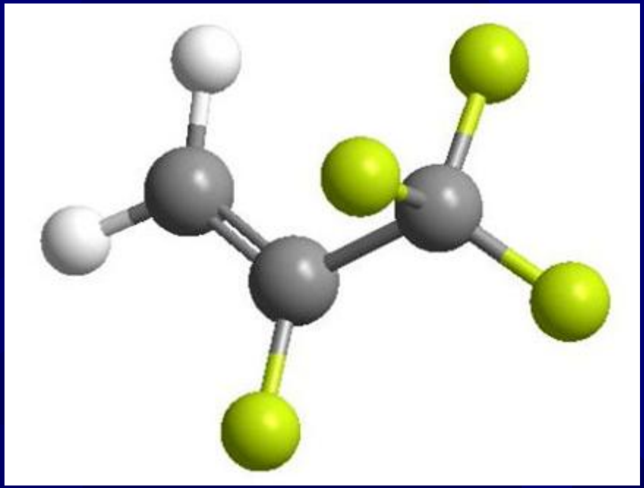
Summary of SAE CRP1234 Refrigerant Evaluation and Risk Assessment

July 15, 2010



Agenda

- **Overview of CRP1234**
- **Overview of testing Conducted during CRP1234**
- **SAE CRP1234 Risk Assessment of R-1234yf**
- **Conclusions**

R-1234yf Cooperative Research Programs

- Cooperative Research Programs (CRP) have been sponsored by Vehicle Makers and Tier One/Two Suppliers
- Global Vehicle Makers
  - Audi, BMW, Chrysler, Daimler, Fiat, Ford/Volvo, General Motors/Opel, Hyundai, Porsche, PSA, Renault, Shanghai Automotive, Tata, Jaguar Land Rover, Toyota, VW
- Tier One/Two Suppliers
  - DuPont, Honeywell, Conti Tech, Dayco, Delphi, Denso, Doowan, Dow, Freudenberg, Goodyear, Hutchinson, Maflow, Egelhof, Parker Hannifin, Sanden, Trelleborg, Valeo, Visteon

R-1234yf Cooperative Research Programs

- Research was conducted over the last two years at international laboratories to access the best available expertise and to guarantee common worldwide acceptance
  - Originally Proposed in October, 2007
  - Phase 1 completed in Feb, 2008
  - Phase 2 completed in Apr, 2009
  - Phase 3 completed in Nov, 2009
- Issues Investigated include:
  - Toxicity, Flammability, MAC efficiency and performance, Material compatibility, Safety and risk assessment
- Extensive testing at third-party facilities did not identify significant risks for the use of R-1234yf in mobile air-conditioning systems

Toxicity Input Data

- Toxicity
  - Toxicity testing by TNO, WIL and Hamner Institutes
- Based on results of risk assessments, exposures are not of concern from the standpoint of refrigerant toxicity

The Hamner Institutes for Health Sciences

WIL Research Laboratories
The United States

TNO Pharma
The Netherlands

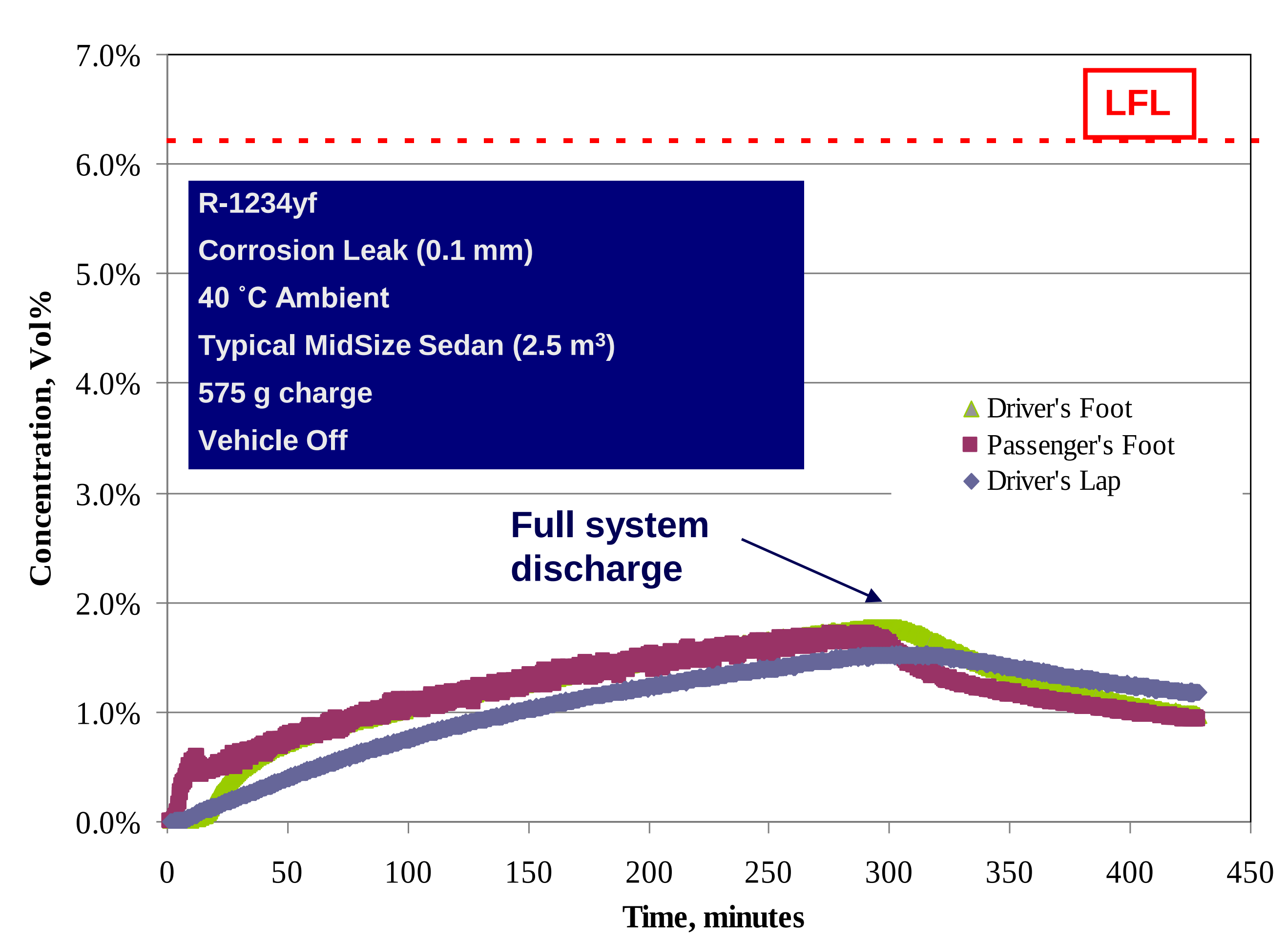
R-1234yf does not pose an exposure risk due to chemical toxicity

Risk Assessment Input Data: Concentration Measurement Data

- Refrigerant Concentration after Accidental Release
  - Vehicle Makers concentration measurements in vehicles (4 Vehicle Makers, different vehicle types)
    - Health-based limit never exceeded
    - LFL exceeded in a few instances with severe collision scenarios (typically in recirculation mode, low blower, near floor, generally away from possible ignition sources)
      - Refrigerant concentration alone is not enough to produce a risk of refrigerant ignition or HF exposure
      - Sufficient refrigerant and sufficient ignition source must be present at the same time and location, occupant must also be present in limited area where ignition occurs
  - All measured concentrations and the scenarios leading to these were considered in the Fault Tree Analysis

Ignition and thermal decomposition risks addressed in FTA

Typical Concentration in Vehicle Interior with Corrosion leak



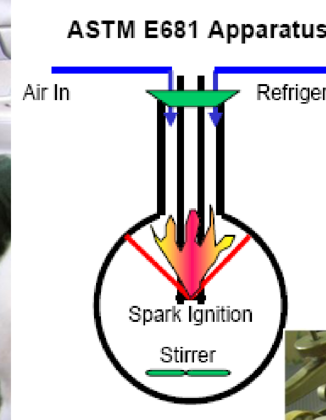
- Interior cabin corrosion leaks do not develop refrigerant concentrations of concern
- FTA focus on leakage during collisions

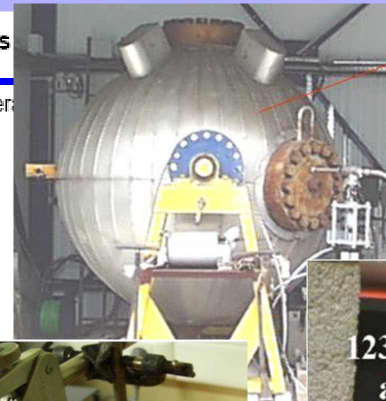
Measurements of cabin R-1234yf concentration for corrosion leaks did not exceed 2%

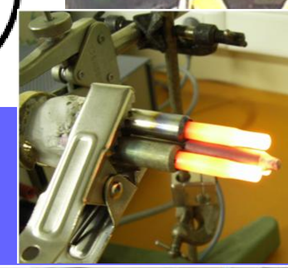
Flammability Testing

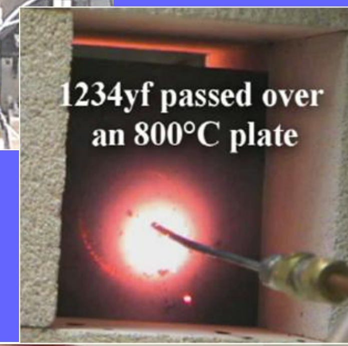
Testing in Interior and Underhood of Vehicle

Basic Property Testing by DuPont/Honeywell/Ineris

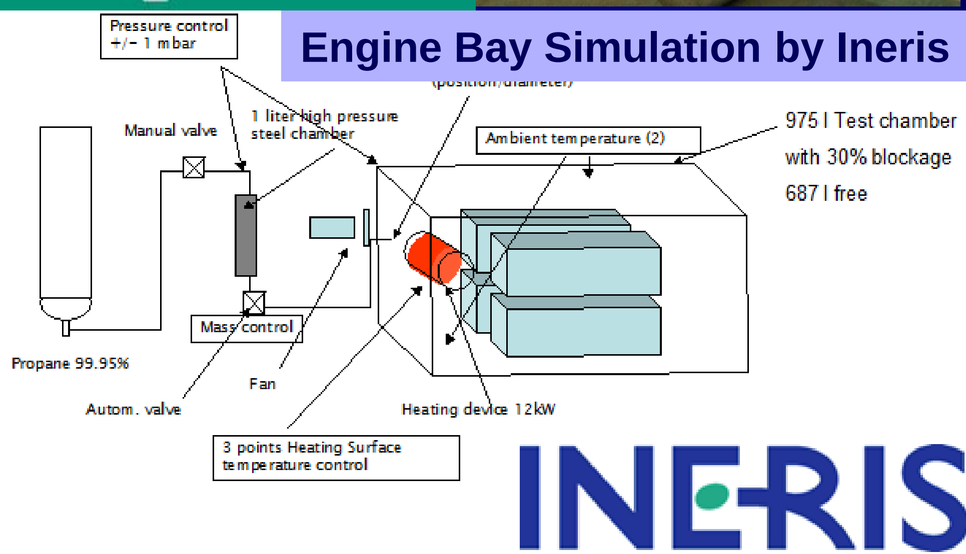




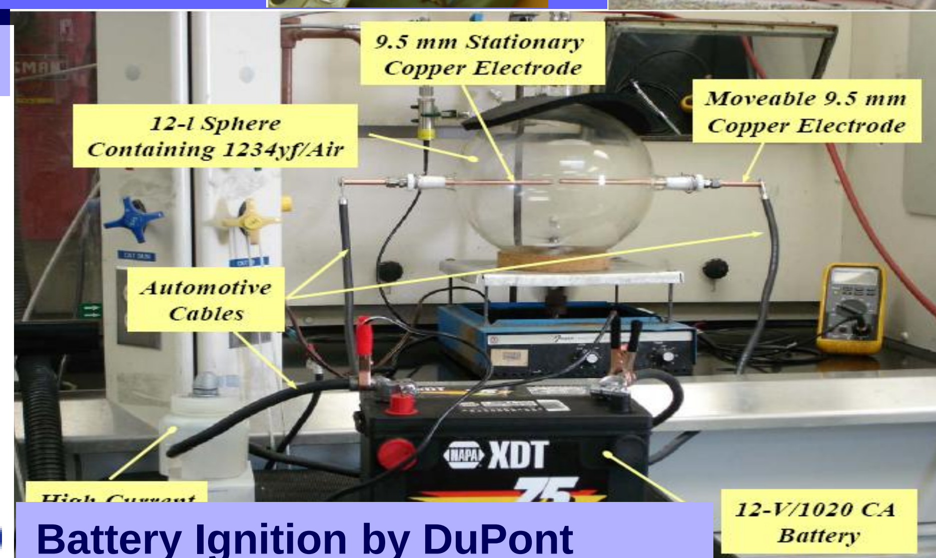




Engine Bay Simulation by Ineris



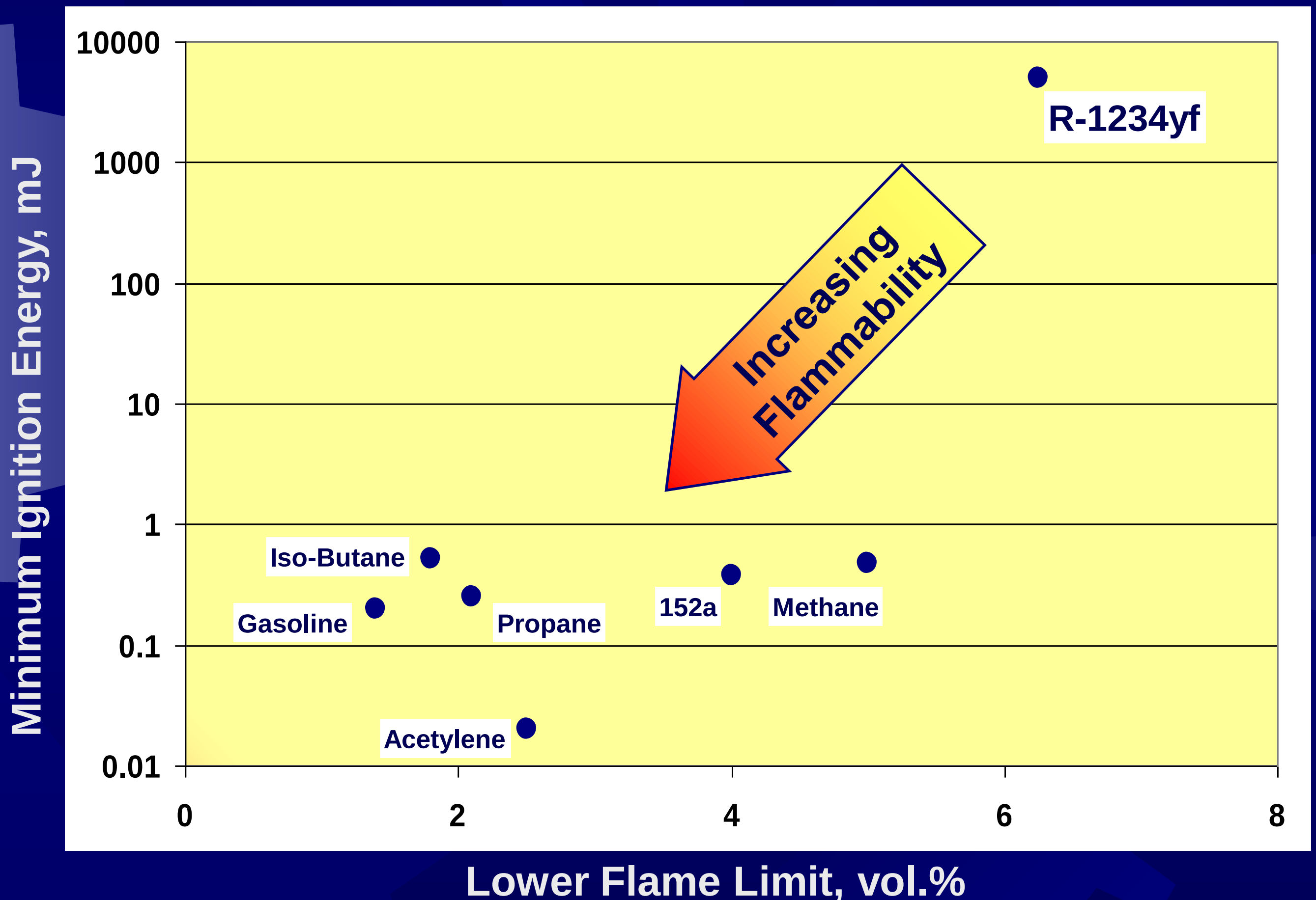
Battery Ignition by DuPont



R-1234yf Flammability Properties

Flammability is evaluated by 'Chance of Flame occurring' and 'Effect of Flame occurring'

- **Chance of Flame occurring -> Lower Flame Limit, Minimum Ignition Energy**

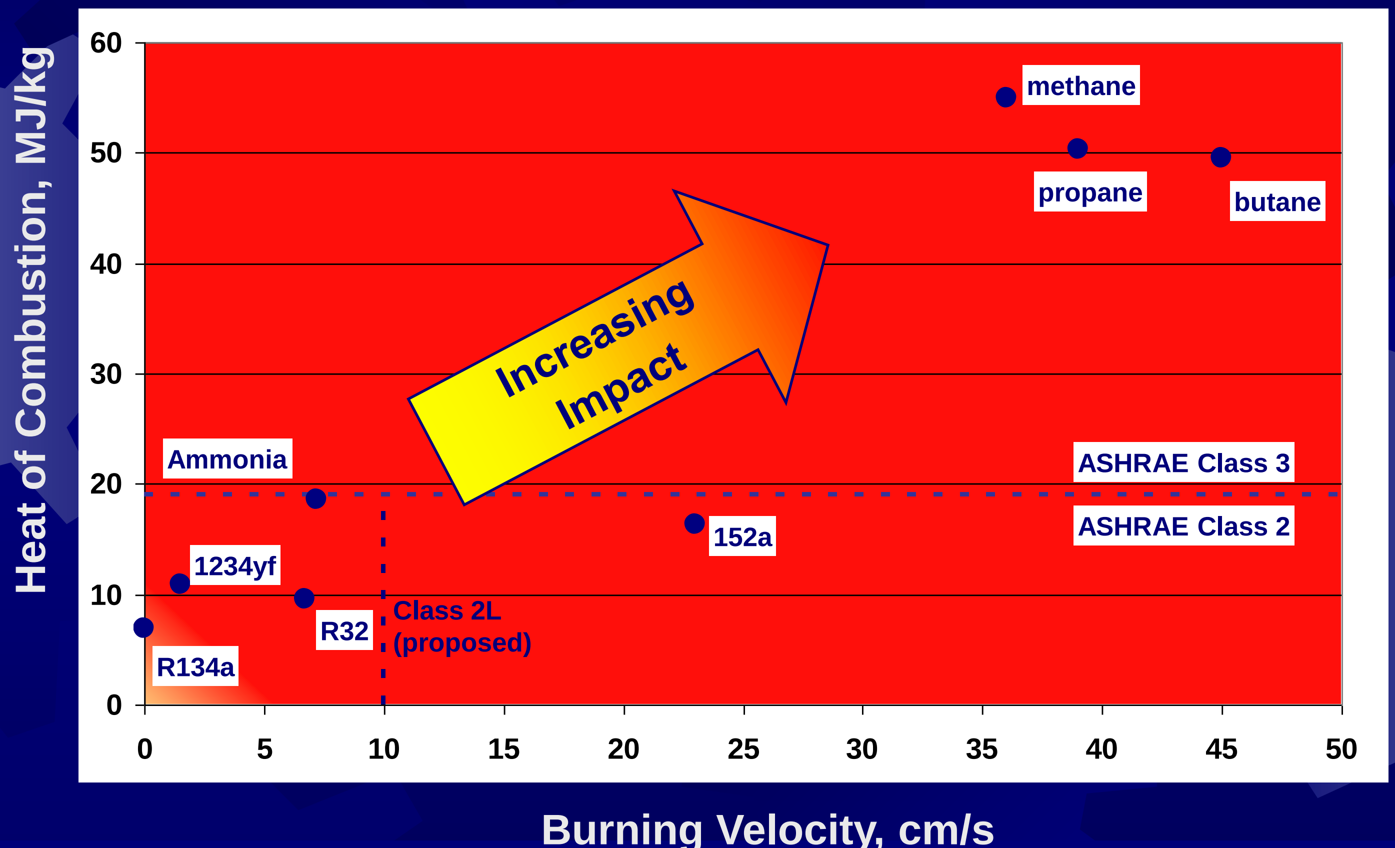


Difficult to ignite R-1234yf due to high Minimum Ignition Energy

R-1234yf Combustion Energy

Flammability is evaluated by 'Chance of Flame occurring' and 'Effect of Flame occurring'

- **Effect of Flame occurring -> Burning Velocity, Heat of Combustion**



* Burning Velocity of 1234yf has been measured at AIST. (Advanced Industrial Science and Technology / Japan)

Even if ignited, R-1234yf burns only weakly, would have limited effect

Flammability Input Data

- Flammability
  - R-1234yf is substantially different from flammable refrigerants such as R-152a
  - Much more energy is required to ignite R-1234yf
  - Much lower burning velocity/much lower flame stability
  - Lab tests conducted by SAE CRP1234 have required considerable effort to ignite refrigerant
- The energy released when the refrigerant ignites is also much less than other flammable substances used in vehicles
- Although very difficult to ignite, the possibility of refrigerant ignition does exist; therefore the risk of ignition was fully addressed in the Fault Tree Analysis and Risk Assessment of CRP1234

To be conservative, refrigerant ignition was addressed in FTA

Sources for Ignition

- Potential ignition sources were evaluated by INERIS, DuPont, and Honeywell
- Only credible sources were considered in the FTAs, such as:
  - Match (butane lighters are not operable above 4 vol%)
  - PTC heater un-fused electrical short failure
  - Hot surfaces in the engine compartment under extreme vehicle use

Possible ignition sources for R-1234yf are limited

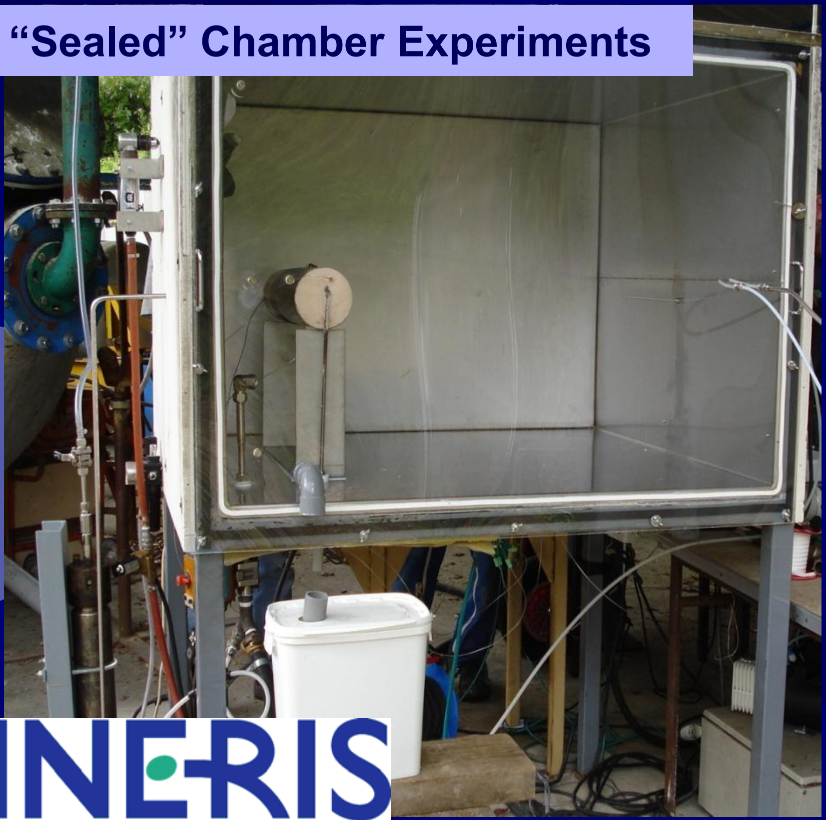
Thermal Decomposition/HF Generation below LFL

- All fluorinated refrigerants, when exposed to sufficient energy sources, can decompose to produce primarily HF
  - The amount of HF generated depends on the amount of refrigerant in contact with energy source, size of energy source, and time of contact
  - Testing of HF generation conducted with an actual vehicle (Hughes Associates) and with “bench-top” studies (INERIS, Honeywell, DuPont)
- Measured HF concentrations were evaluated using NRC AEGL-2 values
  - AEGL-2 limit for HF [95 PPM, 10 minute exposure] applies explicitly to acute, accidental exposure situations
  - AEGL-2 protects against escape impairing or irreversible effects
  - Value adopted by the CRP1234 toxicologists for short time exposures, highly conservative approach
  - Irritancy perception (3-5 ppm) is well below the AEGL-2

Extensive testing and evaluation of HF generation potential

Thermal Decomposition Testing

"Sealed" Chamber Experiments



INERIS

Interior and Underhood testing

HUGHES ASSOCIATES, INC.

Vehicle HF Concentrations Produced by Thermal Decomposition

- Passenger cabin - HF concentration due to R-1234yf thermal decomposition below the LFL after refrigerant release and exposure to flame source
  - Highest HF breath level concentration achieved was well below AEGL-2
  - Lighter had to be augmented with strong spark to get a butane flame [no ignition of refrigerant]
- Engine compartment - HF concentration measurements after R-1234yf released onto hot surface
  - Highest HF breath level concentration was well below AEGL-2 in passenger cabin, based on….
    - Extreme engine operation (700ºC)
    - Hood seal removed allowing direct path to cabin air intake
      - Secondary failure
    - Blower on outside air, high speed (full suction from engine)

Estimated occupant HF exposures would not exceed AEGL-2 value

CRP Risk Assessment Methodology

- Uses Fault Tree Analysis [FTA} methods for key exposure scenarios
  - Vehicle exposures
  - Repair exposures
- Qualitative evaluation of other scenarios with limited impact
  - Assembly plant workers
  - Parking garages, tunnels
  - Ecological impacts
- Fault Tree Inputs are based on measured data, public databases, and consensus by the Vehicle Makers HVAC and Safety engineers
- Results are compared to other non-AC related automotive risks
- Results have been validated by Safety Engineers

Example Fault Tree Approach (simplified)

Potential risk of open flame in Engine Compartment — Top Event

AND

1 Frequency of Initiating Event (e.g. vehicle collision)

2 Probability Refrigerant Concentration Exceeds LFL

3 Probability of Sufficient Ignition Source occurs (e.g. hot surface)

4 Probability attenuating factors absent

1: Considered collisions, AC and non-AC failures, vehicle fires

2:
- Event causes refrigerant release
- Refrigerant not dispersed by air currents
- Concentration in contact with ignition source exceeds LFL

3: Considered normal operation, system fault, and extreme operating conditions

4:
- No other leak in system
- Person present
- Person doesn't leave
- Windows/doors closed
- Blower
- Vehicle speed
- OSA/recirc

All factors are required to cause the top event

Fault Tree Scenarios

- Vehicle Collisions
  - Passenger compartment release
    - Occupant exposure (exposure to open flame and HF)
  - Engine compartment release
    - Investigating occupant (exposure to open flame and HF)
    - Good Samaritan (exposure to open flame and HF)
    - Aspiration by blower into passenger compartment (HF, refrigerant concentration will be diluted below LFL)
- AC system leak in engine compartment (non-collision, e.g. abraded hose)
    - Investigating occupant (exposure to open flame and HF)
    - Aspiration by blower into passenger compartment (HF, refrigerant concentration will be diluted below LFL)

Fault Tree Scenarios (cont)

- Vehicle fire in engine compartment due to non-AC component failure
  - Investigating occupant (HF, refrigerant itself contributes minimally to fire)
  - Aspiration by blower into passenger compartment (HF)
- Vehicle fire due to vandalism
  - Owner (HF, refrigerant itself contributes minimally to fire)
- Release during repair by professional service workers
  - Exposure to open flame
  - Worker struck by hose

Gradient

R-1234yf Risk Comparison to Other Vehicle Events

Risk	Risk per vehicle per operating hour	Citation
Risk of being in a police reported vehicle collision	5×10^{-5}	NHTSA, 2007
Risk of vehicle collision due to vehicle brake failure	3×10^{-7}	New York State DMV
Risk of highway vehicle fire (any cause)	1×10^{-7}	Ahrens, 2008; BTS, 2004
Risk of an airbag-related fatality associated with a vehicle collision	2×10^{-10}	NHTSA, 2001
Risk of vehicle occupant/former occupant experiencing HF exposure above health based limits associated with an R-1234yf ignition event	5×10^{-12}	Current analysis
Risk of vehicle occupant being exposed to an		Current

Risks for Vehicle Occupants of using R-1234yf in MAC systems are very small

R-1234yf Risk Comparison to Other Service Events

Risk	Risk per working hour	Citation
Non-fatal recordable injury at work (all occupations)	2×10^{-5}	NSC, 2004
Risk among automotive repair technicians of being struck by object resulting in lost work days	2×10^{-6}	BLS, 2007
Risk of recordable incident involving repair technicians being struck with high pressure R-1234yf equipment hose (risk per hour of vehicle service)	3×10^{-8}	Current analysis
Risk of service technician exposure to an open flame due to R-1234yf ignition	1×10^{-20}	Current analysis

Risks for Repair Workers of using R-1234yf MAC systems are very small

Conclusions of CRP1234

- Risk Analyses is completed
  - Based on Conservative assumptions
  - Based on Scientifically valid inputs
  - Reviewed by industry experts
- Experimental Test Program for Ignition and HF production is completed
  - International, independent test laboratories in US, Europe and Japan
- Performance Impact of R-1234yf is understood
- Basic Impact of R-1234yf on Materials is understood
- SAE Standards to assure proper system design, engineering, manufacturing and servicing for R-1234yf refrigerant use in passenger motor vehicles are developed
- R-1234yf is acceptable for market without concentration limits