ADDITIONAL RISK ASSESSMENT OF ALTERNATIVE REFRIGERANT R-1234yf

Prepared for

SAE INTERNATIONAL
Cooperative Research Program CRP1234-4
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Executive Summary

From 2006 to 2009 SAE International administered a cooperative research project (CRP1234) which evaluated R-1234yf, a new low global warming potential (GWP) automotive refrigerant. Using fault tree analysis (FTA) the results of the CRP1234 assessment showed that the risk associated with the use of R-1234yf in automotive vehicles is well below those commonly considered acceptable by the general public and regulatory agencies. The risk assessment was submitted to the U.S. Environmental Protection Agency (US EPA) as part of the Significant New Alternatives Policy (SNAP) approval process, and the US EPA subsequently approved R-1234yf for use in US vehicles.

In the EU, manufacturers are required to comply with the Mobile Air Conditioning (MAC) Directive (2006/40/EC) for new vehicle types effective 1 January 2011 with enforcement deferred to vehicles built on or after 1 January 2013. The EU commission has supported the introduction of R-1234yf as this meets the requirements of the MAC Directive. Manufacturers who have certified new vehicle types to this directive are obliged to build vehicles from 1 January 2013 with a low global warming potential (GWP) refrigerant.

On September 25, 2012 the German automotive manufacturer Daimler issued a press release suggesting that new testing conducted by the company had shown R-1234yf to pose a greater risk of vehicle fire than was estimated by the prior CRP1234 analysis. To address the Daimler claims, a new CRP (CRP1234-4) was organized in October of 2012. All Original Equipment Manufacturers (OEMs) were invited to attend.

After extensive testing and analysis, the new CRP concluded that the refrigerant release testing completed by Daimler was unrealistic. Their testing created extreme conditions that favored ignition while ignoring many mitigating factors that would be present in an actual real-world collision.

At the same time, the new CRP, with input from Daimler, initiated two new fault tree scenarios to realistically address these claims. The new CRP also reviewed and analyzed extensive new OEM test data which was used to complete the new FTA. The two new fault tree scenarios consider the possibility of an individual being unable to exit the vehicle due to a collision or a non-collision event that involves a refrigerant/oil release, the refrigerant/oil being ignited and the fire propagating. The FTA examined average risks across the entire global fleet and used a number of conservative assumptions to ensure that the final risk estimate would be more likely to overestimate rather than underestimate actual risks.

Based on the updated analysis, the estimated overall risk of vehicle fire exposure attributed to use of R-1234yf is conservatively estimated at 3×10^{-12} events per vehicle operating hour. This is nearly six orders of magnitude less than the current risk of vehicle fires due to all causes (approximately 1×10^{-6} per vehicle operating hour) and also well below other risks accepted by the general public. The table below shows the current overall risk of occupant exposure to adverse events based on R-1234yf usage is on the same order of magnitude as that estimated in the prior work of CRP1234. Therefore, the conclusions of the former CRP risk assessment are still valid: risks are still very small compared to the risks of a vehicle fire from all causes and well below risks that are commonly viewed as acceptable by the general public. All OEMs in the new CRP have indicated agreement with these conclusions. The members[1] are European, North American and Asian OEMs: Chrysler/Fiat, Ford, General Motors, Honda, Hyundai, Jaguar Land Rover, Mazda, PSA, Renault and Toyota.

[1] Daimler, BMW and Audi initially participated in the new CRP but eventually chose to withdraw.

Table ES.1 Probability of Various Adverse Events Compared to Estimated Probability of Events Associated with Vehicle Operation-Related Leaks of R-1234yf

Event	Probability per vehicle per operating hour	Citation
Probability of being in a police reported vehicle collision	4×10^{-5}	NHTSA, 2013
Probability of automotive vehicle fire (any cause)	1×10^{-6}	Ahrens, 2013; FHA, 2009
Probability of vehicle collision due to vehicle brake failure	3×10^{-7}	New York State DMV, 2008
Probability of dying in a regularly scheduled plane trip in a developed nation	7×10^{-8}	Barnett, 2011
Estimated probability of vehicle occupant/former occupant experiencing HF exposure above health based limits associated with an R-1234yf ignition event	5×10^{-12}	CRP1234, 2009
Estimated probability of vehicle occupant being exposed to a vehicle fire due to R-1234yf ignition (due to leak and ignition in engine compartment)	3×10^{-12}	Current analysis
Estimated probability of vehicle occupant being exposed to an open flame due to R-1234yf ignition (primarily due to leak and ignition in cabin)	9×10^{-14}	CRP1234, 2009

1 Background

1.1 SAE CRP1234

Due to concerns about global warming, the use of refrigerant R-134a (*i.e.*, 1,1,1,2-tetrafluoroethane), has been prohibited in the EU for use in new type approved vehicles as of January 1, 2013 (European Fluorocarbon Technical Committee, 2007). Regulations developed by the European Union require that any refrigerant(s) intended to replace R-134a have a global warming potential (GWP) less than or equal to 150 based on a 100-year time horizon.

To assist member companies with selection of an R-134a replacement, SAE International administered a cooperative research project (CRP1234) to evaluate a proposed replacement candidate for R-134a: 2,3,3,3-Tetrafluoropropene (R-1234yf). The intended goal of the SAE CRP process is to bring together technical experts from different segments of the automotive industry to capitalize on individual member's expertise and to develop solutions which benefit the automotive industry as a whole. Fifteen different automakers (OEMs) joined the CRP, along with sixteen HVAC component suppliers including DuPont and Honeywell International, the developers and suppliers of R-1234yf. The CRP1234 evaluation of R-1234yf addressed the risks to vehicle occupants as well as first responders, vehicle assembly and service workers resulting from accidental releases of these refrigerants such as might result from damage to vehicle air conditioning systems or improper use of vehicle service equipment. Because R-1234yf is mildly flammable (ASHRAE Class 2L) the primary concern was refrigerant ignition. The evaluation also addressed possible exposures to hydrogen fluoride (HF) formed during combustion or thermal decomposition of this refrigerant. The CRP1234 risk assessment followed the general approach of the U.S. EPA-sponsored risk assessment of R-152a and CO_2 (Blackwell *et al.*, 2006) so as to employ a consistent methodology and generate an analysis familiar to regulatory agencies. This involved the development of potential exposure scenarios for different endpoints of concern and estimation of the risks for those considered plausible using fault tree analysis (FTA). FTA is a methodology that analyzes the sequence and combinations of failures that lead to a particular outcome. FTA typically uses conservative inputs where values are known with less than ideal certainty so the overall risk estimates are believed to overestimate the true risk of the adverse events of concern actually occurring.

The risk assessment incorporated various types of data including toxicity data, bench scale testing results (*i.e.*, flammability and HF generation studies), modeled air concentrations, and vehicle measurements (*i.e.*, measurements of passenger compartment and engine compartment concentrations of chemicals in air and, where applicable, ignition tests). These data were collected from various sources including government databases as well as publicly available and confidential reports. Data not found in existing reports were generated by consulting groups and/or CRP1234 members.

The results of the risk assessment indicated that R-1234yf is comparable to the current automotive refrigerant (R-134a) in terms of both human health effects and ecological effects. Results of extensive toxicity studies indicate that potential R-1234yf exposures of vehicle passengers in the event of AC system leaks into the passenger compartment would be below levels associated with potential health effects. Similarly, R-1234yf exposures of AC service technicians would be well below levels associated with potential health effects. Potential exposures of automotive assembly workers, which could occur due to small losses of refrigerant during vehicle assembly and/or service, were also estimated to be below levels of health concern based on exposure data collected for R-134a. Thus, potential health effects from exposures to R-1234yf were not judged to be a source of concern in the risk assessment.

With respect to the potential ignition of R-1234yf, the CRP1234 risk assessment considered several scenarios:

- Rupture of evaporator tubing in the event of a vehicle collision, refrigerant release in the passenger compartment, and ignition of the refrigerant inside the passenger compartment,
- Rupture of the AC system under hood in the event of a collision and ignition under hood when the vehicle occupant looks under hood to investigate the problem,
- Rupture of the AC system under hood due to a part failure (*i.e.*, non-collision) and ignition under hood when the vehicle occupant looks under hood to investigate the problem.

When the risks for the three potential ignition scenarios were combined, the FTA indicated that the risk of an occupant (or former occupant) being exposed to an open flame due to R-1234yf ignition were extremely low, on the order of 9×10^{-14} events per hour of vehicle operation. Nearly all of this risk would be attributable to release and ignition of refrigerant in the passenger cabin as a result of a vehicle collision. Risks for certified AC service technicians were also found to be inconsequential (1×10^{-26} per vehicle service hour) because modeling studies indicated air concentrations of R-1234yf in service areas would only reach the LFL at a distance of 10 cm or less from the source of the AC system leak. The CRP1234 members judged that ignition sources would not be located this close to the AC system given the presence of other flammable materials in the engine compartment.

CRP1234 also evaluated potential exposures to hydrogen fluoride (HF) that might occur in the event of R-1234yf ignition or thermal decomposition.[2] The risk assessment considered potential HF exposures in the following scenarios:

- Exposure in the passenger compartment due to refrigerant entering the compartment after a collision and being ignited in the passenger compartment,
- Exposure in the passenger compartment due to HF entering the compartment after being produced in the engine compartment should the refrigerant burn or undergo thermal decomposition,
- Exposure under hood for various receptors (former occupants, good Samaritans) when refrigerant is released during a collision and burns or decomposes,
- Exposure under hood for various receptors (former occupants, good Samaritans) when refrigerant is released due to a non-collision related AC component failure and the refrigerant burns or decomposes,
- Exposure under hood when refrigerant burns due to a vehicle fire that is caused by another, non-AC system related event (*e.g.*, vandalism, fires due to failure of other parts).

When the risks for these potential HF exposure scenarios are combined, the FTA indicated that the risk of an individual being exposed to HF above the relevant health-based limit was extremely low, on the order of 5×10^{-12} events per hour of vehicle operation. The risk was almost entirely and equally attributable to

[2] HF is produced during the burning or thermal decomposition of all fluorocarbons, including the current automotive refrigerant R-134a.

two scenarios: HF generation by vehicle fires arising from failure of non-AC vehicle components and decomposition of refrigerant in the engine compartment after a vehicle collision with subsequent aspiration of HF into the vehicle cabin. Because the first scenario also exists at the current time with R-134a (which produces HF when present in a fire), the CRP determined that the HF exposure risks associated with use of R-1234yf were not significantly greater than those currently present.

To place the risk estimates developed in the FTA into perspective they were compared to risks of other analogous events that are generally considered acceptable by the public (Table 1.1). This analysis showed that the risks associated with the use of R-1234yf in automotive AC systems were well below those commonly considered acceptable by the public and regulatory agencies. Overall, the CRP1234 risk assessment concluded that R-1234yf is suitable for use in direct-expansion air-conditioning systems.

The CRP1234 risk assessment report was submitted to the U.S. EPA Significant New Alternatives Policy (SNAP) office which subsequently approved R-1234yf for use in mobile air conditioning systems (MAC).[3] This approval became official on March 29, 2011. The U.S. EPA did not impose any use or design restrictions on the use of R-1234yf beyond the requirement that OEMs conduct their own Failure Mode Effects Analysis (FMEA)-type analysis and follow SAE J639 (Safety Standards for Motor Vehicle Refrigerant Vapor Compression Systems) for their specific vehicle models.

Table 1.1 Probabilities of Various Adverse events Compared to Estimated Probabilities of Events Associated with Leaks of R-1234yf in Prior CRP 1234 Study

Vehicle-Related Event*	Probability per vehicle per operating hour	Basis
Probability of being in a police reported vehicle collision	4×10^{-5}	NHTSA, 2013
Probability of automotive vehicle fire (any cause)	1×10^{-6}	Ahrens, 2013; FHA, 2009
Probability of vehicle collision due to vehicle brake failure	3×10^{-7}	New York State DMV, 2008
Probability of dying during a commercial plane flight in a developed nation	7×10^{-8}	Barnett, 2010
Estimated probability of vehicle occupant/former occupant experiencing HF exposure above health based limits associated with an R-1234yf ignition event	5×10^{-12}	CRP1234, 2009
Estimated probability of vehicle occupant being exposed to an open flame due to R-1234yf ignition (primarily due to leak and ignition in cabin)	9×10^{-14}	CRP1234, 2009
Service-Related Event*	**Probability per service hour**	**Basis**
Non-fatal recordable Injury at work (all occupations, per working hour)[1]	2×10^{-5}	NSC, 2004
Estimated probability of AC service technician exposure to an open flame due to R-1234yf ignition (per hour of vehicle service)	1×10^{-26}	CRP1234

* The basis for calculating the comparison risk values are provided in Table 5-1 (vehicle-related events) and the SAE CRP1234 (Phase III) risk assessment report (service related events).

[3] The regulatory situations in the U.S. and EU are somewhat different. The EU requires the phased in use of an automotive refrigerant with a GWP less than 150 but does not grant approvals for individual refrigerants. In the U.S., all new refrigerants must be approved by the US EPA SNAP program prior to use in the market. The U.S. Environmental Protection Agency (EPA) encourages the use of low GWP refrigerants through the use of emissions credits.

1.2 Testing by Daimler

On September 25, 2012 the German automotive manufacturer Daimler issued a press release suggesting that new testing conducted by the company (independent of the SAE CRP) had shown R-1234yf to pose a greater flammability hazard than previously understood. Specifically, Daimler stated: “In the new real-life test scenario, the refrigerant is dynamically dispersed at high pressure near to hot components of the test vehicle’s exhaust system. This corresponds to a serious head-on collision in which the refrigerant line is severed and the reproducible results demonstrate that refrigerant which is otherwise difficult to ignite under laboratory conditions can indeed prove to be flammable in a hot engine compartment. Similar tests of the current R-134a refrigerant did not result in ignition.” While the press release indicated that the refrigerant was flammable (a fact already known), statements by Daimler representatives indicated that their testing revealed a greater risk of vehicle fire than was estimated by the CRP1234 FTA.

Details of the exact nature of the Daimler testing were not readily available at the time of the press release. Subsequently obtained information clarified that Daimler did not conduct or simulate an actual vehicle crash test but rather simulated an engine compartment release, for example due to a part failure. Initial reports that the Daimler test corresponded to a serious head-on collision are therefore erroneous because, unlike a collision scenario, the Daimler test involved no damage to other vehicle components which could serve as mitigating factors for refrigerant ignition. Efforts by one OEM to reconstruct the Daimler tests also indicated Daimler used a specific type of release nozzle that is not consistent with a broken or crushed AC line. This specialized nozzle produced a fairly slow rate of release and was apparently pointed directly under the shielding surface that covered the turbocharger. This configuration may have allowed the refrigerant to accumulate at sufficient concentrations near the hot surface. Additionally, a long metal tube connected the production refrigerant line to the nozzle and was routed in close proximity to the turbocharger surface. During the reconstructed tests it was found that such a configuration pre-heated the refrigerant passing through the tube by approximately 20°C. Daimler apparently also added valves to the production-level vehicle which could be used to throttle refrigerant flow such that gas velocity was reduced. The combination of the specialized nozzle, the pre-heating tube, and the refrigerant release throttling are all factors that artificially promote ignition. The reconstructed tests show that inclusion of the Daimler setup resulted in refrigerant ignition with a particular vehicle that was not observed when a realistic nozzle configuration was used on that same vehicle. Refrigerant ignition was typically only achieved when the engine cooling fan was manually overridden to be switched off (a situation which would normally not exist when the engine is hot). Thus Daimler's test results indicate that in the event of an isolated line break, where refrigerant is released at a slow rate towards a hot surface achieved during extreme driving conditions, and where no mitigating factors (hood buckling, engine cooling fan operating, release of coolant/steam under hood) are present, the refrigerant can be ignited and lead to a vehicle fire. But, because multiple mitigating factors are in fact expected to co-occur during a vehicle collision, the proper interpretation of the Daimler results was unclear.

2 CRP1234-4

To study and confirm the results of the Daimler tests, the automotive members of the original CRP1234 organized as a new CRP (CRP1234-4) starting in October 2012.[4] All OEMs were invited to attend, and most did join the new group, including Daimler and other German OEMs.[5]

The purpose of CRP1234-4 was as follows:

(1) to evaluate the testing conducted by Daimler to determine its relevance to real-world vehicle situations,

(2) to determine whether the existing CRP1234 fault tree structure should be expanded to address the new Daimler information, and if so, to guide that process,

(3) to provide a forum whereby the OEM members could coordinate their own in-house testing and share the results.

The CRP1234-4 members agreed that the scope of the new CRP would not involve a complete reevaluation of the prior CRP1234 FTA. The prior fault trees addressed scenarios not related to the Daimler tests (*e.g.*, ignition of refrigerant in the vehicle cabin) and were developed after several years of study as a consensus product of all the prior CRP members. The CRP1234-4 members therefore had confidence that the prior fault trees fully addressed their relevant scenarios and that reinvestigation of the earlier FTA work was not required.

The members of the new CRP held an initial organization meeting in October 2012. A number of face-to-face meetings were subsequently held in Europe and the U.S. Work was also conducted *via* a series of twice weekly conference calls. The intent was to respond quickly to the Daimler test results and arrive at a final conclusion regarding the suitability of R-1234yf for MAC system as soon as possible, consistent with sound engineering and vehicle safety.

[4] To avoid any bias in the new CRP, it was decided that only OEMs would be allowed to participate in the new study. Refrigerant manufacturers were also excluded because vehicle application issues are the responsibility and expertise of the OEM's. Under SAE policies, because the membership was effectively changed, it was necessary to organize a new CRP.

[5] The members of CRP1234-4 were: Audi, BMW, Chrysler/Fiat, Daimler, Ford, General Motors, Honda, Hyundai, Jaguar Land Rover, Mazda, PSA, Renault, and Toyota. Daimler, BMW and Audi (a part of Volkswagen) subsequently withdrew from the CRP in early February 2013.

3 Scenarios Evaluated

Based on a review of the results of the Daimler testing, the CRP members decided to add two new fault trees into the analysis of refrigerant flammability. As noted above, the original CRP1234 fault trees considered risks of refrigerant ignition when the vehicle occupant leaves the vehicle and investigates in the engine compartment. The original FTA did not consider the possibility of individuals being unable to leave the passenger cabin in the event of a vehicle fire starting in the engine compartment. This was due to test data indicating the low burning velocity and heat of combustion of R-1234yf, which suggested a minimal risk of rapidly moving vehicle fire even if the refrigerant was ignited. Based on the additional concerns raised by Daimler, the CRP members decided to revisit this decision and include two remaining passenger scenarios in the FTA (Table 3.1). The new scenarios are as follows:

- A scenario where there is a refrigerant/oil release during vehicle operation due to a system part failure, such as a broken refrigerant tube (*i.e.*, non-collision). The released refrigerant/oil could then be ignited assuming a sufficiently hot surface is present in the engine compartment and the ignition event could propagate to other engine compartment materials such that a vehicle fire affects the passenger compartment. The scenario would require a simultaneous failure prohibiting the individual from leaving the vehicle (e.g., a failure of door locks). It also includes the possibility that an individual was able to enter the vehicle and able to drive but unable to exit the vehicle in a case of a vehicle fire. Note that the refrigerant release described in this scenario is most similar to the conditions of the Daimler test. This was analyzed as fault tree I6.

- A scenario where a refrigerant/oil release occurs in the vehicle engine compartment due to a collision. The released refrigerant/oil could be ignited by a hot surface, spark or glowing wire and the ignition event could propagate to other engine compartment materials such that a vehicle fire affects the passenger compartment. This scenario also requires that the collision produces conditions where the vehicle occupants are unable to exit the vehicle, for example by damaging the doors on the side of the vehicle. This was analyzed as fault tree I7.

The CRP 1234-4 members also considered evaluating the effects of HF generation and reached a conclusion based on the following information:

- The prior CRP1234 conducted an extensive evaluation of potential exposures to HF that might occur in the event of R-1234yf ignition or thermal decomposition. That analysis indicated that the risk of an individual being exposed to HF above the relevant health-based limit was extremely low (5×10^{-12}) and was not significantly greater than the risk present with R-134a.
- In a presentation made on September 17, 2012, the VDA members Daimler, Audi, BMW, and Opel stated that thermal decomposition will not lead to relevant concentrations of HF in or around the vehicle. In the event of a refrigerant fire, the VDA confirmed that similar behavior, regarding HF generation, exists between R-134a and R-1234yf. Therefore, the VDA concluded that there is no additional HF-exposure risk to occupants, first emergency responders, and firefighters associated with the usage of R-1234yf.

- Due to the irritancy of HF, individuals will leave the area unless unable to do so. The idea of individuals being unable to leave the vehicle is already reflected in the new scenarios described above.
- Due to some HF-specific mitigation factors (e.g., convection of HF away from the vehicle by the heat generated from the fire), the risk of HF being present above the health based limit should be even lower than the risk of vehicle fire, i.e. the conclusions in the above bullets are conservative.
- The CRP1234-4 members are also aware that studies conducted by another SAE CRP (the MRB CRP) have shown that even in the event of R-1234yf ignition, HF concentrations at the vehicle exterior (i.e., along the side of the vehicle) do not exceed the health based HF limit of 95 ppm.

The current understanding of HF generation indicates that significant HF exposure is only relevant in the event of sustained refrigerant fire and not because of thermal decomposition. In the two new scenarios described above, the risk of having HF present above the health based limit would therefore be no higher than the risk of exposure to a vehicle fire. Given the current understanding of HF generation, CRP1234-4 concluded that the prior analysis of risks associated with HF is still valid. For the new scenarios considered, the risk that could be estimated for HF exposure would be equal to or less than the risk of exposure to a vehicle fire, which is assessed by the new trees.

Table 3.1 Ignition Scenarios Evaluated by CRP 1234 and CRP 1234-4

Triggering Event	Location of Refrigerant Release	Location of Potential Exposure	Exposed Individual	Exposure to open flame (ignition)	Fault Tree ID
Collision	Passenger compartment	Passenger compartment	Vehicle occupant	Evaluate *via* FTA	I3
AC system leak (non-collision)	Engine compartment	Engine compartment	Former occupant investigating engine	Evaluate *via* FTA	I4
Collision	Engine compartment	Engine compartment	Former occupant investigating engine or good Samaritan assisting remaining occupants	Evaluate *via* FTA	I5
AC system leak (non-collision)	Engine compartment	Passenger compartment	Remaining occupants	Evaluate *via* FTA	I6*
Collision	Engine compartment	Passenger compartment	Remaining occupants	Evaluate *via* FTA	I7*

*New fault trees developed in this study

4 FTA Structure and Inputs

The original CRP1234 trees took a highly conservative view concerning refrigerant ignition and vehicle fires, using a single parameter (*i.e.*, air currents do not extinguish ignited refrigerant) to differentiate brief isolated ignition events which pose no risk from those which could lead to ignition of other vehicle components. Because the reported Daimler tests suggested that refrigerant ignition events might be more sustained and likely to involve other vehicle components than originally believed, CRP1234-4 adopted an expanded structure for fault trees I6 and I7 which examined in more detail the factors that allow a refrigerant ignition event to propagate into a vehicle fire.[6] This is shown in simplified form in Figure 4.1. Each of the new trees therefore contains a refrigerant ignition section which feeds into a higher level portion of the tree which evaluates the probability of propagation of ignition to other vehicle components. The resulting risk of vehicle fire in turn feeds into the top level portion of the FTA which considers the possibility of an individual being present and involved in the fire (*i.e.*, occupant unable to leave). Each of these levels is discussed below.

It should also be noted that CRP1234-4 opted to use a new terminology to describe the categories of vehicle collisions being studied. The prior CRP referred to high, medium and low speed collisions. These were tied to speeds of > 50 kilometers per hour (kph), 16 to 50 kph, and < 16 kph. However, these speed ranges actually refer to the closing speed of the vehicles on impact rather than the speed of the vehicles while under operation prior to the accident. To avoid confusion and be more consistent with OEM vehicle accident terminology, the current fault trees refer to high, mid and low *severity* collisions. The new terms refer to the same impact speed categories as before and are similarly broken down by side or front impact location. It is thus a matter of clearer terminology rather than a change in the actual conditions being assessed. The original CRP fault trees also used these collision speeds to determine the likelihood of having extremely hot exhaust surface temperatures prior to collision. Using this concept, high speed collisions were more likely to have hot exhaust surface temperatures and low speed collisions were less likely to have similar temperatures. CRP1234-4 noted that even low speed collisions could occur after high speed driving given the amount of braking that occurs before the collision. The new fault trees therefore use a factor for preconditioning (% of vehicle drive time that vehicles would have extremely hot exhaust surface temperatures) that is independent of collision speed.

[6] This expanded structure was not used for the previously evaluated scenarios but because the original analysis took a more conservative approach, the risks for the earlier fault tree scenarios would also be expected to be decreased.

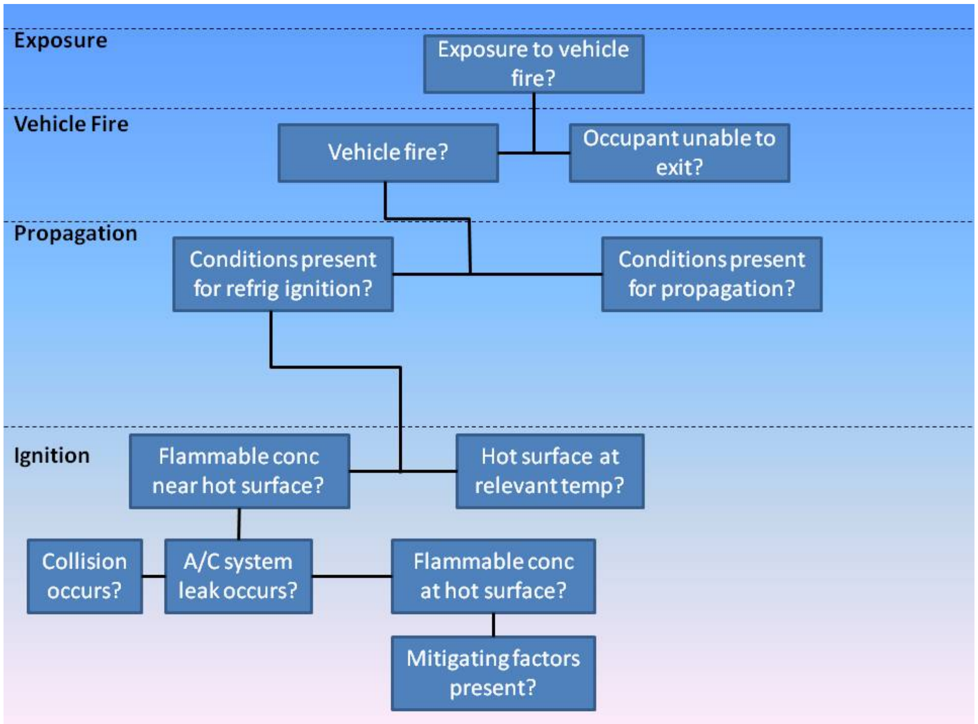

Figure 4.1 Overview of General Structure for New CRP1234-4 Fault Trees

4.1 Refrigerant Ignition

The portions of fault trees I6 and I7 addressing refrigerant ignition consist of several elements. For the collision case, three potential ignition sources are considered: a hot surface such as a manifold or catalytic converter (above a temperature of 700°C), an electrical short of sufficient energy, and a hot glowing wire such as an exposed and shorted battery cable. For each ignition source, conditions are also considered which must be present in order to have a flammable refrigerant concentration occur in the vicinity of the ignition source. These include the following:

- the frequency of a collision of a certain severity (high severity front, high severity side, mid-severity front, *etc.*),
- the probability that such a collision causes a breach in the AC system,
- the probability an AC system breach releases refrigerant in the vicinity of the hot surface,
- the probability the engine cooling fan is not operational,
- the probability that crushing of the engine compartment does not reduce the air volume near the hot surface to preclude ignition, and
- the probability that mitigation does not occur due to the release of coolant and steam during the collision.

Many of the inputs for the mitigating factors are shared among the three potential ignition sources. For the non-collision case the structure is simpler; the only ignition source is the hot surface (because glowing wires or significant sparks require a collision to occur) and the list of mitigating effects is reduced to those that do not involve a collision (the direction of the release and the operation of the cooling fan).

The identification of potential mitigating factors for refrigerant ignition was one of the major topics of discussion by the CRP and was informed by extensive data gathering. For example, the mitigating impact of the vehicle cooling fan in dispersing the refrigerant and creating air current that limit the degree of refrigerant contact with the hot surface is borne out by multiple OEM vehicle tests, including those conducted by Daimler. Similarly, if refrigerant is released in a direction away from the hot surface (*e.g.*, out towards the front of the vehicle) then ignition is extremely unlikely. This is particularly relevant for frontal collision scenarios where damage to portions of the AC system at the front of the vehicle (*i.e.*, the condenser) is likely in cases where more rear-ward portions (*i.e.*, nearer the hot surface) are also damaged. For example, one OEM examined vehicle crash data for one vehicle model and observed that in all cases when a crash was severe enough to damage AC lines inside the engine compartment, the condenser at the front of the vehicle was also damaged. Studies conducted by another OEM indicated that approximately 20-70% of the refrigerant is contained in the condenser (depending on operating conditions) and an additional 3 to 9 percent is contained in the evaporator (*i.e.*, inside the cabin). Similar data were obtained by another OEM which examined refrigerant distribution in vehicles operating at mid-ambient and high demand (*i.e.* high load) conditions. In this case, it was found that 70 to 78 percent of the system charge was contained in the condenser. More detail on these OEM studies is contained in Attachments A and B. These data support the concept that in some types of vehicle collisions, most of the refrigerant will be released out the front of the vehicle and in the event of an underhood line breach only a small amount of refrigerant will be released underhood.

With regards to release of steam or engine coolant as a mitigating factor, the OEMs considered that crashes severe enough to cause refrigerant releases inside the engine compartment are also highly likely to damage the radiator and/or coolant tanks. Because the hot exhaust surface condition required for possible refrigerant/oil ignition implies hot coolant as well, the release of coolant which is hot and under pressure will create a steam cloud that will both drive refrigerant out of the engine compartment and displace the oxygen needed to initiate refrigerant ignition. This was evident when reviewing frontal impact crash test results obtained by several of the OEMs. These vehicles were crashed while containing production level fluids like coolant, engine oil, and R-1234yf/PAG oil. While the OEMs did recognize that the glycol portion of coolant is flammable, they also considered that a period of time is required for sufficient water to be boiled off from the released coolant for the material to become flammable. The time period required for this to occur will be longer than the time frame for a refrigerant release. Additional detail on the potential effects of coolant/steam release in a collision is provided as Attachments C and D.

A critical consideration for the ignition portion of the FTA is the temperature of the hot surface that is necessary to ignite the refrigerant after it is released. Various studies conducted by multiple CRP1234-4 members have indicated that temperatures of 750°C or higher are generally required to ignite R-1234yf in an engine compartment (See for example Figure 4.3). Daimler reported that refrigerant ignition was observed at temperatures below 700°C although additional testing has indicated that the temperature being measured was not at the hottest location on the exhaust surface in the Daimler studies.[7] To be certain of the temperature of the exhaust surface required to ignite a flammable mixture of refrigerant and oil, hundreds of new release tests (> 500 individual tests) on multiple vehicles were run.[8] No ignitions were ever observed below 700°C and many releases showed no ignition at temperatures as high as 850°C (see Attachments E and F for more detail). To be conservative, the CRP risk assessment assumed that a

[7] One of the OEMs did extensive testing with Daimler's B class vehicle and noted that the hottest portion of the exhaust system was on the back surface of the exhaust system (closer to the engine). Daimler reportedly measured exhaust surface temperatures on the front side of the exhaust surface which was found to be 25 to 30 degrees lower in temperature.

[8] Refrigerant release testing on hot surfaces to simulate the damage caused by collisions fails to consider numerous mitigating factors of a collision. The OEM refrigerant release testing was done to better understand the exhaust surface temperatures and shield parameters required to ignite a refrigerant and oil mixture.

refrigerant temperature of 700°C would be sufficient to always ignite a flammable concentration of the refrigerant and oil.[9]

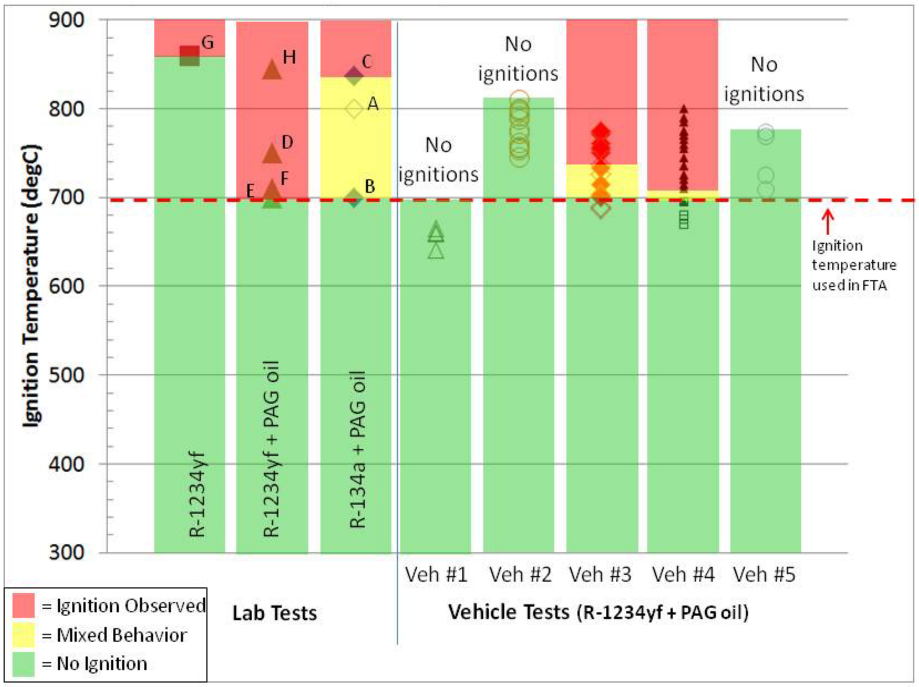

Figure 4.2 Example Results of OEM Lab and Vehicle Testing for R-1234yf Ignition Temperatures
For vehicle testing each data point represents a separate release for a particular vehicle. Open symbols indicate no refrigerant ignition, filled symbols indicate ignition.

To account for the differences noted in ignition characteristics between 700°C and 850°C, during initial discussions the CRP had considered the possibility of a distinction between exhaust and heat shield designs that tend to create a stagnant zone for the refrigerant and oil mixture to be heated and those that tend to allow the refrigerant and oil mixture to flow up and away from the hot surface creating a non-stagnant zone case. Studies conducted by CRP members suggested that refrigerant ignition in the range of 700°C requires a static pocket of refrigerant and oil in close proximity to the hot surface such as might occur if the hot surface were covered with a heat shield with limited ventilation. This would allow the refrigerant to rapidly acquire enough heat from the hot surface in order to become ignited (API, 2003). The stagnant/non-stagnant zone approach was proposed as a way of reconciling the Daimler results (which reported ignition) with those of other OEMs (which did not observe ignition). Several OEMs observed that Daimler tested a vehicle with a highly restrictive heat shield. After considerable testing and discussion, the CRP decided that, although information was consistent with the idea of a distinction between stagnant and non-stagnant conditions, there were insufficient exhaust and shield configuration data to fully parameterize this in the FTA. It was therefore decided to conservatively assume that a stagnant zone condition could exist in any vehicle which could result in refrigerant ignition if the refrigerant, oil and air mixture came into close proximity with a surface at or above 700°C. The implications of this decision are explored *via* sensitivity analysis in Section 6.

[9] The earlier CRP1234 FTA assumed a value of 550°C would be sufficient to cause ignition, although testing conducted at INERIS and Hughes indicated much higher temperatures in the range of 750°C. The higher temperature is now supported by results multiple tests conducted by the OEMs as part of the current effort. CRP1234-4 is also aware of testing conducted by another CRP (SAE CRP MRB) which included R-1234yf as a comparison material. In those tests as well, R-1234yf ignition also occurred at approximately 750°C (Peral-Antunez, 2011)

4.2 Propagation

After reviewing many of the release tests, the CRP determined that refrigerant and oil ignition was frequently brief and represented little more than a flash under hood. Some ignition events lasted longer and were generally accompanied by yellow/orange flames which were understood to represent oil ignitions that may have lead to propagation of an under hood fire. To consider possible propagation of the refrigerant ignition event, the CRP considered 3 different situations: propagation by ignition of combustible solids, propagation by ignition of combustible fluids, and propagation by ignition of flammable fluids. In the context of the FTA:

- Combustible solids refers to plastic parts that might be present in the refrigerant ignition zone. Each part has its own thermal properties (*e.g.*, depending on material and thickness) and would require some period of exposure to the ignited refrigerant/oil mixture to itself become ignited.
- Combustible fluids are materials such as motor oil, brake fluid, or transmission fluid that have relatively low vapor pressures and would also require exposure to a heated exhaust surface (to vaporize some of the fluid) or an extended period of exposure to the burning refrigerant-oil mixture in order to become ignited. In addition, these fluids are normally contained within vehicle systems and would need to be released (*e.g.*, in the event of a collision) in order to be exposed to the ignition event.
- Flammable fluids pertain to gasoline/petrol or diesel fuel. Unlike combustible fluids, these materials have a high vapor pressure and would likely ignite upon contact with a burning refrigerant-oil mixture. On the other hand, due to their flammable nature, vehicles are specifically designed to avoid release of these materials. Note that two other flammable materials, the methanol portion of window washer fluid and the ethylene glycol portion of coolant do not factor prominently into this analysis. In both cases, the material is typically a mixture with water and the water would have to be evaporated in order for the mixture to become flammable. It was assumed that the point at which this occurs would be well after the refrigerant ignition has occurred. Moreover, as pertains to washer fluid, in many car designs the tanks are in the very front of the vehicle or in the wheel well and therefore not in proximity to the hot surface.

For fault tree I7, the collision case, all three propagation sources were considered possible. For fault tree I6, only the combustible solids were considered viable because combustible and flammable fluids require significant damage to the vehicle in order to be released.

In addition to the probability that each type of combustible/flammable material is released and exposed for a sufficient time to the ignited refrigerant to itself become ignited, a number of mitigating factors are considered. These include:

- the probability that combustible or flammable materials are released away from the refrigerant ignition zone,
- the probability that air currents due to a collision extinguish the ignited refrigerant before the flame can propagate to other materials.

These factors are not included in the flammable fluids case because the high vapor pressure of these materials was believed to exclude much of the effect of mitigation. Each propagation branch also has an input that excludes the possibility of direct production of a vehicle fire due to ignition of the combustible/flammable material (without any role for the refrigerant). The rationale is to exclude vehicle fires where the refrigerant is not an initiating factor because the goal of the FTA is to determine the added risk of using this refrigerant, not the overall risk due to all vehicle systems.

With regards to the effect of crushing of the engine compartment due to a collision, the CRP members considered that in some collisions (primarily severe frontal collisions), crushing of the engine compartment could push parts close enough to the hot surface so as to nearly eliminate any air gap around the hot surface where refrigerant could be present (Figure 4.2). Crushing could create conditions similar to those found in a flame arrestor, where the available air gap, between the hot surface and cooler components, is so small as to quench the ignition kernel and prevent propagation to the surrounding flammable gas (Edwards, 1991). Essentially, crushing the front-end components (condensers, radiators and fans) would have a quenching effect as these relatively cool components tend to quench the flame as it expands away from the space around the hot surface, reducing the potential for propagation (Zabetakis *et al*., 1965).

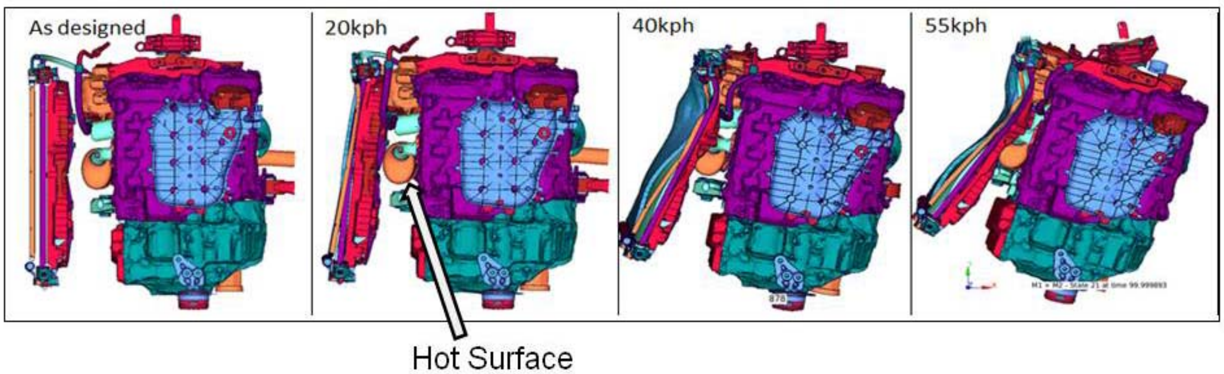

Figure 4.3 Computer Aided Engineering (CAE) Modeling of the Possible Impact of Collision-related Crushing on Available Airspace Around the Hot Surface

Numerous factors that would provide a mitigating effect in preventing ignition also can be expected to have a mitigating effect in preventing propagation. For example, hood buckling has been shown to provide a mitigating effect in preventing ignition by allowing refrigerant concentration to flow out of the engine compartment. If the refrigerant were to still ignite in such a scenario, the buckled hood aids in preventing propagation by creating an air space above the ignition zone. This allows the ignition to consume the refrigerant in a region free of combustible solids. Once the refrigerant is consumed, the ignition kernel extinguishes with a reduced risk of propagation to other materials. Other factors (e.g., release of steam) likely play a similar role in providing mitigation for both ignition and propagation scenarios. Nonetheless, the CRP decided in the current analysis to only consider the mitigating aspects of these factors at one level of the FTA. This generally meant elimination of several mitigation factors during consideration of propagation. There was a concern that including the effects of these factors in the ignition and propagation trees could be perceived as diluting the overall risk ("double counting"). As a result, the risk associated with propagation is likely overstated in the fault trees. However, this leads to a more conservative assessment of the refrigerant and the CRP1234-4 members decided to move forward with this more conservative approach.

4.3 Exposure to Vehicle Fires

A vehicle fire will not necessarily result in injury of the vehicle occupants. In most instances, the occupants will be able to leave the vehicle and avoid the potentially dangerous situation. It is only in cases where the occupants are unable to exit that exposure to the vehicle fire could occur. In the

CRP1234-4 trees, the risk of vehicle fire therefore feeds into a higher level of analysis where the likelihood of a passenger remaining in the vehicle is considered. For the non-collision scenario, the only input at this level is the likelihood that a vehicle fault prevents the occupants from existing. For the collision scenario, the relevant inputs are the probability that the collision causes vehicle occupants to remain in the vehicle and the probability that first responders or other individuals do not help the occupants to leave before the passenger cabin becomes involved in the vehicle fire.

4.4 Fault Tree Inputs

Once the structure of the FTs was established, values for each of the inputs were assigned as probabilities based on information obtained from a range of sources (Figure 4.4).

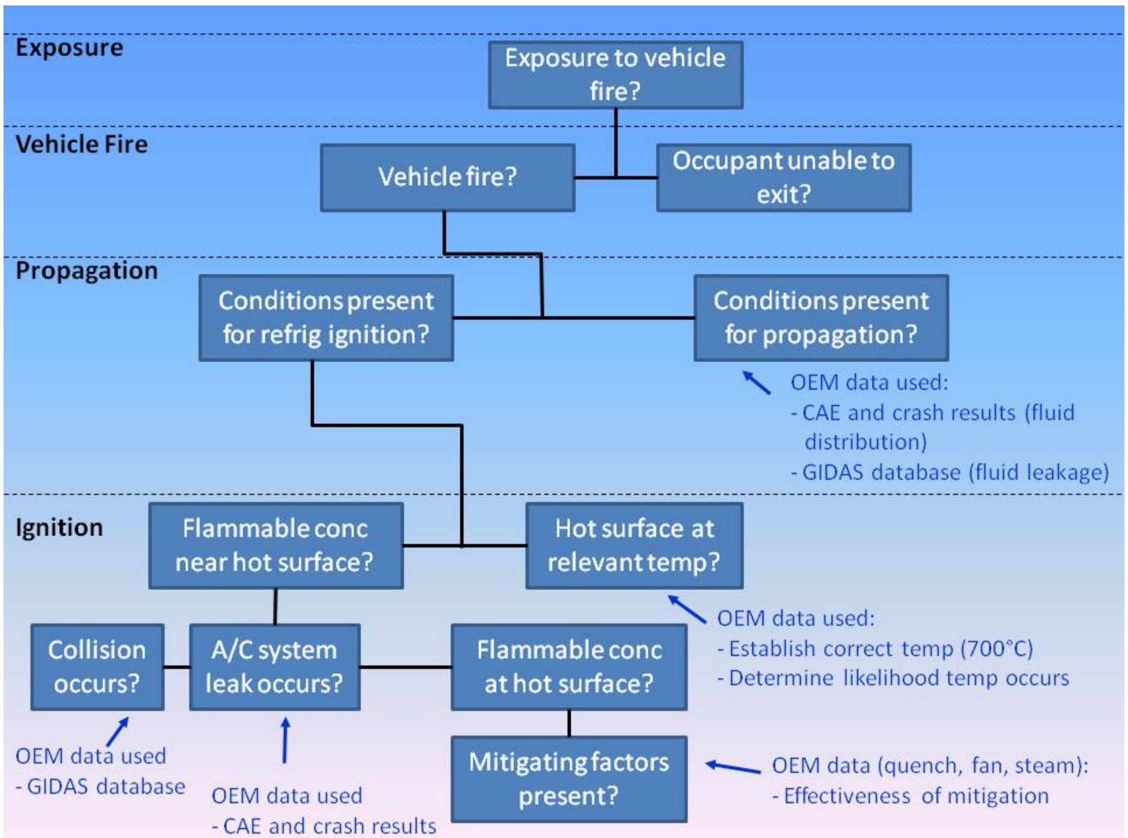

Figure 4.4 Inclusion of Input Data into FTA

4.4.1 Probability Hot Surface Exceeds 700°C

The likelihood of exhaust-surface temperatures exceeding 700°C is a key input for the FTA and is linearly related to the top event probability. The CRP1234-4 members agreed on a value of one percent (0.01) as indicative of the likelihood that a typical vehicle has a hot surface exceeding 700°C at any given time. This is supported by an analysis conducted by one OEM which evaluated 57 customer vehicles with 4 cylinder, V6, and V8 gasoline powered engines in North America and Europe. The vehicles were equipped with sensors that recorded both engine temperature and operating conditions. Based on prior thermal testing, the operating conditions which could allow a vehicle to reach temperatures above 700°C were (1) operation at wide-open throttle (WOT), (2) continuous climbing at greater than 4% grade for more than 90 seconds, and (3) operation at maximum velocity (Vmax). Vmax was defined as the maximum possible speed of vehicle operation on a level road as well as speeds 50 kph below this level.

Each vehicle was analyzed to identify the percentage of time spent at the three conditions. The results were then combined and processed through a Weibull analysis to generate an aggregate vehicle operation profile. According to the results, an average (50th percentile) customer engages in operating conditions that could result in hot surface temperatures above 700°C less than 1 percent of the time (0.12% or 0.0012, nearly 1 order of magnitude below the value used in the FTA). The analysis indicated that a customer with a more aggressive driving style (90th percentile) engages in operating conditions that could result in hot surface temperatures above 700°C 1.5% of the time (*i.e.*, 0.0153). The methodology employed in this analysis was conservative for a number of reasons:

1) It was assumed that every vehicle will achieve exhaust surface temperatures > 700°C when driven at WOT, continuous grade, or Vmax. Such an assumption disregards diesel applications, hybrid vehicles, and certain naturally aspirated vehicles that are incapable of achieving 700°C.
2) It was assumed that whenever a vehicle experiences WOT for any period of time that a temperature > 700°C is achieved. Thermal characterization data suggests that repeated back-to-back WOTs are necessary to achieve such a temperature.
3) It was assumed that all continuous grade operation when grade > 4% and duration > 90 seconds will result in a temperature greater than 700°C. This does not account for grade driving at low load conditions.
4) The analysis neglects the impact of operation at low ambient temperatures.
5) It was assumed that Vmax operation is relevant for all global regions. When the OEM characterized Vmax operation, it found that there were no relevant occurrences of Vmax in North America (likely due to speed limits well below Vmax). However, Vmax operation was identified in Europe and this occurrence rate was considered for all global usage. Additionally, the OEM included speeds 50 kph lower than Vmax and counted their occurrence rate as a Vmax occurrence to add an additional level of conservatism.
6) Data were combined across all three categories and fed into the Weibull analysis. This assumes that the same customer is always driving under the three conditions, which is highly unlikely (*e.g.*, individuals who frequently drive at Vmax may not also use their vehicles to tow loads up steep grades).

All of these assumptions would tend to overestimate the likelihood that a vehicle will be operating with a hot surface above 700°C. More detail on these tests is provided in Attachment G.

Data was obtained by another OEM which conducted road testing to measure underhood exhaust temperatures. The vehicle studied had a turbocharged gas powered engine, and was tested under two load conditions; loaded to near its gross vehicle weight rating (GVWR) and towing a trailer at its gross combined weight rating (GCWR). Testing was conducted across variable roads and grades in the vicinity of Phoenix, AZ. When the vehicle was driven without the trailer, an underhood exhaust temperature above 700°C was reached 0.3% to 1% of the time and the longest time exceeding 700°C was less than 2 minutes. Even during testing with a trailer the longest period of time the vehicle underhood exhaust temperature exceeded 700°C was less than 4 minutes. Although with a trailer, 700°C was exceed 6 to 16% of the total route time, it must be considered that customers tow a trailer less than 1% of the time which makes the contribution to the overall average time above 700°C insignificant. More detail on these tests is provided in Attachment H.

4.4.2 Other Ignition-Related Probabilities

A number of input probabilities were retained from the prior CRP1234 analysis, including the frequency of different types of vehicle crashes, the probability that the AC system leaks in the event of a collision of a given severity/type, the probability of a non-collision related AC system leak, and the probability of an electrical spark or hot glowing wire ignition source being present after a collision. Many of these were taken from the German GIDAS database. The GIDAS (German In-Depth Accident Study) database is built on the analysis of over 22,000 completely documented and reconstructed motor vehicle accidents which were extensively investigated as to cause and contributing factors. The work related to GIDAS is funded by the German Federal Highway Research Institute (BASt) and the German Association for Research in Automobile Technology (FAT).

Input probabilities concerned with the presence of flammable refrigerant concentrations in the engine compartment near the hot surface were determined based on studies conducted by several OEMs which described the distribution of refrigerant within the different portions of the AC system during different stages of AC system operation. They were also based on knowledge of engine compartment configurations and the frequency of vehicle designs which would place the engine compartment portion of the AC system (the compressor) on the same side of the engine block as the hot surface. Vehicle crash analysis surveys were used to assess the likelihood that various engine compartment components (*e.g.*, AC lines, engine cooling fan, radiator and coolant tanks) would be damaged in the event of a crash as well as the degree of crushing that occurs in the engine compartment after crashes of different types. Finally, a number of inputs were based on the consensus of industry experts with knowledge regarding automotive system design and operation.

As concerns refrigerant ignition, a number of the potential mitigating factors are affected differently by collision severity (Figure 4.5). For example, the probability of the engine cooling fan is damaged and non-operational is large for a high severity front collision and very small for a low severity side collision. On the other hand, the probability that steam is <u>not</u> released is small for a high severity collision and large for a low severity collision. Thus the combination of mitigating factors for refrigerant ignition is complex and non-linear.

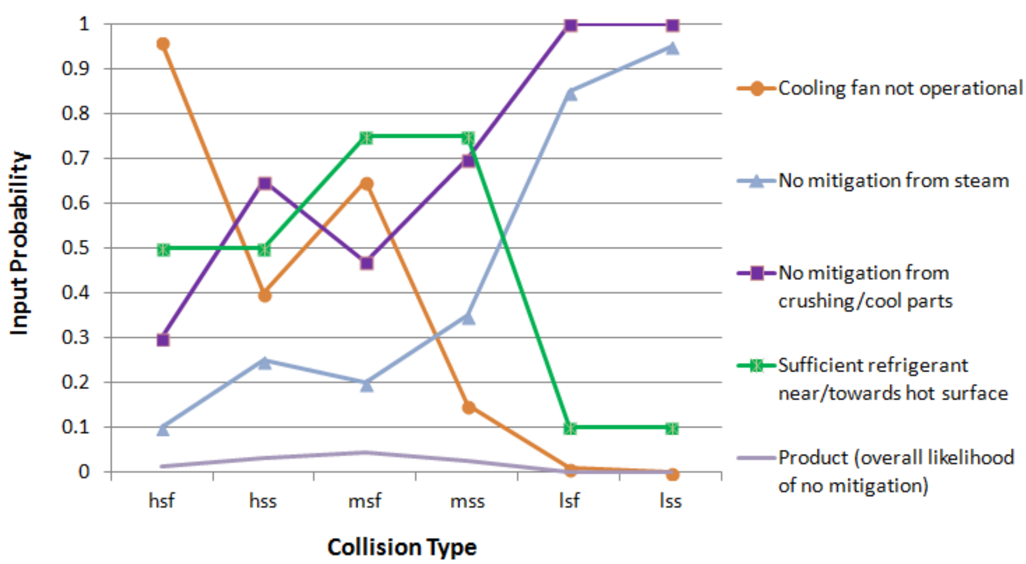

Figure 4.5 Mitigating Factors for Refrigerant Ignition by Crash Type

4.4.3 Propagation and Exposure-Related Probabilities

Important probabilities for the propagation portion of the FTA are the probabilities of release of combustible and flammable fluids and the probabilities these materials would ignite due to the collision without involvement of the refrigerant. Input values for these parameters were obtained from the GIDAS database and the supporting documentation is included as Attachment I.

Probabilities addressing the likelihood that the vehicle occupants cannot exit vehicle after a collision were based on a study by Funk *et al*. (2002) as well as statistics collected by various law enforcement agencies in US jurisdictions (Attachment J).

5 Results

5.1 Results of Current Analysis

Due the very low likelihood of a refrigerant tube rupture or similar event while the vehicle is operational and mitigating factors are absent, the non-crash scenario (I6) is estimated to pose negligible risk of exposure to a vehicle fire (10^{-19} events per vehicle operating hour). This is not surprising because in the prior CRP1234 analysis, the non-collision related leak was also not a significant contributor to overall risk. The more important scenario for the present analysis involves fault tree I7, the collision-related release in the engine compartment that produces a vehicle fire and where the passenger remains in the vehicle. The overall risk of vehicle fire exposure in this situation is 3×10^{-12} events per vehicle operating hour. This is several orders of magnitude less than the pre-existing risk of vehicle fires due to all causes (approximately 1×10^{-6} per vehicle operating hour) and also well below other risks generally accepted by the public. The primary contributors to the overall risk of fire exposure in fault tree I7 include high severity crashes (due to greater likelihood of a passenger remaining in the vehicle but also greater likelihood of mitigating factors being activated) and mid-severity crashes (due to lower likelihood of mitigating factors being activated but also lower likelihood of a passenger remaining in the vehicle).

5.2 Comparison to Results of CRP1234

Table 5.1 shows the results of current risk assessment in the context of the results obtained by CRP1234. As shown in the table, the risk of a vehicle fire which involves the vehicle occupants is on the same order of magnitude as the previously estimated risks of HF exposure above a health based limit. The risk of vehicle fire involving the occupants is approximately 2 orders of magnitude greater than the ignition risks estimated for CRP1234. That assessment had as its most significant scenario refrigerant ignition inside the vehicle cabin, a scenario where the hot engine compartment surface is not relevant. The more comparable scenario in CRP1234, which involves the occupant investigating in the engine compartment and being exposed there to the refrigerant ignition, had a value of 9×10^{-15} and as part of that scenario assumed a very low likelihood (10^{-4}) of the occupant being willing or able to investigate inside the engine compartment after a collision. Because the probability of a passenger remaining in the vehicle without being aided is several orders of magnitude higher than the probability of the occupant investigating, it is not surprising that the risks calculated in the present analysis are higher. Nonetheless, as shown in Table 5.1, the overall conclusions of the former CRP1234 risk assessment are still valid: risks are still very small compared to the risks of a vehicle fire from all causes and well below risks that are commonly viewed as acceptable by the public.

Table 5.1 Probabilities of Various Adverse Events Compared to Estimated Probabilities of Events Associated with Vehicle Operation-Related Leaks of R-1234yf

Event	Probability per vehicle per operating hour*	Citation
Probability of being in a police reported vehicle collision[1]	4×10^{-5}	NHTSA, 2013
Probability of automotive vehicle fire (any cause)[2]	1×10^{-6}	Ahrens, 2013; FHA, 2009
Probability of vehicle collision due to vehicle brake failure[3]	3×10^{-7}	New York State DMV, 2008
Probability of dying during a regularly scheduled plane trip in a developed nation[4]	7×10^{-8}	Barnett, 2010
Estimated probability of vehicle occupant/former occupant experiencing HF exposure above health based limits associated with an R-1234yf ignition event	5×10^{-12}	CRP1234, 2009
Estimated probability of vehicle occupant being exposed to a vehicle fire due to R-1234yf ignition (due to leak and ignition in engine compartment)	3×10^{-12}	Current analysis
Estimated probability of vehicle occupant being exposed to an open flame due to R-1234yf ignition (primarily due to leak and ignition in cabin)	9×10^{-14}	CRP1234, 2009

[1] There were 5,338,000 police reported vehicle collisions in the U.S. in 2011. This is divided by the number of registered vehicles in that year (257,120,000) and the average number of hours each vehicle is operated (approximately 500 hours based on SAE J2766, Table 6).

[2] Ahrens reports that there were an average of 152,300 vehicle fires per year in the U.S. from 2006 to 2010. This is divided by the size of the US vehicle fleet in 2008 as a midpoint (247 million vehicles, FHA, 2009) and the average number of hours a vehicle is operated per year (approximately 500 hours based on SAE J2766, Table 6).

[3] The New York State Department of Motor Vehicles reports 1753 accidents in 2008 attributed to brake failure (NYSDMV, 2008) and roughly 11 million registered vehicles in New York State in 2008. Combining these data with the "operating hours per year" suggested in J2766 (~500 as an average) yields the an accident frequency per vehicle operating hour.

[4] Includes both commercial jet and propeller aircraft flights. Risks in developing or underdeveloped nations are higher.

6 Sensitivity Analysis

In order to better understand the impact of some key assumptions on the results of the FTA, the CRP1234-4 members conducted a sensitivity analysis. Parameters that were felt to be uncertain were changed to other plausible values and the resulting frequency of the top event (*i.e.*, exposure to a vehicle fire) was then compared to the value obtained using the original assumption. The results of the sensitivity analysis are summarized in Table 6.1. The parameters evaluated in the sensitivity analysis of the R-1234yf fault trees consisted of the following:

- <u>Probability the hot surface reaches 700°C</u>. As noted above, the CRP members decided to conservatively use 700°C as the temperature needed to ignite a mixture of R-1234yf and oil. Based on OEM studies concerning the frequency of specific vehicle operating temperatures, the CRP decided to use a value of 0.01 to represent the probability that vehicles had hot surfaces at or above 700°C (*i.e.*, that as an average over the global vehicle fleet and across all vehicle operating times, vehicles might reach or exceed 700°C one percent of the time). OEM discussions revealed however, that there was substantial variation among OEMs concerning fleet operating temperatures. It was noted that much of the variation was due to uncertainty of converting OEM vehicle test data to actual customer usage profiles. In general, smaller turbocharged vehicles tend to operate at higher average and extreme temperatures while many engines and especially diesel engines typically operate at lower average and extreme temperatures. One OEM conducted an analysis of customer use profiles on three different types of vehicles and evaluated the probability of achieving underhood temperatures exceeding 700°C for the 50th and 90th percentile customer. The results varied considerably by vehicle type with the 50th percentile customer exceeding 700°C approximately 0.03% of the time in a mid-size diesel turbo van to 3.1% of the time in a small turbocharged gas powered crossover vehicle. Even in the latter vehicle type which is considered the worst case vehicle for this OEM, the 90th percentile customer only exceeded 700°C 5.7% of the time despite operating the vehicle under extreme conditions. These data are summarized in Attachment K. To assess this variability, the probability was increased in the FTA from 1% to 3% to the extreme of 10%. These changes increased the frequency of the top event in both fault tree I6 and I7 and the increase was linear resulting in up to an order of magnitude change.
- <u>Direction of refrigerant release</u>. The OEMs were uncertain about the impact the direction of the refrigerant release relative to the hot surface has on the ignition potential. It is clear that releases pointing directly away from the hot surface (*i.e.*, out the front of the vehicle) would have a substantially reduced probability of producing refrigerant ignition (Figure 6.1). The extent to which releases to the side or up or down would reduce the refrigerant concentration near the hot surface is less clear. To assess this uncertainty, the base value for the high severity case (0.5) was increased to 0.75. Alternatively, the base value for the mid severity case (0.75) was decreased to 0.5 (the mid severity case has a higher base probability because a high severity collision is more likely to buckle the hood and allow the refrigerant to move upwards rather than laterally). Neither change had an appreciable impact on the risk of the top event (*i.e.*, the risk of the top event did not change).

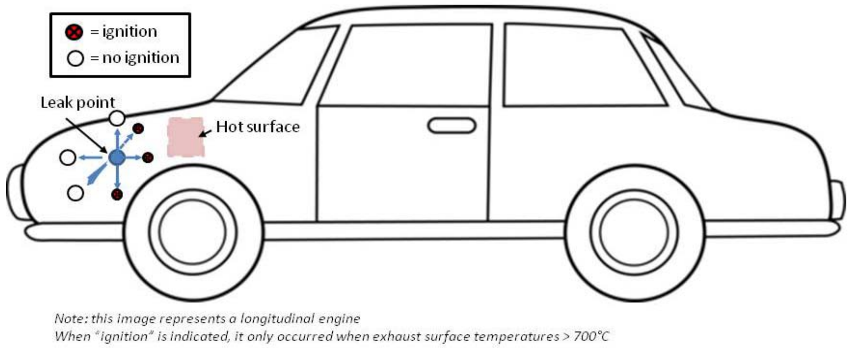

Figure 6.1 Effect of Release Orientation on Ignition Potential

- Inclusion of nonstagnant zone. As noted above, the CRP members did not believe they had sufficient data to support including the distinction between a stagnant and non-stagnant zone in the base case FTA and thus they assumed that a stagnant zone could be present in all vehicles. However, testing by CRP members has suggested that stagnant zones are only likely with specific vehicle conditions relating to air flow, heat shields, and under hood configuration. To better understand how this idea affects the FTA result, the fault trees were modified to include stagnant and non-stagnant zone branches with respect to the hot surface. It was assumed that 20% of vehicles are configured in such a way that a stagnant zone is possible and that in such cases, a temperature of 700°C is sufficient to ignite the refrigerant. However, in the 80% of vehicles without such configurations, a hot surface temperature of 750°C would be required to ignite the refrigerant (this value is consistent with prior testing done at INERIS and Hughes as well as newer OEM data). It was assumed that vehicles reach this temperature only 0.1% of the time. For the non-stagnant case it was also assumed that only 10% of the time was the refrigerant release velocity low enough to enable refrigerant ignition (this was a critical finding from the OEM studies and also supported by the literature, *e.g.*, API, 2003). The result of this analysis was a 65% decrease in the risk of exposure to a vehicle fire.

- Combustible solids located where they could be exposed to ignited refrigerant. In the base case analysis, the OEMs assumed that combustible solids (*e.g.*, plastic or rubber parts) would nearly always be located close enough to the ignited refrigerant in order for propagation to occur (0.99). However, it is possible that OEMs could redesign their vehicles to eliminate or substantially reduce this possibility (*e.g.*, by switching to more fire resistant materials). To explore the potential impact of such a change, the probability of this value was reduced from 0.99 to 0.5 or to 0.1. These changes have a minimal impact on the risk of the top event because propagation due to release of flammable fluids is a sufficient contributor in the high severity cases so that a change concerning combustible solids does not have a major effect on the overall risk. Note however, that the risk of a vehicle fire (irrespective of whether an individual is present) is reduced to a greater degree (by a factor of 6) because the greatest contributor the vehicle fire risk (as opposed to exposure) is the mid severity front collision where the role of flammable fluids is negligible compared to the role of combustible solids.

Table 6.1 Results of Sensitivity Analysis

Change	Estimated Risk of Exposure to Vehicle Fire	Impact
Base Case	3E-12	
Increase prob of hot surface above 700°C from 0.01 to 0.03 (3x higher)	9E-12	Risk of top event changes linearly with the change in probability the hot surface reaches/exceeds 700°C
Increase prob of hot surface above 700°C from 0.01 to 0.1 (10x higher)	3E-11	
Direction of refrigerant release towards hot surface for high severity cases *increased* from 0.5 to 0.75	3E-12	Negligible change because the mid severity case still contributes substantially to the risk
Direction of AC release towards hot surface for mid severity cases *decreased* from 0.75 to 0.5	3E-12	Negligible change because the high severity case still contributes substantially to the risk
Inclusion of stagnant zone, non-stagnant zone temperature set at 750°C	7E-13	Modest reduction in risk (65%). The stagnant zone case becomes the risk driver but is present in limited percentage of the vehicle fleet.
Probability combustible solids are located where they can be ignited by the refrigerant decreased from 0.99 to 0.5	2E-12	Minimal reduction in risk because propagation due to release of flammable fluids contributes enough in the high severity cases to keep risks at the same order of magnitude Note that risk of vehicle fire would be changed to a greater degree [~6 times decrease] because the risk driver there is the mid severity front collision where the role of flammable fluids is minor.
Probability combustible solids are located where they can be ignited by the refrigerant decreased from 0.99 to 0.1	1E-12	

7 Conclusions

As noted in the original CRP1234 evaluation, R-1234yf is a non-ozone depleting substance with a GWP of 4. It has equivalent or lower toxicity compared to R-134a in terms of both acute human health effects and ecological effects. HFO-1234yf is flammable, but extensive testing has indicated that the ignition potential of this chemical is far less than that of other flammable refrigerants (*e.g.,* R-152a). The risk assessment conducted by the prior CRP indicated that use of R-1234yf in automotive vehicles would involve an acceptable level of risk. For example, the FTA indicated that the risk of an occupant (or former occupant) being exposed to an open flame due to R-1234yf ignition would be extremely low, on the order of 9 x 10^{-14} events per hour of vehicle operation. The analysis indicated that the risk of an individual being exposed to HF above the relevant health-based limit was also extremely low, on the order of 5 x 10^{-12} events per hour of vehicle operation. A comparative analysis showed that these risks were well below those commonly considered acceptable by the public and regulatory agencies. The risk assessment was submitted to the U.S. Environmental Protection Agency (US EPA) as part of the Significant New Alternatives Policy (SNAP) approval process, and the US EPA subsequently approved R-1234yf for use in US vehicles.

In response to a press release issued by Daimler which suggested a greater fire risk for R-1234yf than previously estimated, a new CRP was convened (CRP1234-4) to study the Daimler claims and to determined whether revision of the prior FTA was necessary. During numerous and frequent face-to-face and phone meetings, the CRP members determined that the refrigerant release testing completed by Daimler was unrealistic in that it created extreme conditions that favored ignition while ignoring many mitigating factors that would be present in an actual real-world collision. These factors include the potential dispersing effect of the engine cooling fan, the quenching effect of front end compartment deformation, the extinguishing effect of steam released due to radiator breakage, and the diversion of refrigerant through a damaged condenser to the exterior of the engine compartment. At the same time, the CRP members developed two new fault tree scenarios to realistically address the Daimler claims. They also reviewed and analyzed extensive new OEM test data which was used as input for the new FTA. The two new fault tree scenarios consider the possibility of an individual being unable to exit the vehicle after a refrigerant release (either due to a collision or a non-collision related AC system fault), the refrigerant being ignited and the refrigerant fire propagating to other vehicle components. The FTA examined average risks across the entire global fleet and used a number of conservative assumptions to ensure that the final risk estimate would be more likely to overestimate rather than underestimate actual risks. Based on the updated analysis, the estimated overall risk of vehicle fire exposure is on the same order of magnitude as that estimated in the prior work of CRP1234. Therefore, the conclusions of the former risk assessment are still valid: risks are still very small compared to the risks of a vehicle fire from all causes and well below risks that are commonly viewed as acceptable by the public.

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