



Daimler's Observations on Risk Assessments of R1234yf

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Daimler AG
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Mercedes-Benz

Review

- The 2009 FTA compiled by SAE CRP 1234-3 showed that R1234yf might ignite, but not that the fire could propagate to the vehicle.
- Tests by Daimler in 2012 (and, more recently, by KBA^{*}) demonstrated that propagation leading to a vehicle fire was indeed possible.
- This finding led to the re-evaluation of the use of R1234yf by Daimler, since:
 - New technologies must provide an at least equal safety level as the technologies they replace (state of the art principle).
 - In this case, a flammable fluid (R1234yf^{**}) was to replace a non-flammable fluid (R134a).^{***}
- As a minimum requirement it is hence necessary to prove that the safety performance and potential negative side effects of the replacement refrigerant are practically equivalent to the former refrigerant.

* KBA Project report on R1234yf, 08.10.2013

** Honeywell Safety Data Sheet, Solstice™ yf Refrigerant (R-1234yf), 000000011078, Version 2.1 Revision Date 06/13/2013

*** Honeywell Material Safety Data Sheet, Genetron® 134a, December, 2005

Requirements for Risk Assessments

- In view of the different properties of R1234yf and R134a, a risk assessment must be governed by due diligence and populated with numbers using a conservative approach.
- Guiding principles:
 - Determine the relevant top event with prudence.
 - Keep the risk analysis as simple as possible to avoid dilution.
 - Avoid use of input data that cannot be assessed quantitatively.
 - If vague data is used, make conservative assumptions.
 - Do not combine basic events that cannot be proven to be statistically independent.

Determining an Appropriate Top Event (1/3)

- For all German OEMs, the top event deemed appropriate for the safety assessment of a refrigerant is ***a vehicle fire caused by that refrigerant.****
- This is hence also the approach taken by the VDA FTA.**
- Vehicle fires may result in a multitude of injuries to occupants and former occupants – the associated potential risk is neither acceptable nor reasonably quantifiable.
- However, the SAE fault trees suggest just that - and inappropriately further dilute this top event by a factor 10^{-3} for the occupant not being able to exit the vehicle***.

* SAE CRP 1234-4 Paris Meeting, 15.11.2012

** VDA FTA Final Report, 22.05.2013

*** SAE CRP 1234-4 Attachment J, “Supporting Data for the Probability Vehicle Occupants are Unable to Leave the Vehicle Post-Collision“, 24.07.2013

Determining an Appropriate Top Event (2/3)

- The SAE sensitivity analysis on the fault tree encompassing the vital parameter “Occupant cannot exit vehicle” results in a factor of close to 200. This is the factor of all fault tree variations and clearly shows how sensitive the choice of the top event is, once human actions are included and varied.
- The choice of the top event is one of the ***fundamental differences*** between the SAE risk analyses claiming negligible additional risks of R1234yf, and the conservative safety approach taken by both VDA FTA and Daimler AG.

Determining an Appropriate Top Event (3/3)

- Daimler is dedicated to delivering safe products. Consequently, the relevant top event is the vehicle fire, without further dilution by human factors.
- The new finding that an ignition of R1234yf will lead to vehicle fire and additional measures in the engine compartment are not fully effective leads to a new position on R1234yf compared to CRP 1234-3.
- A significant number of potential additional vehicle fires resulting from the choice of an alternative, more inflammable refrigerant is not compatible with the safety philosophy of Daimler AG and is *the* deciding factor against its use.

Keeping it Simple

The revision of the FTA of the former SAE CRP 1234-3 has led to a questionable and inflationary expansion of the number of basic events, which per se implies the danger of diluting the risk rates.

- Almost 280 gates for the ignition trees alone with complex assumptions and uncertain values
- Most gates are AND-gates, which in conjunction lead to very low probabilities
- The VDA FTA addressing the same issue has a grand total of 133 gates in all trees

Using Valid Input Data and Dealing with Uncertainties (1/3)

- In contrast to an FTA based on technical component failure rates, the revised SAE fault trees contain a number of basic events where input parameters cannot be quantified in a robust, data-driven way (unlike accident statistics).
- Unknown risk parameters should be set conservatively, and not based on opinion. A large number of the parameters used in the FTA were based on expert judgment and only limited data. The values used were the product of discussions by individuals who were experts in the field of AC automotive systems, not accidentology.
- In the VDA FTA, the quality of input data was rated on a scale of 1-4. In the sensitivity study, lower and upper boundaries were adjusted reciprocally proportional to the level of agreement on level 4 data: less agreement → greater variation range.

Using Valid Input Data and Dealing with Uncertainties (2/3)

Example from SAE CRP R1234yf fault trees on mid-severity frontal crashes

- The estimated probability of refrigerant ignition in mid-severity frontal crashes yields a potential of 30 incidents in Germany p.a., if all vehicles were equipped with R1234yf.*
- The coolant/steam mitigation parameter was set to 20%, while Daimler and KBA testing have shown coolant/steam to have no effect or an effect increasing the reaction intensity. (Varying this parameter from 20% to 50% already yields 72 incidents in Germany p.a.)
- The propagation factor was approximated at 22%, instantaneously reducing the number of resulting vehicle fires to 6.
- In Daimler competitive testing, observed propagation was close to 1.

* 43,000,000 passenger vehicles in Germany, at an average 400 operating hours p.a.; see also Annex 2, VDA FTA Final Report, 22.05.2013

Using Valid Input Data and Dealing with Uncertainties (3/3)

- For various basic events, representative test results are not available, and it is extremely difficult - if not impossible - to design surrogate tests that appropriately replicate real world effects. Example: INERES vs. BAM tests on ignition temperatures.
- Especially parameters that must be estimated subsequent to a crash event cannot be quantified by test data, since real world crash deformations occur in an abundance of variations. In these cases, agreement on appropriate input parameters must be governed by due diligence.
- In a conservative approach input parameters for basic events that lack data supporting a reduction in probability should be set to 1.00, thus making several related new basic events superfluous.
- Example: Combination of conditions that make ignition of refrigerant improbable

Maintaining Robustness and Stability

- For rare top events especially, it is characteristic for FTAs that few changes in input parameters may change the result by several orders of magnitude. This is particularly relevant for probabilities below 1.0×10^{-11} .
- A single real world event would suffice to put the risk analysis into question (see e.g. Boeing's Dreamliner battery event), a second would disprove it.
- Based upon the current fault trees: If all 43 million passenger vehicles in Germany were equipped with R1234yf as of today, only one case would occur in 11.6 years.
- In the light of the Daimler and KBA test results*, this seems highly unrealistic.

* KBA Project report on R1234yf, 08.10.2013

Daimler's Summary of the SAE CRP Risk Assessment



Principal differences exist between the choice of the top event between SAE and VDA / Daimler.



The SAE risk assessment unduly dilutes the risks incurred by R1234yf and does not reflect a conservative estimation.



Assumptions lacking both scientific evidence and diligent conservative estimations exist in the SAE risk assessment.



Real tests by Daimler showing R1234yf ignition and propagation put into question many assumptions of the SAE risk assessment.

Daimler's Evaluation of Material Presented at JRC #1

- DuPont, Koban et. al.
- Honeywell
- SAE

Dupont Presentation: Koban et al.

- **“HFO-1234yf very difficult to ignite in actual vehicle testing”**
→ *Repeatedly disproved by Daimler vehicle testing; ignition is not difficult to achieve.*
- **“HFO-1234yf/PAG ignition ~700°C”**
→ *Disproved by Daimler testing, where a minimum refrigerant ignition temperature of 635°C was observed.*
→ *INERES lab tests* have yielded a relevant auto ignition temperature (AIT) of ~ 750°C. However, these result were produced in an artificial environment (vertical tube in steel box) that does not adequately represent an engine compartment, with different deflection and convection characteristics.*
→ *On the other hand, the R1234yf AIT of 525°C at IDT=2s or 400°C at IDT=50s established by BAM** along EN 14522 are equally not applicable.*

* INERES: “Ignition sensitivity and toxics generation by a refrigerant when submitted to a high temperature”,
N° INERIS-DRA – 11-121447, 26.1.2011

** BAM „Zündverzugszeiten bei Selbstentzündungen des PKW Kältemittels R1234yf“

SAE CRP 1234-4: OEM Test Data on Vehicle Operating Temperatures^{**}

Percent of Time Exhaust Surface Temperatures are above 600°C and 700°C*

Vehicle/ Powertrain Description	50th Percentile Customer Percent of Customer Hours			90th Percentile Customer Percent of Customer Hours		
	> 600°C	> 700°C	>600 <=700°C	> 600°C	> 700°C	>600 <700°C
Medium Size Van FWD Turbo Diesel	2.6%	0.0335%	2.5%	4.4%	0.0197%	4.4%
Small Van FWD Gas Non-Turbo	3.9%	1.8%	2.1%	5.3%	2.4%	2.9%
Small Cross Utility FWD Gas Turbo Direct Injection	6.2%	3.1%	3.2%	10.9%	5.7%	5.2%

*Based on Standard Thermal Test Results and Customer Use profile



The results of this analysis incorporated into the SAE CRP FTA Sensitivity Analysis

- A shift towards lower temperatures increases the operating temperature probabilities and modifies the outcome of the sensitivity analysis^{***}.

** SAE CRP 1234-4 Attachment K, "OEM Test Data on Vehicle Operating Temperatures", 24.07.2013

*** SAE CRP 1234-4 Report, Section 6 "Sensitivity Analysis" and Table 6.1

Dupont Presentation: Koban et al.

- **“Potential HF generation already safely managed through standard auto design and safety standards”**
 - *HF is generated by ignition of the refrigerant, or pyrolytically by contact of the refrigerant with hot surfaces without ignition - there is no safety standard to avoid this phenomenon*
 - *In conflict with the KBA conclusion: “However, ignition and hydrogen fluoride exposure have occurred in additional tests which have been performed by the KBA complementary to the product safety investigations, while comparison tests with R134a did not result in any critical events.”**
- **“R-134a and HFO-1234yf can potentially generate HF”**
 - “Both refrigerants have similar HF formation in vehicle fire”**
 - *Confuses cause and effect - HF is generated from R134a only after burning in a full vehicle fire, while HF is a direct combustion gas of ignited R1234yf.*

* KBA Project report on R 1234yf, 08.10.2013

Dupont Presentation: Koban et al.

- **“With the application of new safety standards, the specific requirements of HFO 1234yf are considered to maintain the safety of the vehicle at today’s level” (quoting SAE CRP 1234-3)**
 - *In conflict with the KBA conclusion “that there are still issues with respect to the use of the refrigerant R1234yf in air conditioning systems of motor vehicles. Therefore from the standpoint of general safety considerations, we strongly recommend to carry out further investigations for in order to improve the assessment of potential risks.”**
 - *“...a tendency to a higher risk is obvious compared to R134a. The process of inflammation and/or HF-generation is not completely clear → further studies are necessary”***

* KBA Project report on R1234yf, 08.10.2013

** KBA presentation “Examination of MAC with R1234yf in Motor Vehicles – State of Play”, 20.11.2013

Honeywell Presentation

- **“ISO standard 13043 and SAE standard J639 recommend safe and proper engineering design standards for HFO-1234yf (and R-134a)”**
→ *Even though these standards have been incorporated into vehicle designs, inflammation and propagation are possible (Daimler and competitor vehicles).*
- **“All fluorocarbons including R134a and 1234yf will produce HF when combusted in a fire.”** → *Inflammation is the issue, not combustion. KBA tests showed non-negligible amounts of pyrolitically produced HF **without** ignition.**
- **“The Daimler testing, which represents an extreme set of conditions, adds no new data that has not been considered in the SAE CRP studies.”**
→ *SAE CRP recognized that indeed significant new data had been produced, which lead to the initiation of CRP 1234-4 and the development of two new fault trees. New facts include: Lower observed ignition temperature; expected mitigating effects coolant steam, crush space, folded hood, shields, thermal insulation are not fully effective.*

* KBA Project report on R1234yf, 08.10.2013

SAE Presentation

- **“Coolant release always mitigated ignition of refrigerant”**
→ *Disproved by Daimler testing, where coolant/steam introduced into the combustion either did not change the reaction or even increased the inflammation intensity.*
- **“specific design of the air intakes, fan strategies, specific design of the heat shields to lower the skin temperatures of the critical components”***
→ *Shielded designs cannot be reliably maintained in crash situations.*

* PSA Peugeot Citroen contribution to SAE presentation

SAE Presentation

- **“specific design of the heat shields to either limit the fluid trapping around hot surfaces (e.g. exhaust manifold) or insure a good thermal insulation to avoid contact with hot surfaces (e.g. catalysis system)”***
→ *Daimler testing of competitor vehicles featuring extensively shielded and padded exhaust manifolds and turbine housings also showed inflammation of the refrigerant.*
- **“Front right-side crash, 35 km/h, 40% overlap, rigid barrier: worst-case scenario selected (much lower than the probability in the ETA)”***
→ *Real crashes happen in an abundance of configurations (speed, horizontal and vertical overlap, impact angle, collision object stiffness, shape and mass, etc.) – this can only be a small excerpt and individual vehicles will have individual worst case scenarios.*

* PSA Peugeot Citroen contribution to SAE presentation

Daimler's Conclusions



New facts generated by Daimler tests: Lower ignition temperature; expected mitigating effects by coolant steam, crush space, folded hood, shields, thermal insulation are not fully effective



ISO standard 13043 and SAE standard J639 are no sufficient measures to safely manage the risks incurred by R1234yf.



Significant amounts of HF can be produced by R1234yf by pyrolytic reaction on hot surfaces, even without ignition.



Accidents with refrigerant release will occur in a multitude of scenarios; ignition cases resulting in vehicle fires are foreseeable.



Real tests by Daimler showing R1234yf ignition and propagation put into question many assumptions of the SAE risk assessment.



Daimler AG maintains the position that CO₂/R744 is the preferred follow-up refrigerant for R134a.