiangping Chen
Lifeng Cheng
Gumbae Choi
Sourav Chowdhury
Timothy D. Craig
Magnus Eisele
Hans Fernqvist
Walter Ferraris
Yunhua Gan
Mahmoud Ghodbane
Inguk Hwang
Yunho Hwang
Prasad Kadle
Sangeet H Kapoor
Jaeyeon Kim
J. E. Koerner
Carrie Kowsky
Haejun Lee
Lindsey Leitzel
Ming Li
Wanyong Li
Xiaotong Li
Guidan Liu
Rui Liu
Yusheng Liu
Carloandrea Malvicino
Anurag Maurya
Jagvendra Meena
Zhenyuan Mei
Jan Christoph Menken
Samual Yana Motta
Prasanna V. Nagarhalli
Frederick Oddi
Manju Oh
Steven G. Schaeber, Jr.
Lawrence P. Scherer
Bernie Serriani, Delphi
Nancy J. Sherman
Junye Shi
Melinda Soffer
Klaus Strasser
Kristen N. Taddonio
Haixu Teng
Santosh Venu
Dandong Wang
Kai Wang
Paul Weissler
Thomas A. Weustenfeld
Edward Wolfe
Baolin Yi
Zhanjun Yu

Appendix L. Historic Motor Vehicle Air Conditioning Graphics

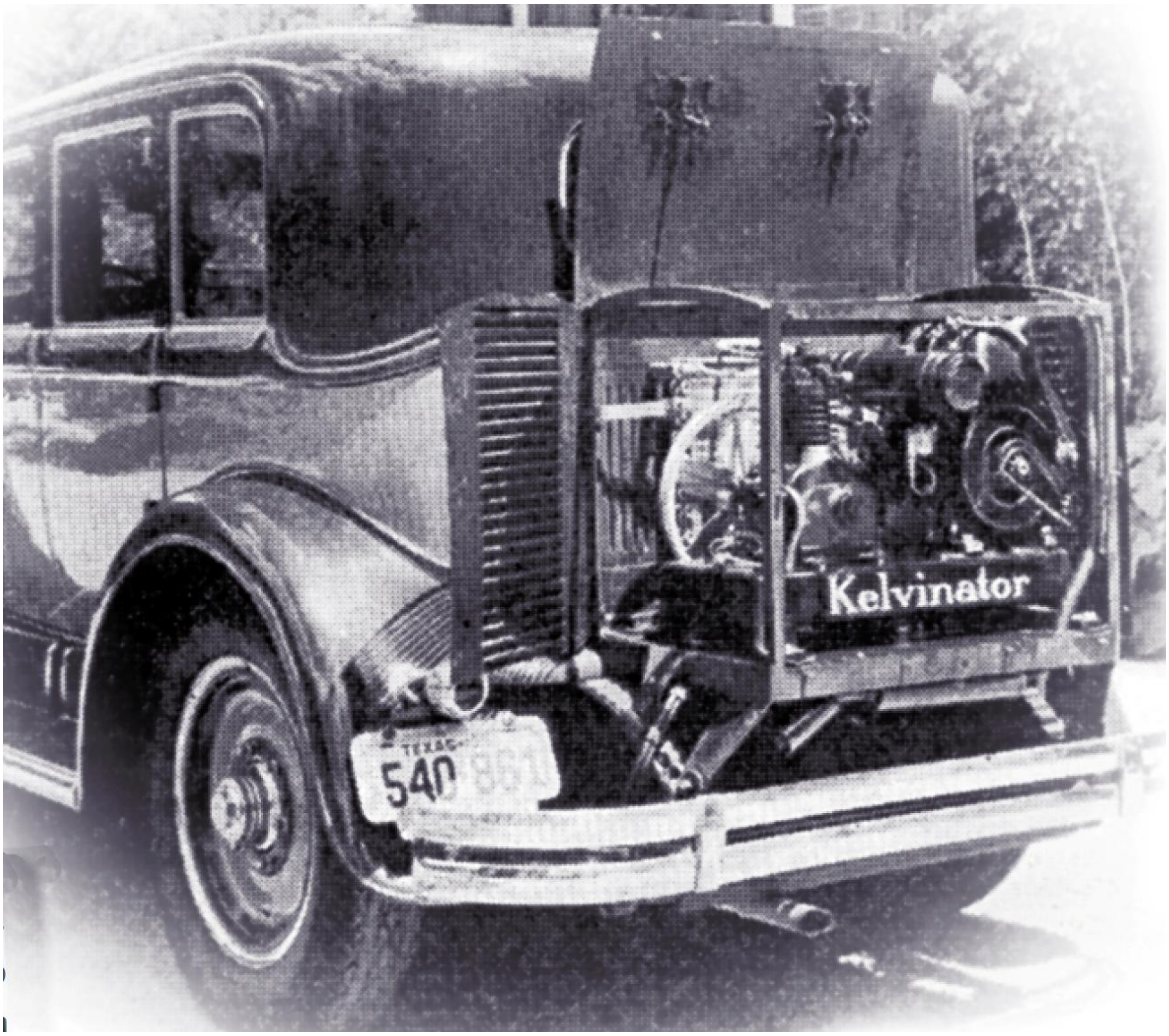


Figure A-1. First demonstration of automobile A/C rear bumper mounted and powered by auxiliary gasoline engine wing condensers extending on each side into the air flow

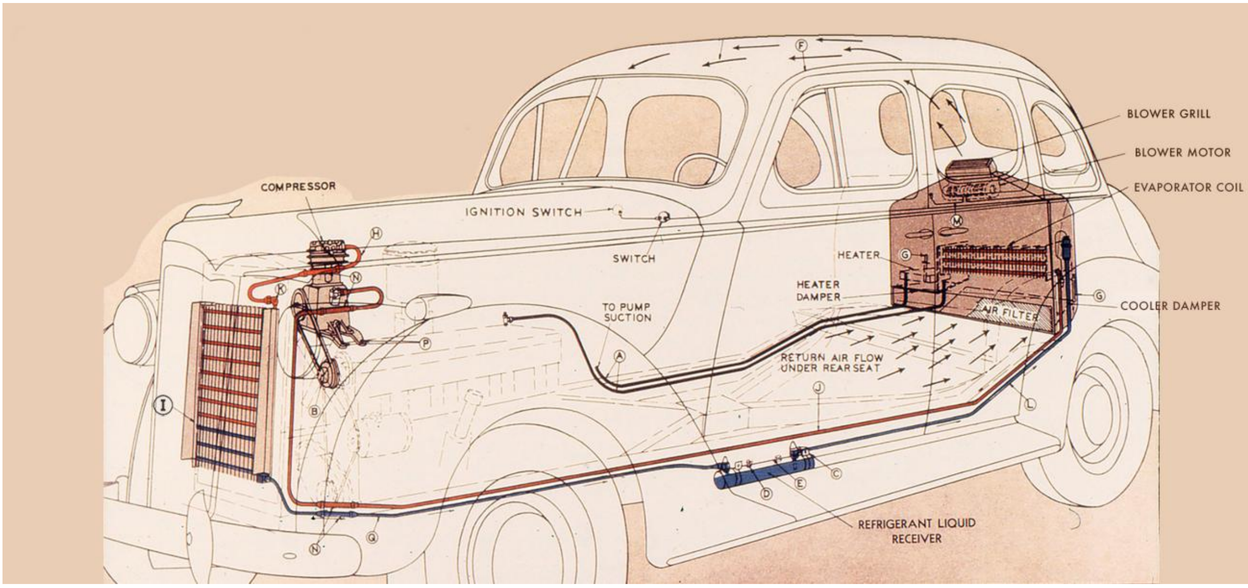


Figure A-2. First automobile with factory-installed A/C

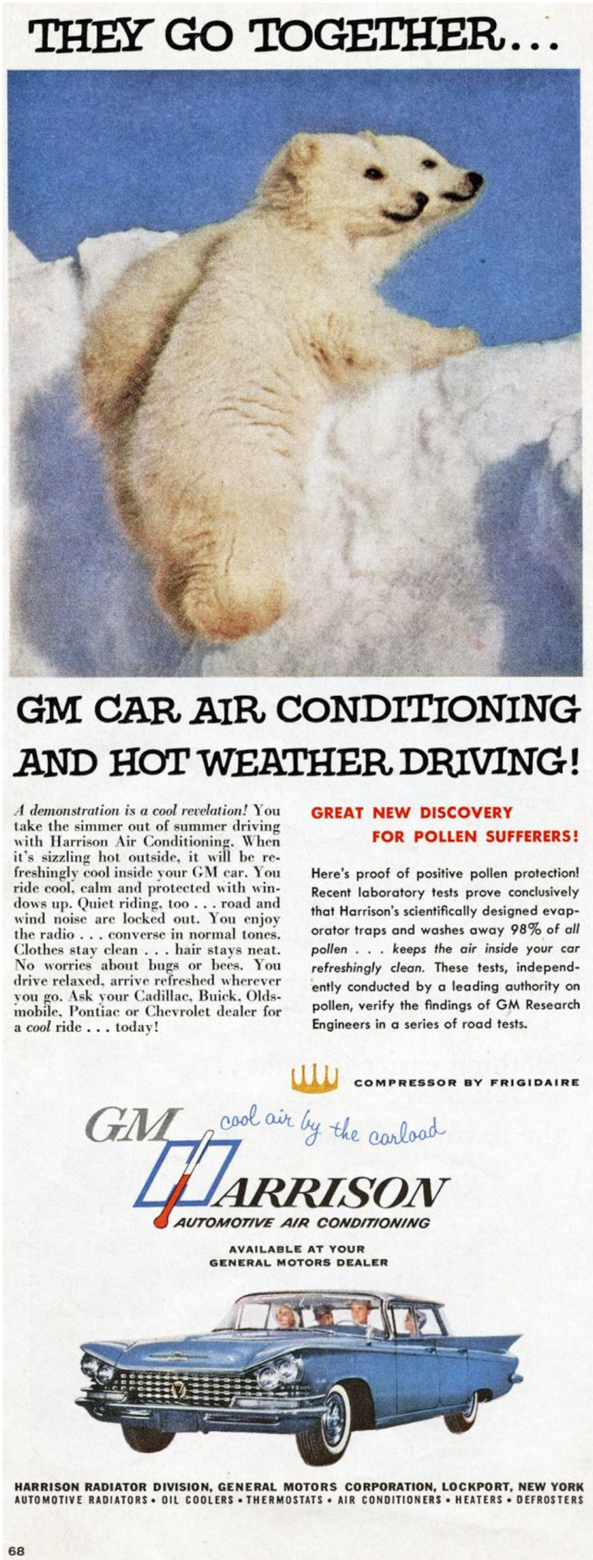


Figure A-3. Harrison Radiator A/C advertisement featuring 1959 Buick

Figure A-4. Harrison 1958 factory-installed A/C

Appendix M. Personal Perspectives of Pioneers in SL-MAC Architecture

Dr. Stephen O. Andersen on Government/Industry/Environmentalist MAC Partnerships

The MAC partnerships had the unusual advantage of members who were respected and influential with one or more of the authorities that had responsibility for key decisions. Whenever there was consensus on the MAC partnership team the cumulative influence was usually able to align technical feasibility with policy both in the USA and globally.

For example, Jim Baker with General Motors was an undisputed technology communicator trusted to put forward the best ideas regardless of source; Elizabeth Cook with FOE, David Doniger at the Natural Resources Defense Council (NRDC), and Alan Miller at the Center for Climate Change were trusted by global environmental activists to insist on ambitious outcomes; Simon Oulouhojian and Elvis Hoffpauir at MACs were absolutely trusted by service companies and service tool suppliers to profitably professionalize MAC service to protect the stratospheric ozone layer; Ward J. Atkinson, Chair of SAE Interior Climate Control Standards Committee (ICCSC), was trusted by everyone to implement best practices in MAC design, manufacture, service, and safety; and at EPA John S. Hoffman, Eileen Claussen, Stephen Seidel, Kristen N. Taddonio, and I were trusted to honour partnership agreements that accomplished equal or greater stratospheric ozone protection than command-and-control regulations might have otherwise accomplished without cooperation and likely with conflict.

James A. Baker on SL-MAC Invention

In early 1986, I was working on MACs at Delphi, which was then a subsidiary of General Motors. Probably because I had both a chemistry and engineering background, my Chief Engineer, Robert Bishop, assigned me to look into the science and regulatory implications of ozone depletion. I quickly reported to management that, despite significant industry scepticism, the ozone depletion threat was to me credible, and I recommended Delphi look into immediate emissions reduction and search for an ozone-safe replacement for CFC-12. I argued we needed a head start on regulation sure to come, and I offered an initial outline of the path forward recognizing R-134a as the most promising candidate. Delphi's then current United States CFC-12 suppliers denied the science and declined to help even General Motors.

Our Engineering Director, Kurt Hollasch, was unimpressed with the position of fluorocarbon manufacturers and suppliers and contacted a European refrigerant manufacturer, Imperial Chemicals (ICI – United Kingdom) that was seeking to become a GM supplier. Kurt successfully negotiated enough R-134a for us to get a good head start and for him to officially authorize our R-134a program. We quickly confirmed that R-134a was similar to CFC-12 in chemical and physical properties and likely safe for the ozone layer, non-flammable, and with comparatively low toxicity. In first testing R-134a delivered comparable cooling capacity but compressors quickly failed with the lubricant used with CFC-12.

I contacted Bill Brown at Union Carbide and worked closely with him to develop a new class of lubricants for MACs, called polyalkylene glycols (PAGs). But by the time the

Montreal Protocol was signed in 1987 Bill and had identified the proper lubricant, and our engineers were busy optimizing components and controls for acceptable energy efficiency.

Our growing confidence allowed General Motors representatives to attend EPA stakeholder meetings unafraid of regulation and ready to transition, as needed. In January 1988, just four months after the Montreal Protocol was signed, I connected with Simon, Stephen, and Ward and we formed a collegial partnership that went full speed ahead on supporting recycle recovery commercialization and plans to replace R-12 with R-134a as fast as feasible.

I am very proud that pioneering work by GM was successful and so quickly disclosed to the MAC community, which was one reason R-12 was so quickly replaced with R-134a by the automotive industry.

James A. Baker on Industry Ambassadors to the Montreal Protocol

A remarkable part of the global effort was Dr. Stephen O. Andersen's recruitment of scientists/engineers like me who were at the forefront of new technology to persuade global companies and governments to get on board the Montreal Protocol. I was recruited by the US State Department for a delegation to Hungary and the Union of Soviet Socialist Republics (USSR) that included the Vice President of AT&T Dr. David Chittick and his wife Eileen, Nortel ODS Phaseout Manager Arthur FitzGerald, DuPont Freon Products Manager Dr. Joseph Glas, United States Air Force Major E. Thomas Morehouse, halon phaseout manager for the United States Department of Defense, and Stephen.

Everyone but Dr. Glas made the unequivocal scientific case for fast replacement of ODSs. David Chittick and Art FitzGerald described in detail how aqueous solvents and no-clean soldering could rapidly replace CFC-113 and methyl chloroform solvents at comparable cost and higher technical performance (fewer products failures and less hazardous waste). Major Morehouse explained that over 90% of halon emissions were in testing, training, and accidental discharge that could quickly be eliminated without jeopardy to national security; I made the case for R-134a replacing R-12 in motor vehicle AC with an added cost of just US $5.00 that would hardly be noticed in the purchase price of a car or truck.

Dr. Glas argued that scientistic evidence was not yet 99% (5 Sigma) confident that CFCs were the cause of the Antarctic Ozone Hole and global ozone depletion, and all that was necessary was to get ready in case that were ever proven. Dr. Andersen was far more persuasive on the atmospheric and environmental science and made the economic case for precaution in avoiding emissions of chemicals with atmospheric life of well over 100 years.

Of course, Dr. Glas was wrong about the science, and our team did help persuade Hungary and USSR to strengthen the Montreal Protocol. AT&T, GM, and Nortel actually strengthened our resolve in response to the bad advice of DuPont to simply stand by waiting for someone else to tell companies when to embrace next generation technology. Each of our companies was at the forefront of ODS phaseout, with head starts that saved money by confidently choosing technically and economically superior replacements.

Timothy Craig on the Power of Teams Working Outside the Box

One of the many remarkable outcomes of thinking way outside the box was the discovery that -- contrary to expectations -- secondary loop energy savings outweigh the energy penalty of the additional heat exchange. The traditional direct expansion (DX) MAC system has one heat transfer from refrigerant to air within the passenger compartment. The SL-MAC system has a first heat transfer from refrigerant to liquid coolant within the engine compartment with coolant then pumped into the passenger compartment for a second heat transfer from coolant to air. The worry was that it would take longer with two heat transfers to cool down a hot vehicle to a comfortable temperature and that two heat transfers would use more energy.

The amazing reality is that despite the inherent temperature difference between the refrigerant and coolant, its effect on cooling performance was found to be "measurable but not noticeable." This was verified by professional MAC designers in road tests of identical vehicles comparing the DX and SL systems.

The equally amazing reality is that in ICE and hybrid vehicles the fuel savings of prolonged idle stop and load shifting can more than offset the small amount of energy that additional heat transfers require. And that, in all-electric vehicles, the energy savings of cooling only when the battery and inverter are at peak performance (i.e., when motion and other energy loads are minimum) more than offsets the extra heat transfer.

And best of all, the faster cooldown after a brief stop is very noticeable and appreciated by drivers and passengers in both hybrid and all-electric vehicles. Higher ownership satisfaction of hybrid and all-electric vehicles provides cleaner air and a climate safer for this and future generations.

Peter Coll

I will never forget the meeting Dr. Andersen chaired to break the logjam over the global choice of refrigerant to replace R-134a. Everyone but German automakers were clear they wanted R-1234yf with GWP comparable to R-744 and much higher cooling capacity and energy efficiency and lower system cost but higher refrigerant cost. Out of pride of invention and pressured by European governments and ENGOs, German automakers were deadlocked against the world.

After a long and contentious discussion, Stephen said something like: "All in favour of R-1234yf raise your hands." All but three or four hands went up. "The vote is overwhelming, R-1234yf is the choice, the report will note the minority vote. Thank you all for your support, the meeting is closed!"

The leadership demonstrated by Dr. Andersen during this contentious time not only solidified the direction of mobile A/C but laid the groundwork for future system development. The careful study of both R-152a and R-744, and the potential advantages of MAC secondary loop as a future system architecture was not lost on the participants in the R-1234yf transition. While not yet ready for prime time during the initial transition away from R-134a, the secondary loop opportunity continued to be studied by Tata with the collaboration and leadership of Mr. Timothy Craig.

This work, combined with major advancements in electric vehicle technology, has led back to MAC secondary loop systems emerging as the leading candidate to solve the challenges of both heating and cooling passengers and vehicle electronics in the EV space.

Hans Fernqvist with an Industry View from the EU

I am very proud and satisfied to have been actively involved in the development and testing of secondary loop mobile air conditioning systems (SL-MACs). This type of system offers many benefits and advantages not only with flammable refrigerants like R-152a and R-290 but also for existing non-flammable, or mildly flammable refrigerants like R-134a and R-1234yf, respectively.

Secondary loop architecture also offers the possibility to collect virtually all waste heat in electric and hybrid vehicles and, in combination with a heat-pump system, could significantly increase driving range before the need for battery recharge. The deep-rooted and historically long-lasting resistance to implement secondary loop systems has been based on the belief and argument that the additional heat exchanger step, refrigerant-chiller-water/glycol, and the additional thermal mass in the water/glycol loop, results in an unacceptable loss of cooling performance and a delay in cooldown performance. This is, to some extent, theoretically correct, but reality has shown that this is not the whole story. The better heat exchange between refrigerant and water/glycol in the chiller, vs. refrigerant to air in a traditional evaporator, plus the absence of refrigerant maldistribution, causing hot and/or cold spots in a traditional evaporator, seems to compensate for the additional heat exchanger step. This have been demonstrated in both real-world tests as well as in laboratory testing.

One example is the Volvo XC90, presented at a Phoenix Forum (RACES), that had been rebuilt to a SL system with a front and a rear cooling point and using R-152a as the primary refrigerant. The original front and rear evaporators (clean flushed) were used as “cooling cores” as the coolant-to-air heat exchangers. Even without optimized components the Volvo, at the “Ride & Drive” evaluation, performed with perfectly acceptable cooling performance. Some direct expansion (DX) systems performed somewhat better and some slightly worse than the Volvo SL-MAC with R-152a.

A second example is the results from the SAE Alternative Refrigerant Cooperative Research Project, Phase 1 (ARCRP 1) in 2001-2005, which most probably is one of the most extensive and well performed test of MAC systems performed. The evaluation included four different systems. 1) a standard R-134a “state of the art system,” 2) a next generation improved R-134a system, 3) a transcritical R-744 (CO_2) system and 4) a secondary loop system using R-290 (propane) as primary refrigerant. All four systems were run following an extensive test matrix. The standard R-134a were run first to set the target cooling performance for each condition in the matrix. The three alternative systems were then run to match the “state of the art” R-134a cooling performance and the necessary compressor power was recorded for each test point.

After all four systems were run through the test matrix the annual energy consumption was calculated for various driving conditions. The improved/next generation R-134a and the transcritical R-744 used 24-25% less energy than the standard R-134a baseline system for the same cooling comfort. The non-optimized SL R-290 system used about 14% less energy.

It should be noted that the SL R-290 system in this test program was run as an orifice tube system with an internal heat exchanger (IHX) between suction- and liquid line, downstream the accumulator. The reason for that was that this type of system utilizes the full potential of a plate type heat exchanger (the "chiller"), making it run flooded and the IHX make sure compressor inlet gas is "dry" and slightly superheated. The last point is essential if R-290 (propane) is used as the primary refrigerant.

Later tests, performed in a vehicle with DX system at Volvo Cars product development facilities, have shown astonishing results when introducing an IHX in an orifice tube system. Significantly better cooling capacity, lower discharge pressures (>4bar) and up to 25% less power consumption at high cooling loads vs. an identical DX system without the IHX. Below is a listing of pros and cons for secondary loop systems that I began summarizing around 2008.

Every reason for me to be proud and satisfied that secondary loop MACs, combined with heat-pump function, hopefully will dominate in all-electric vehicles adding value in driving range, systems reliability, safety, and comfort.

Hans Fernqvist's list of secondary loop system advantages and disadvantages:

Advantages

- Flammable and/or toxic refrigerants can be used.
- Charge of refrigerant less than a comparable direct system.
- No increase of refrigerant charge for multiple cooling point systems.
- No issue for proper refrigerant charge depending on number of cooling cores in operation.
- More than one "cooling point" can easily be utilized.
- No limitation to just two cooling points.
- No air temperature variations due to phase separation or maldistribution of refrigerant.
- No "cold spots" where frosting can start and grow from.
- Absolutely no risk for frost or ice formation anywhere on the cooling core as long as the inlet temperature of secondary fluid is above freezing temperature (0 °C / 32 °F).
- No issue for "oil trapping"/OCR compared to double evaporator/direct systems with rear unit turned off.
- No flow noise from TXV or orifice.
- Isolation of compressor working noise (line/refrigerant transferred).
- Possible to have "cold storage" function for red light stop, short parking, etc.
- Copper/brass cooling core with no bad smell since no bacteria/fungus.

- Using propane (R-290) as primary refrigerant, annual energy consumption is 8 to 13% less than for a baseline, direct evaporative R-134a system (SAE ARCRP results).
- On vehicles where LPG (liquefied petroleum gas) is used as engine fuel, the necessary evaporation heat for turning the LPG from liquid to gaseous phase can be utilized for cooling the secondary loop flow (water/glycol). Estimated heating demand for the LPG = free cooling performance is approx. 1 kW.
- The very small variation of temperature of secondary fluid and air off the cooling core (< ± 0.2°C) for a fixed displacement compressor under cycling operation allows for a raised "set-point" at a much higher level (~12-13 °C) compared to a direct evaporative, cycling compressor system, without experiencing moist (bad) smell.
- For leakage (emission) measurements, the primary refrigerant circuit of a Secondary Loop system, requires the same mini-SHED test chamber, as an ordinary single evaporator system.
- Cooling core does not need any noise isolating seal between core and HVAC case/housing.
- Rated as an inherently safe design by US EPA, independent of refrigerant used.
- System needs no additional safety devices.
- Fully possible to have same packaging/layout of primary refrigerant loop, independent of left-hand or right-hand drive vehicles.
- Same packaging/layout of primary refrigerant loop, use of today's R-134a or tomorrow's refrigerant, between conventional cars and electrified.
- With a "shunt" operated sub-loop, temperature of a battery pack in a hybrid or electric vehicle can be well monitored and kept within very narrow limits.
- With a shunt operated sub-loop, temperature of the battery pack can be held above dew point of the ambient air = no risk for internal or external condensation.
- Main brine (water/glycol) loop acts as thermal mass for battery sub-loop, reducing compressor running time and number of on/off cycles.
- Thermal mass of secondary loop will increase ON-time as well as OFF-time for a fixed displacement, cycling compressor and thereby increase overall system efficiency for all load conditions except maximum load/continuous running.
- For an externally controlled, variable displacement compressor, the thermal mass of the secondary loop will raise the threshold level for evaporator heat load where—from an efficiency standpoint—it is more beneficial to run the compressor on full/maximum displacement and cycle it versus running it continuously on reduced displacement.

Disadvantages

- Higher total weight.
- Higher total cost versus a traditional, single-evaporator system.
- More components (circulating pump, chiller, expansion tank for brine (secondary) loop, secondary loop hoses …).
- More electric power needed (circulating pump(s)).
- Soak and cooldown performance.

- Most suitable refrigerant.
- Design of chiller: type and material.

Bill Hill, General Motors on Global Cooperation for Environmentally Superior MACS

Reading this comprehensive history reminded me of how many people have worked over the past fifty years to reduce refrigerant leaks, implement environmentally superior refrigerants, to recover and reuse refrigerants, and to improve cooling capacity and energy efficiency for a world that is hot and getting hotter. I am proud of the leadership of General Motors, I am grateful to have been a member of the many teams, and in looking back I can hardly believe the amazing cooperation of experts worldwide. Actually, it's a nearly perfect life for people like me who love how engineering can make lives better.

The history narrative captures the various activities and calls out some of the creative tension of fluorocarbon companies aggressively defending their chemical markets and the automotive community doing our best to minimize environmental impact while satisfying our customers.

Tens of thousands of hours and millions of dollars were spent on cooperative projects faithfully shared at global conferences like the SAE Phoenix Forums and the VDA Saalfelden Workshops. With Ward Atkinson (SAE) and Suntest and Gary Pollak (SAE), I helped manage most of the Phoenix Forums where companies combined their wisdom and experience and avoided duplication of effort in head-to-head competition for best next technology.

My team at General Motors with the inspired help of Delphi demonstrated R-152a SL-MACs that were equal or better in conspicuous cooling performance but superior in comfort recovery after brief stops and in higher energy efficiency from prolonged idle stops made possible by the thermal ballast of the coolant. Now, with electrically drive compressors, that comfort can be efficiently delivered in internal combustion vehicles and in all-electric vehicles. That is amazing!

Dr. Yunho Hwang, Co-Director of the University of Maryland Center for Environmental Energy Engineering (CEEE)

With colleagues, I have published a half dozen papers spotlighting the environmental and technical potential of secondary-loop system architecture in motor vehicle air conditioning. I share the view that SL-MACs are the technology of the future and a refreshing break from the ordinary. A dozen more of our publications are informed and made more elegant by understanding exactly how and why secondary loop can be applied in other applications where engineering has been stagnant.

A smaller refrigerant charge separated from vehicle occupants allows safe use of more efficient yet flammable refrigerants without atmospheric degradation to TFA, considered in some regulatory definitions as a per- and polyfluoroalkyl substance (PFAS); these are commonly known as "everywhere and forever chemicals."

SL-MACs are superior in designs with two or more cooling points, including large passenger vehicles and all-electric vehicles, where inverters and batteries need heating and cooling for driving range and extended battery life.

Thermal ballast makes possible prolonged idle stop, faster acceleration with no interruption in heating and cooling, and lower carbon footprint by optimizing the thermal demands and carbon intensity of thermal supply.

One reason for pride in what we are doing at CEEE is that we cross over between stationary and mobile air conditioning and heating, making the most of engineering innovation and thinking way outside the box. This attracts the best students with ambition to use engineering in support of society and the best industry partners with ambition to go beyond customer satisfaction with value added to society.

The history reported in this publication makes it clear that engineering to protect Earth is not easy and is sometimes ruthless, but that honourable people working together with shared goals can accomplish what seemed impossible for this and future generations.

Sangeet H. Kapoor on Demonstrating SL-MAC Technical and Environmental Superiority

With India being a signatory to the Kigali Amendment to the Montreal Protocol, there is a strong national imperative to transition to low-GWP alternatives.

In my lifetime of engineering, I have never experienced the cooperation and creativity that exists in the continuous improvement of MACs to protect stratospheric ozone and climate, including our success in planning rapid transition to secondary loop heat pumps in all-electric vehicles. In India, the secondary loop engineering architecture will also be applied to conventional direct expansion and hybrid systems using small charge with sealed motor-compressor systems for high cooling capacity, safety, and fuel efficiency.

In India, Tata Motors collaborated with global suppliers for technical solutions and in exchange, challenged those engineers to consider longer, hotter, and more humid cooling seasons typical of Africa, India, and Southeast Asia, but now becoming a universal problem due to global warming since many countries already have regions as hot as anywhere else.

Tata Motors is proud of its contribution towards development of novel SL-MAC architectures that work safely with alternate low GWP refrigerants like R-152a, which are slightly flammable. The Tata engineers who worked side-by-side with Mahle engineers are living proof of the professional value of collaboration that brings the best engineers together to solve the most important and urgent problems such as stratospheric ozone protection and climate.

The engineers are currently developing MAC architectures that work safely with flammable refrigerants having much lower GWP, like R-290. A significant focus of the project is the evaluation of safety risks associated with R-290's flammability. Tata Motors will conduct a detailed risk analysis and develop safety guidelines and standard operating procedures to mitigate potential hazards. These safety protocols are crucial for ensuring the secure operation of R-290 systems in vehicles and form the foundation for future industry adoption. In addition, electronic control units and sensor systems will be designed and integrated into the vehicle prototypes to monitor performance and safety parameters. The project will on-board local vendors to supply R-290 refrigerant, thereby promoting domestic supply chain development.

These collaborative efforts have continuously strengthened in-house development competencies of thermal systems in internal combustion (ICE) and all-electric vehicles – in simulation methodologies, component sizing and prototyping, integrating the same in full vehicle prototypes, validating cooling and heating performance at extreme climate conditions – all of which are crucial for the success of any OEM, particularly in warmer territories such as India.

It is a matter of great pride for Tata Motors engineers to work on the development of safe, novel and unique MAC system architectures that work with alternate, low-GWP refrigerants that are flammable. This extraordinary cooperation with indigenous and global suppliers has proven valuable for automotive companies headquartered in both developed and developing countries.

The Government of India has mandated the timelines for phasing down HFCs and is expected to on board regulations for safely transitioning from non-flammable to flammable refrigerants, which will allow global sales of the same new vehicle and value added for vehicle owners who move across borders.

The role and impact of public-private partnerships, technological innovation, and regulatory alignment, in achieving sustainable industrial transformation will be crucial for the success of transitioning to low-GWP alternatives in the MAC sector and automobile industry.

Denise San Valentin, UNEP Climate and Clean Air Coalition (CCAC) on the United Nations SL-MAC Connection

I am proud to have been the Climate and Clean Air Coalition (CCAC) project manager on the demonstration by Tata Motors, Mahle, and IGSD of R-152a in the new MAC technology called "Secondary-Loop Motor Vehicle Air Conditioning – SL-MAC," one of the first technology demonstration projects funded by the CCAC in 2014 and undertaken from 2016–2019 with the aim to promote alternatives to the climate-harming, high-GWP HFCs and give confidence to policymakers and Montreal Protocol Parties to add these in the list of controlled substances.

In contrast with the earlier mainstream technologies, SL-MAC uses a smaller charge of refrigerant completely isolated from the occupied spaces of a vehicle with cold or heat supplied by circulation of a non-flammable antifreeze.

Now, a decade later and almost 10 years after the Kigali Amendment was adopted, I am the CCAC project manager working with the United Nations Industrial Development Organization (UNIDO) and Tata Motors demonstrating the safety, cooling performance, and environmental advantage of R-290 (propane) in MACs of passenger all-electric vehicles and small commercial vehicles with the safety of SL-MAC. By demonstrating the feasibility of R-290 in cooling and heating applications for both passenger and commercial all-electric vehicles, this initiative could drive a systematic shift in the global MAC sector, accelerating the transition towards climate-friendly refrigerants.

Beyond the technical achievements described in this publication is the extraordinary collaboration of the automobile community in proving and perfecting this technology, taking advantage of engineering centres of excellence and hundreds of engineers committed to protecting the stratospheric ozone layer and the climate and combatting extreme heat. Somehow, they all came to agreement to share their best ideas in a technology almost free of patents that would otherwise slow commercialization or even price the technology our of some markets. "One for all, and all for Earth."

In December 2024, Ford Motor Company on behalf of motor vehicle manufacturers and MAC component and system suppliers asked the US EPA to list R-290 as acceptable in SL-MACs for all-electric vehicles under its SNAP program, which is one of the global badges of honour for environmentally superior technology to protect ozone and climate. In all-electric vehicles, the SL-MAC system will provide both heating and cooling for occupants, for the battery and inverter, and for safety in de-fogging and defrosting windows. Heating and cooling the battery and inverter extends the driving range and prolongs battery life, which both contributes to electric vehicle owner satisfaction and electric vehicle market penetration in the interest of future generations.

Please join the pride of the MAC community in proving for over fifty years that individuals and partnerships can make a positive contribution to future Earth with everyone involved having the time of their lives.

Steven G. Schaeber, Jr., Director of Training and Regulatory Affairs at MACS and Editor-In-Chief of ACtion Magazine

In April 2017, I participated in an event at the Mahle engineering facility in Lockport, New York (formerly Harrison Radiator). The meeting was an update on the progress that had been made on a unique "dual secondary loop thermal management system." Designed by Mahle and installed in a Tata Aria 4x4 SUV with dual-zone climate control, the project was a first of its kind, initiated by IGSD with funding from the World Bank to study the feasibility and energy cost savings of a system design featuring a low cost, patent-unencumbered, flammable refrigerant (R-152a in this case) with a secondary loop architecture using a glycol / water mixture to transfer heat to/from the passenger compartment. Details on this project are outlined elsewhere in this text.

At this event I was joined by other industry participants from Mahle, IGSD, CARB, US DOE, SAE and Tata Motors. My role in representing MACS was to document the event for our publications (*ACtion Magazine* and *MACS Service Reports*), as well as for our training materials.

In particular, information from this project was added to our EPA Section 609 Certification Training Program (taking up much of Page 4 in our technician training manual).

This update to our Section 609 book has been read by countless thousands of technicians since it was added back in 2018. Prior to this, our MACS training (and undoubtedly that of most other mobile air conditioning training classes and books) focused solely on "direct expansion" systems using R-12, R-134a and R-1234yf, where the subject refrigerant is "pumped" from the engine compartment, into the under-dash evaporator (located inside the passenger cabin) where it expands and absorbs heat before moving back into the engine compartment, returning to the compressor.

This new "secondary loop" technology was cutting edge and brand-new to technicians and the broader mobile air conditioning industry back in 2017, and something that they had likely never seen before, never heard of, and never thought would be adapted for use in a vehicle. This technology had been used in commercial and stationary systems for many years, but until the late 1990s, it was never even considered for MACs.

That section on R-152a and secondary loop systems can still be found in the MACS Section 609 Training Manual today (2025 edition). The publication can be downloaded from the MACS website: https://macsmobileairclimate.org/about-609-certification/.

I am proud to carry on the pioneering work that MACS has done with government and industry over the decades, training current and future technicians in best practices and environmental stewardship and working towards a lowest possible impact future for vehicle air conditioning and thermal management.

Appendix N. Regulating HFCs in the MACs of Cars Sold in the EU

Matti Tapani Vainio, Professor of Practice, Green Transition, University of Helsinki matti.t.vainio@helsinki.fi

Matti Tapani Vainio worked at the Directorate-General (DG) Environment of the European Commission (EC) in 1997–2007 and was the central administrator to prepare the first EU regulation on MACs, which was part of the EU's first F-gas regulation that paved the way for the current EU plan to phase out all F-gases by 2050. Most remarkable, the MACs regulation was developed in partnership with the US EPA and European and global automobile industry to be simple, easily enforceable, and cost-effective.

Acknowledgements

This history was documented at the request of the authors of a comprehensive history of industry leadership in continuously improving motor vehicle air conditioning and heat pumps now poised to transition to R-744 (CO_2, GWP = 1)) or R-290 (propane, GWP <1) in all-electric vehicles. Thanks go to Stephen O. Andersen, James A. Baker, Timothy D. Craig, Sangeet H. Kapoor, and Steven G. Schaeber, Jr. for edits and additions to this paper and for incorporating the EU leadership in their history.

Abstract

In 2006, the EU put in place what was then the most far-reaching legislative package affecting MACs in the world. It brought MACs under the EU's "type approval" system under the Council Directive 70/156/EEC and regulated MACs in passenger cars (M1) and LDVs (N1)[24] in an ambitious but cost-effective and balanced manner. The transition period for compliance was relatively long (2011–2017) and the directive was technologically neutral in establishing a maximum GWP of 150 for the refrigerant used. It treated all car manufacturers in the world in an equal manner. Thus, even if refrigerant R-1234yf (CH_2=$CFCF_3$ - hydrofluoroolefin – HFO; GWP < 1) was not known to exist at the time, the GWP of 150 made global penetration of the new refrigerant possible. The regulation was crafted to allow maximum regulatory co-operation, with the test on refrigerant leakage tightness an example. The preparation for the MAC regulation was carried out in a collaborative manner with the US EPA, and car and air conditioning manufacturers and associations[25] being proponents of different air conditioning technologies. The Directive was complemented in the EU by a harmonised test for measuring leakages from certain air conditioning systems and minimum requirements for training programmes for MACs.

The MAC Directive set an environmental performance standard and allowed industry to choose the technical solutions to achieve that environmental improvement. It built on the success of the Montreal Protocol, where the MACs community was a driving force on the full spectrum of cooling innovation to reduce MAC GHG emissions including leakage reduction, more climate-friendly refrigerants, and improved energy efficiency.

The Commission's original proposal to regulate MACs had a very different approach. It was also based on the phasing out of MACs having a refrigerant with GWP above 150 and a maximum leakage rate of hydrofluorocarbons (HFCs) of 40 grams per year for single- and 60 grams per year for dual-evaporator systems. However, it was based on a system of transferable quotas. Such a system would not have been part of the relatively rigid "type approval" system but rather given maximum freedom for vehicle manufacturers to reach the quotas of MACs having refrigerants above 150. To the surprise of the Commission, European vehicle car manufacturers did not want the flexibility that was inherent in the system of transferable quotas and preferred to have a type-approval system.

Twenty years after the EU's MAC Directive, R-134a (HFC CH_2FCF_3; GWP = 1300) emissions in the EU have dropped by 30% in 2023 from their peak in 2017 and are projected to reduce rapidly. The directive paved the way for countries outside the EU, including the US, to phase down or completely phase out R-134a in MACs. New challenges have emerged. R-1234yf breaks down in the atmosphere to produce TFA, which is of major environmental concern, and five EU Member States proposed it to be phased out in EU regulation by roughly 2030 in all-electric vehicles. Furthermore, the electrification of cars brings new challenges and opportunities, as all-electric

[24] The MAC Directive was limited to cars and vans and has not been changed since 2006. It had a provision stating that the Commission should consider whether the MACs buses (M1) and trucks and lorries (N2 and N3) should also be regulated.

[25] These were, amongst others, the Society of Automobile Manufactures (SAE, now rebranded as SAE International), the Mobile Air Conditioning Society (MACS, now rebranded the Mobile Air Climate Systems Association), the European Automobile Manufacturers' Association (ACEA), the German Automobile Manufacturers' Association (VDA), the Japanese and Korean Automobile Manufacturers' Associations (JAMA and KAMA).

vehicles produce far less waste heat than vehicles with internal combustion engines. Fortunately, some car manufacturers in the EU are already offering R-744 as the refrigerant in heat pumps, and car manufacturers are globally considering R-290 as a refrigerant with a secondary loop.

Collaboration among the EU and US regulators was quite successful when the MAC Directive was prepared and adopted in the EU. Such collaboration would be beneficial also today when the new challenges of vehicle air conditioning and heating are being addressed.

1. Introduction: Why did the EU start looking into the emissions of GHGs from cars?

When the EU signed the Kyoto Protocol in 1997, it took an obligation to reduce its GHG emissions by 8% by 2008–2012. The European Commission (EC, Commission) has, by the EU treaty, the sole responsibility to propose legal acts in the EU. Given the global nature of GHG emissions as well as the internal market of free movements of goods, the Commission took the lead in the EU to reduce GHG emissions. Therefore, it started a comprehensive and systematic analysis of what options it had to reduce GHGs in the decades to come.

In May 1999, it sent a communication to the Member States and the European Parliament its intentions (Commission 1999), and in March 2000 established a European Climate Change Programme (ECCP). This programme was a multi-stakeholder consultation held in 2000–2001 and included several working groups. One of them, the Industry Working group, was responsible for the development of the EU's policy framework for fluorinated GHGs (F-gases), namely HFCs, perfluorocarbons (PFCs), and sulphur hexafluoride (SF_6) (Commission 2000a).

The ECCP led to, amongst others, the largest GHG emissions trading system (ETS) in the world (Commission 2000)[26]. It also accelerated the process of reducing the CO_2 emissions from cars and LDVs placed on the EU market, leading to the phase out of fossil fuel powered cars in the EU by 2035.

In ECCP, it became apparent that the EU needed to address F-gas emissions partly because 1) HFCs were rapidly replacing chloro- and hydrochlorofluorocarbons as refrigerants that were phased out thanks to the Montreal Protocol[27] and partly because 2) the share of new vehicles having air conditioners was rapidly increasing in the EU. At the turn of the millennium, two-thirds of new cars placed on the market in the EU had MACs; this was projected to rapidly increase to 100%, which it did. The reasons for the increase in the use of MACs included greater comfort and driver alertness in hot weather, better defogging of the windows, and less noise and better aerodynamics for fuel efficiency with windows up.

A problem related to air conditioning was also related to the additional fuel consumption and related CO_2 emissions. This was not measured in the driving cycles measuring CO_2 but the increased at an average of 0.28 litre/100 km or 7 g/km of CO_2 being 5% increased emissions

[26] ETS covered GHG emissions in power generation and industry. Later, it also covered EU's internal flights and shipping and—from 2027 onwards—road transport and domestic heating.

[27] About 85% of ODSs were replaced by non-fluorocarbon (not-in-kind –NIK) solutions with about 15% replaced by HFCs, mostly in cooling equipment where toxic and flammable ammonia refrigerant, flammable hydrocarbon refrigerant, and where CO_2 could not achieve safety and energy efficiency (Andersen and Sarma 2002; Andersen, Sarma, and Taddonio 2007).

compared with the goal of reaching 140 g/km of CO_2 emissions (Commission 2001). Air conditioning has subsequently been included in vehicle drive cycle testing the regulation (Commission 2018).

This paper focuses on the developments of the regulation leading to the phase out of R-134a refrigerant in MACs in the EU from 2017. It establishes the approach of the proposed Commission regulation in 2003 (section 2), what the key design characteristics of the proposed regulation were (section 3), what the Commission proposed (section 4), and what the Member States (i.e., the Council) and the European Parliament finally agreed (section 5). This note is concluded by recent developments affecting the choice of refrigerants in MACs (section 6).

2. The approach

The Commission service (i.e., "ministry") in charge of the work was the DG responsible for Environment. At the turn of the millennium, very little was known in the EU about the possible environmental problem relating to the use of GHGs. The EU was ignorant of the climate impact of MACs: the leakage rates were not known, but it was clear that a total leakage of R-134a from the air conditioner would be equivalent of the CO_2 emissions of driving for six months! The problem was acute.

A study conducted by a consultant in collaboration with industry experts established that the average annual estimated leakage rate of R-134a was 53 grams per year (Commission 2003a). There seemed to be a wide variation of the leakage rates between different manufacturers[28]. This warranted the establishment of a good industry standard that would need to be followed for design purposes in any case. European vehicle manufacturers indicated during the consultations that they designed their systems to leak at no more than 40 grams of R-134a per year for single-evaporator systems and somewhat more for dual-evaporation systems.

DG Environment did not just establish the leakage rate in a vacuum. As there was a lot of experience in the regulation of vehicle air conditioning systems in the US EPA, DG Environment sought collaboration with US EPA from the beginning. It also participated in MACCPP and their partners in MACS and SAE International.

There was another reason why the Commission sought the collaboration of US counterparts. Many EU car manufacturers either exported their cars to the US or manufactured them in the US (and then sold them there or imported them into the EU). And the same was also true for US-based car manufacturers. Some of the EU manufacturing sites were owned by the US companies (for instance, at that time, GM owned Opel and Saab; and Ford owned Volvo Cars) and the US manufacturers exported cars to the EU. In other words, the two largest car markets in the world—the EU and the US—were very integrated, and it was meaningful for the regulators to collaborate in order to establish conditions which resulted in the improvement of the environmental performance of cars at the least possible cost. As the Korean and Japanese car makers and air

[28] It was also established that the leakage rate for vehicles from the worst performing car manufacturer (with a leakage rate of 81.9 grams of HFC-134a per annum) was three times higher than the leakage rate of the best performer (28.8 grams of HFC-134a per annum). This seems to indicate that there is ample room for improvement by improving the MAC design and, in particular, by car manufacturers acquiring quality parts.

conditioner manufacturers also were active in the EU and US markets, they were also some of the organisations (Japanese and Korean Automobile Manufacturers' Associations, JAMA and KAMA) with which the Commission interacted. Naturally, DG Environment was also in close contact with the institutions and EU Member State competent authorities responsible for F-gases.

As part of the phase of chlorofluorocarbon (CFC)-12 (also known under the DuPont Brand name "Freon™") the car refrigeration experts of the EU, US and Japan had established collaborative platforms. One of them was the German car manufacturers association's (VDA) annual "Winter meetings" (Vainio 2006) held in Saalfelden, Austria and another was the European Automotive Air Conditioner Convention. There were also "SAE Phoenix Forum" annual meetings in the US (Vainio 2003). DG Environment's staff member participated in these meetings to better understand how vehicle air conditioning systems work and particularly how their emissions could be regulated in an efficient manner.

It was noteworthy that the US EPA as well as the producers of F-gases and the developers of alternative technologies, notably CO_2 (R-744)-based air conditioners were part of the collaboration. This gave a unique opportunity for DG Environment to also validate the findings for the leakage rate study, to study the policy options on how to reduce considerably the GHG emissions from air conditioners, and to gain trust of the stakeholders that the Commission was aware of the opportunities and threats that industry had to implement regulation.

The "grand finale" of the stakeholder consultation was the Conference on the Options to Reduce Greenhouse Gas Emissions from Mobile Air Conditioners held on 10–11 February 2003 (EurActiv 2003). The most significant consensus was that a regulation of MACs was needed and that the GWP should be set to 150, as proposed by the EC and supported by most automobile manufacturers because it would allow the choice of R-152a and R744. After this conference, the Commission made its proposal to regulate F-gases in MACs.

3. Key design characteristics

Through the leakage rate study and collaboration with the US EPA, car industry members and in particular their air conditioner teams, and refrigerant manufacturers, the following design characteristics emerged:

1. Mobile air conditioners leakage of R-134a (GWP = 1300) was of major concern.
2. Alternatives to R-134a were available, notably (mildly) flammable R-152a (GWP =138) and non-flammable but technically more challenging CO_2 (R-744; GWP =1). The challenge was to propose a regulation what would not carry an excessive cost.
3. Any regulation would need to be technologically neutral.
4. The EU's regulation of the refrigerant in MACs in the EU would most likely have consequences—perhaps very important ones—in the refrigerant choice throughout the world, through the so-called Brussels effect (Bradford 2012).

While the above findings were evident there were two other aspects that needed to be considered. First, what legal instruments were available and second, how the findings could be taken into account. As DG Environment was preparing an overall regulation of F-gases, it considered that the most expedient option would be to propose the regulation of F-gases in MACs as part of the overall

F-gas regulation. This proved to be a challenge to the EU's car manufacturers, as will be discussed later.

4. The proposal for regulation

The premise for the EU to regulate F-gases in MACs was based on their high GWP, which was at the time estimated at 1300, and the fact that the gases leaked from the system. Table 1 is an update (with GWP 1440) of the table from the Commission's proposal. The GWP has changed over time because scientists have determined that the reference chemical CO_2 set equal to one (GWP = 1) has a much longer atmospheric, aquatic, and terrestrial lifetime, and the lifetime of other chemical substances is changing as a consequence of increasing atmospheric pollution and climate change.

Table A-2. Leakage of HFC-134a during the lifetime (14 years) of a vehicle based on two assumptions, tonnes CO_{2eq}

Leakage	Low	High	Comments
Regular HFC-134a emissions occurring during normal operation of a vehicle	1.07	1.07	53 g of HFC-134a / year
Irregular HFC-134a emissions resulting from accidents, stone hits, defects, etc.	0.32	0.40	16 g of HFC-134a per year in "low" and 20 g in "high" case
HFC-134a emissions during servicing	0.29	0.58	100 g of HFC-134a per service in "low" case 200 g per service in "high" case (service every 7 years)
HFC-134a emissions at end-of-life	0.16	0.39	20% of refrigerant charge lost at the end-of-life in the "low" case, 50% in the "high" case
Other HFC-134a emissions	0.04	0.04	Loss of refrigerant at manufacturing and distribution stages (30 grams)
Total (GWP_{2003} 1440)	1.9	2.5	
Estimate with GWP 1300 was	1.7	2.24	

Source: Reproduced from Table 2 of Commission (2003b) with an updated GWP for HFC-134a (1440). The GWP was updated in 2003.

The premise was that the emissions of F-gases from MACs were estimated in 1995 to be 1.6 Mt CO_{2eq} and that they would increase to 22 Mt CO_{2eq} in 2010.

The actual EU-27, EEA, and the UK emissions of F-gases were, according to EDGAR (2025), 24.1 Mt CO_{2eq} in 2010 (Table 2) but it should be noted that these emissions included at least F-gas emissions from refrigeration as well as stationary and mobile air-conditioning. Thus, either the projections of emissions 2010 were too high, or, due to the F-gas regulation as well as its anticipation the EU industry started to implement different measures to reduce HFC-134a emissions from these sources. It goes beyond this paper to find out which of the two explanations is more plausible, and it might be that both are.

Table A-3. Baseline and projected emissions (MT CO_{2eq}, GWP 1440)

Emissions Source	1995	2010
Refrigeration and air-conditioning	2.5	22.7
Mobile air-conditioning	1.6	22.2
Total	**4.1**	**44.9**
Actual HFC-134a emissions in the EU	3.8	24.1

Sources: EDGAR (2025) and Commission (2003b)

The Commission (2003b) proposal to regulate HFC-134a in MACs was presented just in two articles, namely Articles 9 and 10. The Commission proposed to:

i) set a maximum leakage rate for HFC-based air conditioners at 40 grams per year for single- and for 50 grams per year for dual-evaporator systems and,
ii) phase out HFCs having a GWP above 150 in air conditioning equipment in passenger cars and light commercial vehicles from **2009 to 2013** through a transferable quota system. The quota holder could sell or buy quota without any restriction to other quota holders thus giving the maximum flexibility for vehicle manufacturers to comply with the regulation.

The penalty for non-complying air conditioners was set so that in the following year, two units will be deducted from the quota for each unit that did not fulfil the requirements of this regulation. A financial penalty of €200 per unit was set for non-compliance in a transparent manner by making public those who did not comply with the regulation. A high penalty was required to ensure all car manufacturers were treated equally. The penalty was set at the same level as in the proposed directive on EU-wide trading of GHGs. In that directive, the financial penalty is set at €100 per tonne of CO_2 and a deduction of 1 tonne from the following year's allowance translating into €200 per mobile air conditioner not covered by the quota, given that the life cycle emissions of a mobile air conditioner were estimated to be about 2 t CO_{2eq}. Special provisions have been made for possible *new entrants and* for small producers with a *de minimis* clause.

In the Commission's consultation paper, the costs of use restrictions were estimated—at the 2024 price level [29] at €8-54/$tCO_{2eq2024}$ for HFC-152a, assuming that the flammability issue was resolved. For R-744, the cost was originally estimated at €34-230/$tCO_{2eq2024}$. The high cost of the latter alternative was assuming that industry would not find a low-cost solution to manufacture hoses for air conditioners. If this problem could be resolved, the costs would drop towards €33-66/$tCO_{2eq2024}$.

Based on the responses to the consultation paper, the Commission estimated that the leakage of HFC-134a to be 20–25 $MtCO_{2eq}$ in 2010 and the average cost of use restrictions are €13-30/$tCO_{2eq2024}$ if the flammability issue of HFC-152a was solved, and between €34-75/$tCO_{2eq2024}$ if the cost of hoses in the case for CO_2 as the refrigerant was resolved. To put these costs to perspective, the current price of carbon dioxide in the EU ETS is around €70/tCO_2. The measures proposed in 2003 seem proportionate from that point of view even for the most expensive alternative.

[29] Prices in 2024 were 64% higher than in 2003 in the EU. This has been used as the deflator to bring the 2003 prices to todays' levels.

5. Outcome in 2006

During the negotiating process, both the Member States (i.e., the Council) and the European Parliament were in favour of regulating MACs, but they were not in favour of using the transferable quota system. Their reluctance was based on the views of the car industry, which was able to present its views to the members of the European Parliament and certain Member States. The opposition to the transferable quota system came as a surprise to DG Environment, as it had thought that the car industry would have preferred to have a flexible, cost-effective instrument based on transferable quotas, as was the case in the proposed ETS.

The car industry preferred using the EU's type-approval system based on Council Directive 70/156/EEC. The approach of car manufacturers was understandable in the sense that they were very familiar with the relatively complex EU type approval system and could even use it to their own advantage—even to a point of abuse, as was the case in "Dieselgate" (Wikipedia 2025a). In addition to the favouring of the type-approval system, the European Parliament (2004) was in favour of reducing the GWP of fluorinated gases in MACs from 150 to 50.

The Commission as well as the Council (2005) were against lowering the GWP since that would have been counter to technical neutrality and would have brought little environmental benefit. The Commission rejected the Parliament's suggestion as *"it would exclude the use of HFC-152a, a possible alternative technology, with only minimal environmental benefits."* (Commission 2005). However, the Council and the Commission accepted the splitting of MACs under the type-approval system.

For the Commission, it was imperative that the two legal acts were taken through as a package, partly for coherence reasons and partly because now a second DG (Enterprise) became strongly involved in the legal act. It is worth noting that on 16 April 2003, ten new Member States[30] signed the treaty of accession to EU. The negotiations for the legal acts thus took on board a massive increase in parties as the EU expanded from 15 to 25 countries.

The main consequences in splitting the F-gas regulation to two were the following:

i) DG Enterprise (today DG GROW) instead of DG Environment took the lead in the negotiations of the MAC-related part,

ii) A new proposal for the legal text was needed. The presidency of the Council formally took that role (with the help of the Commission services) to include MACs in the type approval system,

iii) The legal instrument changed from an F-gas regulation to a type-approval directive for MACs. Regulations are more straightforward instruments in the EU as they are applicable directly (in 20 days) in Member States. Directives need to be transposed (in 18 months) by Member States,

iv) The phase out times changed as the type-approval system considered both "new types" of and "new" vehicles, meaning that the new type of a car (i.e., a major overhaul of the model) became the basis for the regulation,

[30] These were Cyprus, the Czech Republic, Estonia, Hungary, Latvia, Lithuania, Malta, Poland, Slovakia and Slovenia. The negotiations for the legal acts thus took on board a massive increase in parties as the EU expanded from 15 to 25 countries.

v) The type-approval directive included the phase in the alternatives in 2011–2017 (instead of the originally proposed 2009–2013),

vi) The type-approval system did not allow any flexibility: if a car manufacturer introduces a completely new car or a major overhaul of an existing model to the EU market it needed to comply with the type approval directive as it was.

After complicated round of negotiations amongst the three EU institutions, Directive 2006/40/EC relating to emissions from air conditioning systems in motor vehicles ("MAC Directive") (European Union 2006a) was adopted on 17 May 2006 simultaneously with Regulation (EC) No 842/2006 on certain fluorinated GHGs (European Union 2006b). The MAC Directive contained the following main elements:

- Maximum GWP of fluorinated gases in MACs was set at 150 based on the IPCC AR4. From 2011, no type-approvals were granted to cars having MACs above 150. From 2017, no vehicles could be placed on the EU market with MACs having HFCs above 150 GWP.
- Leakage rates needed to be below 40 grams of HFCs per year for single- and 60 grams for dual-evaporator systems.

Subsequently, the MAC Directive was complemented in 2007 by a harmonised test for measuring leakages from certain air conditioning systems (Commission 2007). Further, the. Commission (2008) established minimum requirements for training programmes for servicing MACs.

6. Recent developments affecting the choice of refrigerants in the EU

Twenty years after the EU's MAC Directive, R-134a emissions in the EU have dropped by 30% in 2023 from their peak in 2017 and are projected to reduce rapidly. This good development is partly due to the MAC Directive and partly due to subsequent F-gas Regulations.

Since the adoption of the MAC Directive three important developments have taken place:

1. Not only did the EU move away from R-134a, but there were major shifts outside the EU. For instance, as of 2022, 90% or more of new U.S. vehicles are estimated to use R-1234yf (Wikipedia 2025b).
2. TFA from atmospheric degradation R-1234yf is of major environmental concern.
3. Due to climate change, transport sector will rapidly electrify, and this poses new challenges to MACs as electric batteries, inverters, and motors do not produce much heat.

R-1234yf atmospherically degrades to TFA, which under some proposed definitions is a per- and polyfluoroalkyl substance (PFAS). The main problem is that TFA accumulates in the environment, potentially impacting aquatic ecosystems (Wang et al. 2024). These properties were not known at the time of the adoption of the MAC Directive and in particular the fact that "*TFA meets the criteria of a planetary boundary threat*" (Arp et al. 2024).

In 2023, five EU Member States proposed to restrict the use of PFASs in the EU (BauA et al. 2023). At the time of writing (June 2025), this proposal is being assessed by the European Chemicals Agency which provides its opinion to the EC for its decision. As part of the proposal, the use of F-gases—including R-1234yf—would be prohibited in cars with combustion engines after a period of derogation of 6.5 years from entry into force. This could be in 2034–2035, if the

Commission made its decision in 2028. For all-electric vehicles, the proposal is to phase out F-gases 1.5 years after the decision—i.e., roughly in 2030.

At the same time, the share of all-electric vehicles is increasing rapidly in Europe as the EU has effectively banned the sales of combustions engines in passenger cars and vans from 2035 onwards (European Union 2023). As all-electric vehicles do not produce heat, the technological challenge for MACs has changed, and heat pumps are viable alternatives as they provide both heating and cooling. Due to this and the possible prohibition of the use of PFASs in vehicles, alternatives to R-1234yf are being considered. The two main options are R-744 (CO_2) and R-290 (propane).

R-744 struggles with efficiency in high ambient temperatures, especially in air-conditioning applications. R-290 is particularly effective in systems operating at moderate to high ambient temperatures but, due to flammability, it requires a secondary loop architecture.

At the time of writing (June 2025), R-744 based heat pumps are operating in electrical vehicles in the EU while no R-290 based heat pumps are yet commercially in use in cars. VW group has offered a R-744 based heat pump from 2020 onwards in 12 all-electric vehicles[31] (Haroldsen 2014). Furthermore, Ford has done the same in the Electric Ford Explorer, which uses VW's electric vehicle platform. By September 2024, VW has sold 700,000 all-electric vehicles with R744 based heat pumps, predominantly in the EU (ChemSec 2024).

EU's MAC Directive of 2006, which set only an environmental performance standard, is still compatible with the new developments for when car companies decide which refrigerant they would use in MACs and heat pumps in the future. During the preparation of the MAC Directive, there was a heated discussion regarding the refrigerant that would replace HFC-134a: HFC-152a or CO_2. R-1234yf—which came out of the blue—emerged as the "winner." Now the replacement of R-1234yf has bought a new discussion: R-290 or R-744. It will be interesting to see if one or the other, or both, or something else will become the next—and hopefully truly environmentally friendly—refrigerant in cars.

Collaboration amongst the EU and US regulators would help in establishing a level playing field even if they are nowadays only the second and third largest car markets in the world, after China.

[31] These are Audi Q4 e-tron (sedan and sportback); Cupra Born; Skoda Enyaq (coupé and hatchback) and Elroq; and Volkswagen ID.Buzz, ID.3, ID.4, ID.5 and ID.7 (sedan and tourer).

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