

A Critical Assessment of Factors Affecting the Flammability of R-1234yf in a Frontal Collision

Bryan Styles, Jeffrey Santrock, Curtis Vincent, Michael Leffert, and Narasimha Putcha
General Motors Co.

ABSTRACT

An evaluation methodology has been developed for assessing the suitability of R-1234yf in vehicles. This relates primarily to evaluating the flammability of R-1234yf in the engine compartment during a frontal collision. This paper will discuss the process followed in the methodology, the technical rationale for this process, and the results of the analysis.

The specific types of analysis included in the methodology are: exhaust-system thermal characterization, computer simulated crash tests, actual crash tests, teardown and examination of crashed parts, and releases of refrigerant onto hot exhaust manifolds. Each type of analysis was logically ordered and combined to produce a comprehensive evaluation methodology.

This methodology has been applied and demonstrates that R-1234yf is difficult to ignite when factors that occur in frontal crashes are simultaneously considered. Factors considered in this analysis include: crush and deformation of the vehicle structure, airflow in the engine compartment, exhaust system temperatures during different driving scenarios, and coolant release due to damage of the engine coolant system. Such findings support the conclusion of the Society of Automotive Engineers Cooperative Research Team (SAE CRP1234-4) regarding R-1234yf usage: "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."

This methodology can provide a representative and more realistic assessment of the suitability of R-1234yf in automotive air-conditioning systems. The evaluation methodology can be applied to any vehicle.

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INTRODUCTION

The automotive sector has applied significant efforts in the quest to find a refrigerant that can satisfy customer demands and environmental concerns in a way that is safe, efficient, and affordable. In the 1990s, the industry underwent the transformation from CFC12 to R-134a to minimize the ozone-depleting impact of direct refrigerant emissions. Currently, the industry is in the midst of moving from R-134a to R-1234yf to minimize the global warming impact of these same emissions. In both cases, the change was motivated by regulatory action.

The current action is the direct result of the European Union F-gas Regulation [1] which prohibits the use of any refrigerant in automotive systems that has a Global Warming Potential (GWP) > 150. The current refrigerant, R-134a, has a GWP of 1430 [2] and therefore, does not meet the requirement of the F-Gas Regulation. The Mobile Air Conditioning (MAC) sector underwent a period of collaborative investigation in an attempt to identify an acceptable alternative. This collaboration included an extensive risk assessment that was performed by a Society of Automotive Engineering (SAE) Cooperative

Research Project (CRP) known as CRP1234. The refrigerant being assessed was R-1234yf, which has a GWP of 4 [3] - thus meeting the GWP < 150 requirement. Two of the main factors considered in the risk assessment were the risk of refrigerant ignition and the risk of exposure to hydrogen fluoride (HF). This team was comprised of global automakers from Asia, North America, and Europe.

In December, 2009, the CRP members unanimously concluded that R-1234yf is suitable for use in automotive applications [4]. Subsequently, the United States Environmental Protection Agency (US EPA) approved the use of R-1234yf, subject to use conditions, in automotive applications within the US through the Significant New Alternatives Policy (SNAP) in March, 2011 [5] and is also registered under the EU chemical regulation REACH (Registration, Evaluation, Authorization, and restriction of Chemicals)[6].

In addition to the collaborative efforts through SAE, various automakers have independently published research that arrives at the same conclusion regarding the suitability of

R-1234yf as an automotive refrigerant. In 2009, Fiat published their findings concluding that R-1234yf showed no additional risk to professionals and customers during the whole life cycle of the refrigerant [7]. Similarly, Ford concluded that the use of R-1234yf as refrigerant did not increase the risk of fire when compared to vehicle using R-134A as refrigerant [8]. The SAE CRP1234-4 team performed an additional assessment on the automotive usage of R-1234yf, finishing in 2013, and concluded "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." [9]

General Motors has also conducted research to assess the flammability of R-1234yf in MAC applications and has developed an evaluation methodology related to the flammability of R-1234yf. The methodology specifically addresses the question of whether or not the conditions that affect the potential for ignition of R-1234yf and propagation of flame by R-1234yf exist in the engine compartment during a frontal collision. This paper will outline the steps involved in the development of this methodology and present representative results obtained from its implementation.

STATE OF THE ART

There are four primary factors typically identified when discussing fire: oxygen, heat, fuel, and uninhibited free radical chain reactions. More specifically, a flammable gas will ignite and lead to sustained combustion only when sufficient oxygen is present, the concentration of the fuel is within the flammable range, sufficient energy is input to the fuel / air mixture to initiate a rapid, self-sustaining, exothermic oxidation of the fuel that emits heat and light, and nothing is present that inhibits the free radical chain reactions occurring in the flame. [Figure 1](#) shows this interaction as a Venn Diagram rather than the more traditional Fire Tetrahedron to emphasize that these factors must occur at the same time and location to result in fire.

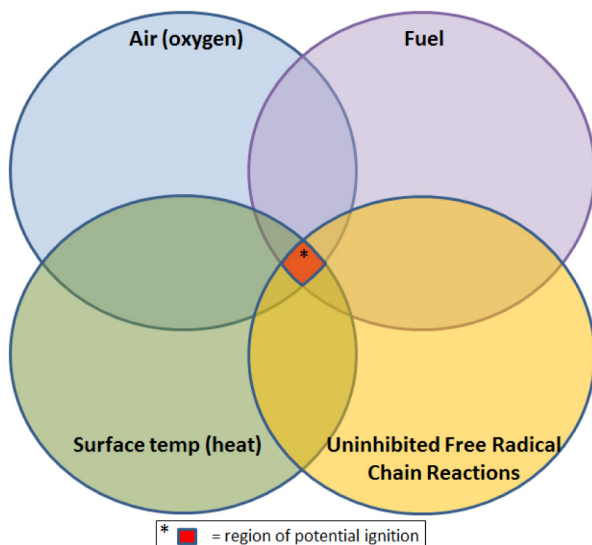


Figure 1. Fire tetrahedron related to R-1234yf implementation in vehicle under hood environment

Flammable Range

Substances that are flammable have a range of flammability generally defined by concentrations at a Lower Flammability Limit (LFL) and an Upper Flammability Limit (UFL). The flammability limits of R-1234yf in air are somewhat uncertain. Takizawa et. al. report a flammable range of 5.8 to 13.0 vol-% for R-1234yf in dry air at 20°C, and 5.0 to 14.1 vol-% for R-1234yf at 100°C [10]. In contrast, Kondo et. al. report a flammability range of 6.85 to 12.00 vol-% for R-1234yf in dry air at 20°C and 5.80 to 12.70 vol-% at 100°C [11]. The present study used the 5.0% LFL value as the threshold for ignition and propagation of R-1234yf under hood. The LFL is expected to decrease further at temperatures > 100°C, but the temperature dependence of LFL and UFL for R-1234yf at temperature > 100°C is not well defined at the time [See discussion in [Appendix 2](#)]. The variability of the LFL may be a limitation of selecting an exact value for a flammability threshold of the refrigerant.

Ignition Source

In the event that a refrigerant concentration within the flammable region exists, an adequate heat source must be present at that same location and time. In a vehicle under hood environment, hot exhaust components are potential ignition sources of R-1234yf. Based on GM's internal testing [12] and the 3rd party testing conducted by SAE, surface temperatures $\geq 700^\circ\text{C}$ are required for ignition of R-1234yf and compressor oil in air [13]. Given that the reported auto-ignition temperature (AIT) of R-1234yf is 405°C [14], some have suggested that 405°C is a more appropriate temperature threshold to use in evaluation of fire risk. It is well known that exhaust system temperatures required for ignition of combustible fluids in motor vehicle are several hundred degrees higher than autoignition temperatures determined by standard laboratory tests [15]. The American Petroleum Institute (API) conducted a series of open-air tests where hydrocarbon/air mixtures were released onto hot surfaces and found that the hot-surface temperature required for ignition was typically 300°C higher than the published AIT [16]. The API study concluded that "AITs under one set of conditions may be changed substantially by different conditions" [16]. This conclusion is consistent with numerous studies of surface ignition of gasoline that showed threshold surface temperatures between 250 and 500°C higher than reported autoignition temperatures for gasoline [17]. These studies indicate that the threshold temperature for hot surface ignition of R-1234yf in a motor vehicle is likely several hundred degrees higher than the reported autoignition temperature of 405°C , consistent with threshold $> 700^\circ\text{C}$ reported by INERIS [13].

Other ignition sources have been considered by SAE CRP teams (electrical short of sufficient energy, hot glowing wire) but it was found that these potential sources are non-risk driving scenarios [4, 9] and do not appreciably contribute to the overall risk. As a result, consideration of these potential ignition sources was not included in this study.

Note that a pre-existing vehicle fire could also provide an ignition source for R-1234yf. However, Ford has shown that in such a scenario, "addition of the flammable R-1234yf refrigerant has a negligible effect to the propagation of a fire within a vehicle when compared to other variables that affect fire propagation." [9]. Therefore, R-1234yf does not add an incremental risk when a pre-existing vehicle fire is present. As a result, an open flame was not considered as a relevant heat source for the present investigation.

Oxygen

In addition to a flammable concentration of refrigerant and an adequate exhaust surface temperature, a sufficient amount of air is necessary to support ignition. At standard temperature and pressure, dry air contains oxygen at approximately 21 vol-%. It is reported that flame extinction for hydrocarbon gases (e.g., methane) occurs when the oxygen concentration drops below about 14 vol-% [18]. Therefore, scenarios resulting in reduced oxygen levels under hood are relevant in assessing the flammability of R-1234yf in such an environment.

Uninhibited Free Radical Chain Reactions

Finally, there must be adequate free space to support the chemical chain reaction that occurs during ignition. The presence of cold components in proximity to the ignition kernel can extract heat and quench the chemical reaction. This is especially relevant for R-1234yf due to its relatively low heat of combustion, slow laminar flame speed, and large quenching distance [11, 13].

As previously stated, if any of these four factors is not in existence at the same location and at the same time, an ignition will not occur. Therefore, an understanding of the events affecting these factors during a frontal collision is essential.

The next section will discuss events that affect exhaust surface temperature, free space, air availability, and refrigerant concentration as they relate to refrigerant ignition during a frontal collision.

METHODS

A test vehicle was selected to analyze relevant events that could occur during a frontal collision. These events were ordered as they relate to the four primary factors impacting refrigerant ignition.

The vehicle selected was a series production vehicle currently using R-1234yf. The relevant events identified are identified in the next section.

The goal of identifying each of the bulleted items was to select a crash speed that would be most likely to create conditions enabling an ignition of refrigerant. This would allow the examination of a realistic worst-case scenario.

Heat (exhaust surface temperatures)

- Vehicle thermal characterization

Uninhibited Free Radical Chain Reactions

- Quenching due to crush

Oxygen (Air)

- Coolant (steam)

Fuel

- Refrigerant present in flammable concentration
- Hood buckle
- Condenser breach
- A/C line breach
- Fan operation

The rationale for each of the bulleted items in the list will now be discussed. As a part of the rationale discussion, the methodology for addressing each of these items through testing and simulation will also be discussed.

Exhaust Surface Temperatures

As previously stated, an ignition of refrigerant will not occur if there is not an adequate source of heat. In the scenario identified herein, the heat source is the exhaust surface temperature.

Every vehicle is different and has a different characteristic behavior regarding the maximum temperature that can be achieved on the exhaust surface. For example, a current General Motors turbocharged diesel application using R-1234yf has maximum surface temperatures < 550°C. This is far below the threshold temperature for hot surface ignition of 700°C as observed in an accompanying study [13]. Therefore, regardless of the concentration of refrigerant in air, low exhaust temperatures in most or all diesel applications would not result in ignition of R-1234yf. Similarly, the test vehicle was thermally characterized to understand the maximum temperature expected during the usage of the vehicle. The test vehicle uses a 3.6L naturally aspirated engine. The exhaust system on the test vehicle was instrumented in more than 20 locations on the front and rear exhaust surfaces with intrinsic thermocouples. A picture of the front takedown is shown for illustration purposes in Figure 2. The rear exhaust takedown was similarly instrumented.

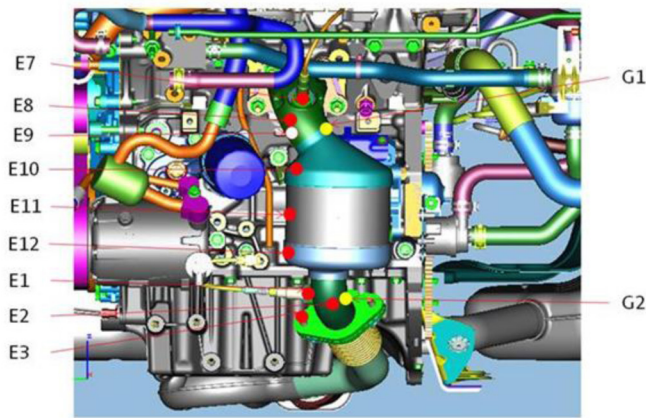


Figure 2. Front exhaust takedown of test vehicle showing instrumentation locations

The vehicle was then driven on a dynamometer at various usage conditions representing continuous, excursion, and extreme customer driving. The continuous driving condition is representative of typical highway, city traffic, idle, and vehicle soaking. As such, it represents the vast majority of driving conditions that a customer will subject the vehicle to. This is well supported by customer usage studies that General Motors has conducted, as well as a recent study by the US EPA [19]. The excursion driving condition corresponds to a customer driving up a steep hill with the maximum allowed weight inside the vehicle at a very high speed. Based on available information, this is deemed to represent < 1% of usage during the vehicle's lifetime. Finally, extreme driving represents driving the vehicle up a steep hill, towing a trailer, and driving the vehicle in a way that is beyond the design capabilities of the vehicle for continuous operation (towing a trailer in Death Valley would be an extreme condition, for example). This type of condition is beyond the design intent of the vehicle, represents an abuse condition, and thus would be a rare event. Based on the data from this thermal characterization, an assessment can be made on whether or not critical temperatures exist in the under hood compartment.

Crush

Crush that occurs in a frontal or front off-set crash results in displacement of objects in the crush zone, thus reducing unobstructed space in the engine compartment. Figure 3 is a top view of the engine and the Condenser, Radiator, Fan Module (CRFM) in the test vehicle. The refrigerant condenser (orange) is the most forward component in the CRFM, followed by the radiator (purple color), then the fan module (red). These components are displaced as a unit into the space between the CRFM and the engine in a frontal or front off-set crash. In a crash of sufficient intensity, the CRFM will be pushed against the front of the engine (see Crash Simulation Tool discussion), resulting in objects with high surface-to-mass ratios and relatively cooler temperatures in the flow path of gas released from a damaged refrigerant system around the exhaust system.

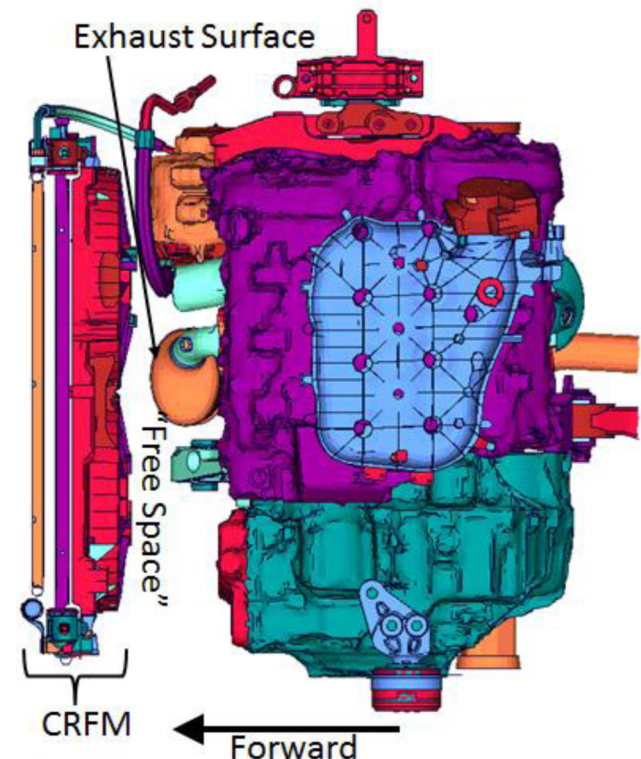


Figure 3. Top view of test vehicle engine showing free space available

Thus, displacement of the CRFM rearward against the front of the engine and exhaust system would be expected to reduce both the probabilities of ignition of R-1234yf by exhaust system components and flame propagation from the ignition zone should an ignition kernel form. In the analysis presented here, a complete collapse of free space in front of the engine was deemed necessary to provide a critical level of quenching in the region of the hot surface. This was assessed through crash simulation tools used as a part of vehicle development (see discussion).

Coolant Release

Most vehicle manufacturers specify a 1:1 (vol:vol) mixture of clean water and an ethylene glycol-based antifreeze, which is generally > 85% 1,2-ethanediol (ethylene glycol) as engine coolant. In a pressurized coolant system, the coolant can exist as a subcooled or superheated liquid, depending on ambient temperature and driving conditions. Normal load driving conditions would be expected to result in coolant temperatures less than the boiling point at ambient pressure (subcooled liquid). Prolonged high speed driving, high load conditions (such as prolonged driving up a grade or trailer towing), and aggressive start / stop driving would be expected to result in coolant temperatures to exceed the boiling point at ambient pressure (superheated liquid). Figure 4 shows plots of the bubble point temperatures of an ethylene glycol-water mixture at 100, 110, 120, 130, and 140 kPa versus mixture composition in vol-% ethylene glycol (left ordinate). The vapor pressure of the mixture was determined from saturation vapor pressures for water and ethylene glycol [24] assuming ideal mixture and ideal gas behavior (Raoult's Law). The liquid composition in mole fraction is shown on the right ordinate for reference.

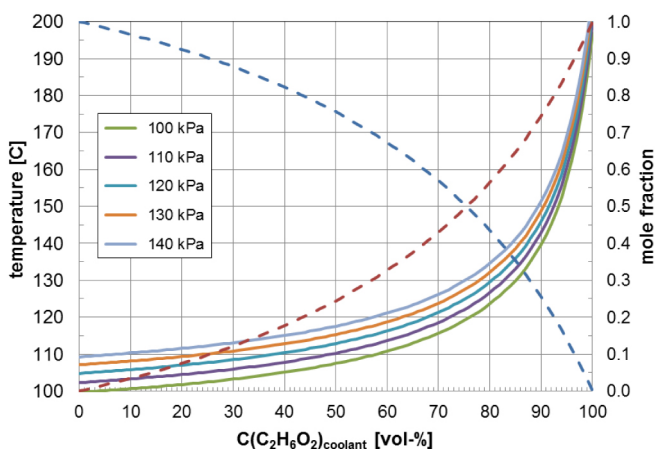


Figure 4. Plots of bubble point temperature versus coolant composition in vol-% ethylene glycol for coolant at 100, 110, 120, 130, and 140 kPa. Plots of mole fraction water (----) and mole fraction ethylene glycol (— · —) are shown for reference.

In frontal or front-offset crash during driving conditions that result in superheated coolant, damage to the coolant system results in flashing two-phase flow where some of the superheated liquid vaporizes rapidly as a result of pressure drop as it discharges from the pressurized coolant system. Because of the rapid pressure drop, vaporization and vapor expansion is an adiabatic process that results in flashing flow out of the coolant system. Figure 4 shows that coolant (1:1 (vol:vol) mixture of ethylene glycol and water) released from a pressurized system at $P = 140$ kPa and $t = 117^\circ\text{C}$ to standard atmospheric pressure ($P = 101.325$ kPa) would boil at $t = 107.9^\circ\text{C}$. Thus, the effluent from the coolant system initially is pure coolant vapor. If the fully expanded vapor and liquid are in equilibrium, the composition of the vapor is a function of temperature. Figure 5 shows plots of the gas-phase concentrations of nitrogen, oxygen, water, and ethylene glycol for coolant vapor and liquid in equilibrium in air at atmospheric pressure.

At $t = 107.9^\circ\text{C}$, the vapor effluent from the coolant system is approximately 99.4% H_2O and 0.6% $\text{C}_2\text{H}_6\text{O}_2$. As the fully expanded coolant vapor mixes with surrounding air, it is diluted and cooled, resulting in condensation of some vapor to form a fine aerosol mist (visible steam) that is in equilibrium with coolant vapor in the surrounding air. Figure 5 shows the composition of the vapor phase as a function of equilibrium temperature. For example, the composition of the vapor phase is approximately 55.5% N_2 , 28.7% H_2O , 15.0% O_2 , 0.7% Ar (not shown), and < 0.1% $\text{C}_2\text{H}_6\text{O}_2$ when coolant liquid and vapor in air are in equilibrium at $t = 75^\circ\text{C}$ (Fig. 6). When coolant is released from a damaged coolant system into the engine compartment during a crash, water vapor and liquid in the form of a fine aerosol mist in the combustion reaction zone dilute the reaction mixture and quenches the reaction. See Appendix 2 for a more detailed discussion of these effects.

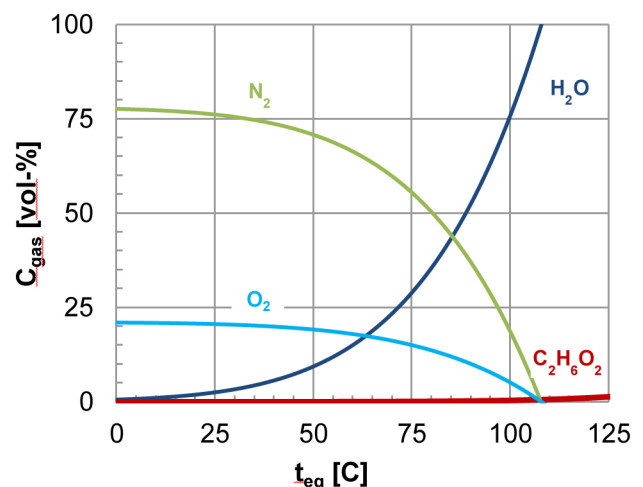


Figure 5. Plots of vapor phase concentrations (vol-%) of nitrogen (—), oxygen (—), water (—), and ethylene glycol (—) for coolant liquid and vapor in air at 75°C .

Refrigerant Release

The presence of refrigerant, in the correct concentration, is the fourth primary factor that is required to enable an ignition. There were four events considered that may occur in a collision: hood buckle, condenser breach, fan operation, and A/C line breach. All four of these events play a significant role in affecting refrigerant concentrations under hood.

The hood is designed to buckle during a collision. This is an intentional feature designed to minimize hood intrusion into the windshield in frontal and front-offset crashes. When the hood buckles, an opening of the engine compartment is created. When this occurs, a pathway is created whereby refrigerant can flow out of the free space region of the engine compartment. This will result in a reduction of the refrigerant concentration residing in proximity to the potentially hot exhaust surface.

Condenser breach is another significant event that impacts refrigerant concentration in the free space. Since the condenser is at the front of the vehicle, it will be one of the first

components impacted during a collision. The expected behavior, in such a scenario, is that the condenser would be breached on the front side of the heat exchanger and release refrigerant outboard and away from the under hood free space. Therefore, while a condenser breach would release refrigerant, it was hypothesized that such a breach may not result in critical concentrations under hood. Despite the hypothesis, it was conservatively assumed that a breach of the condenser may tend to enable ignition due to refrigerant being released from the system. This assumption seemed reasonable given that release behavior was not yet confirmed.

Fan operation plays a significant role in forcing air circulation under hood. It is possible that the fan may continue to operate post-collision if it is not physically damaged by the event. If a breach occurred while the fan was operating, it is expected that refrigerant concentrations will be kept below the LFL. This has been observed to be true during other testing that will be later published.

An A/C line breach is also a relevant event. The A/C lines are located under hood and a breach of an A/C line would most likely result in an increased concentration of refrigerant in the free space under hood. It is not clear how much a line breach would increase concentration under hood especially when considering that a condenser breach would almost always accompany a breach of an A/C line. This is due to the fact that a collision severe enough to breach an A/C line will almost always breach the condenser first. As a result, refrigerant would leak from both the condenser and the A/C line - likely meaning that refrigerant would actively be leaking away from the vehicle and into the free space under hood simultaneously.

Collision Simulation Tool

This section will describe how the events relating to free space, air, and refrigerant were assessed using computer simulations of collision events. As previously mentioned, this analysis is specifically for frontal crash scenarios. Other crash and non-crash configurations were considered by SAE [9] and it was determined that the mid-severity frontal collision presented a potentially higher risk than other crash scenarios considered. These simulations were conducted at 5 kph increments between the speeds of 20kph - 55kph. This speed range was selected so that adequate bookends could be established for the behavior of the vehicle. The two bookends were as follows:

1. Low speed bookend: Minimum speed at which condenser breaches and refrigerant is released. This is necessary to assess the behavior of refrigerant release during a representative collision scenario.
2. High speed bookend: Maximum speed where free space region (Figure 3) is not completely collapsed. Speeds higher than this bookend were deemed not relevant since quenching effects would tend to not support refrigerant ignition and propagation. Additionally, the presence of

deformed parts would tend to physically prevent the flow of refrigerant to that region. Evidence supporting these hypotheses is discussed later in the report.

The collision scenarios were simulated using a 40% offset deformable barrier on the passenger side (Fig. 6).

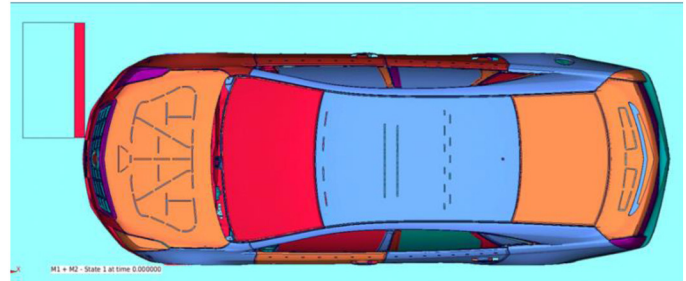


Figure 6. Collision configuration selected for test vehicle

This configuration was selected to maximize the likelihood of breaching the A/C system while minimizing the likelihood of completely collapsing the free space under hood. As can be seen from Figure 3, the A/C lines connecting to the condenser are on the passenger side. Therefore, placing the barrier on the passenger side was deemed as more likely to create a breach in the A/C system than a 0% offset test.

Each of the events from previously identified were placed in a table and individually assessed, at each 5kph increment, to determine if its behavior in that scenario tended to enable ignition or not. As the simulated collision speed increased, the energy associated with the collision also increased. This resulted in further intrusion into the engine compartment at higher speeds. At each collision speed, the strain on each of the identified components was analyzed to determine the likelihood of a breach/failure in that component. At the time of max intrusion, the simulation was paused and each component was individually examined to determine the level of strain associated with that configuration.

For example, aluminum components were analyzed using a threshold strain of 30%. This means that a breach was assumed if any part of the component (i.e. condenser, aluminum refrigerant lines) demonstrated a strain of greater than 30%. Given that the refrigerant is a gas at atmospheric pressure, it was assumed that any leak will allow complete venting of the refrigerant. Plastic components (e.g. end-tank of radiator) were assessed using a threshold strain of 5%. The ductility of the plastic components is much lower than those constructed of aluminum and they demonstrate failure at lower levels of strain. These values were based on validation of simulation results by comparison to crash tests.

During the simulation, fan operation was assessed by identifying if any parts physically intruded into the rotational plane of the fan. In the absence of interference from other parts, the fan blades were examined for any evidence of

breakage or deflection. If there was physical intrusion of other parts, breakage, or any deflection of the fan blades, it was assumed that the fan would be rendered inoperative as a result of the collision.

Hood buckling could also be visually assessed using the simulation tool. The determination of the presence or absence of hood buckling was made after vehicle rebound when the vehicle came to rest. The presence of hood buckling was marked affirmative if the hood remained buckled after the event and a pathway to the underhood could be observed in the buckled portion.

Finally, a determination was made regarding the amount of free space remaining near the exhaust surface. It was assumed that cooler parts would have to physically intrude into the space immediately around the exhaust surface to increase the probability that quenching will occur. If parts did not physically impinge on the exhaust surface, then it was assumed that the probability of quenching would be low.

In areas where a clear determination could not be made, a marginal rating was assigned to that aspect of the simulation.

An example of some of the simulation results is shown in Table 1. It should be noted that the results shown in Table 1 are specific to the test vehicle described herein. Differences in under hood configurations and vehicle design can result in a different collision characteristic than that shown in Table 1. Each simulation result was analyzed at numerous angles in an attempt to assess each event thoroughly. The final result of this analysis is shown in Table 1.

Table 1. Collision simulation summary for test vehicle

Metrics	20kph	25kph	30kph	35kph	40kph	45kph	50kph	55kph
Condenser breach								
Passenger fan broken								
Driver fan broken								
Compressor plumbing								
Hood buckling								
Air Space near exhaust surface								

Does not tend to enable ignition
 Marginal
 Tends to enable ignition

Table 1 visually combines all of the relevant events that related to the presence of air and refrigerant in the free space region under hood. Each of the events was characterized, at each simulation speed, to assess whether or not its behavior would tend to enable ignition. A collision speed could then be selected to represent a realistic worst-case scenario.

An attempt was then made to select a crash speed between the low and high speed bookends previously identified. This selection would result in a breach of the air conditioning system, but still leave air gaps near the exhaust surface. Based on the summarized data, it was determined that this behavior

would likely be observed at a collision speed between 40kph and 45kph. A collision speed of 42.5kph was selected for this vehicle.

Other vehicles may exhibit behavior that would support the use of a higher/lower test speed. However, this would need to be determined after conducting a simulation for that particular vehicle. For example, a longitudinal configuration, with a side exhaust takedown, may show that a higher speed is necessary to fully collapse the free space region around the exhaust surface.

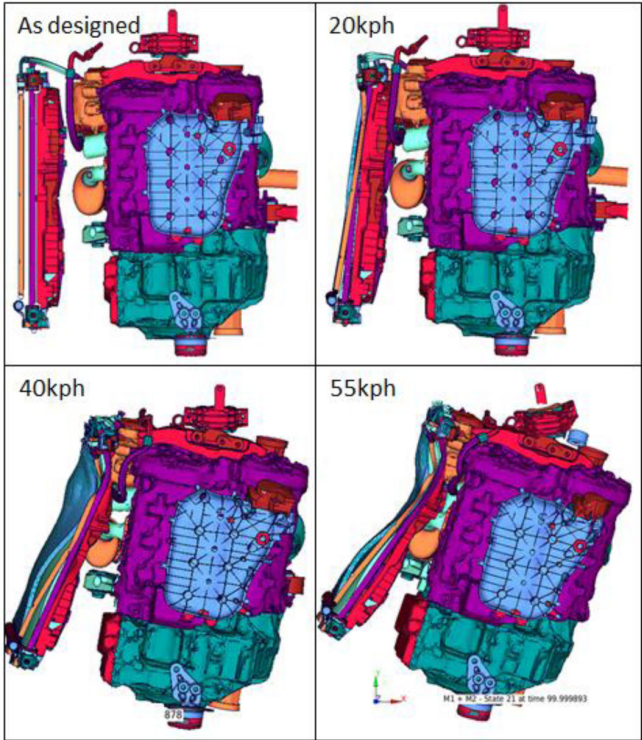


Figure 7. Simulation results for test vehicle at various speeds

Crash Test Methodology

This section will now outline the methodology employed in conducting the crash test with the test vehicle.

The goal in conducting the vehicle crash test was to understand the behavior of the release of R-1234yf during a representative crash scenario. Numerous collision-related events were identified that affect the air and refrigerant portions of the fire tetrahedron. This crash test allows for simultaneous examination of these events.

Three methods were employed in gaining an understanding of R-1234yf behavior during a crash scenario:

1. Observe refrigerant dye witness pathway post-crash
2. Measure refrigerant concentration in under hood free space during/after crash event.
3. Measure pressure bleed-down of refrigerant gas out of the system

The test vehicle is produced with a refrigerant dye in the A/C system for the purpose of diagnosing leaks. When exposed to ultraviolet (UV) light, the dye is clearly visible and identifies any location where refrigerant has leaked from the system. An additional bottle (0.5oz) of refrigerant dye was added to the test vehicle A/C system to ensure easy identification of leak points post-crash.

Refrigerant concentration meters (manufacturer: Henze-Hauck Gas Sensor) were used to measure how much refrigerant was present near the exhaust surface post-crash. The proper placement for the sampling tubes was determined by performing a thermal characterization of the test vehicle's exhaust system (as described earlier), identifying the hottest location of the exhaust, and measuring concentration in that region. The placement of the sampling tubes is shown in [Figure 8](#).

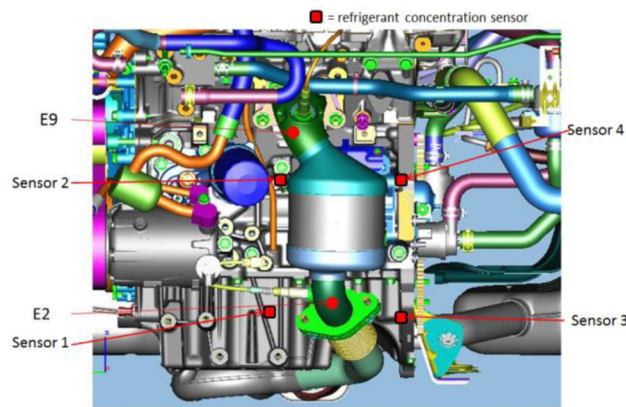


Figure 8. Location of refrigerant sampling tubes under hood

The two locations exhibiting the highest temperatures were locations E9 and E2 shown in [Figure 8](#). As a result, four continuous concentration measurements were positioned so that refrigerant amount in this area, post-crash, could be quantified.

Pressure transducers were added on the high-side and low-side of the system to enable real-time monitoring of refrigerant pressure for the duration of the crash test. Each pressure port was placed outside the crush zone to avoid the introduction of artificial leak points post-crash.

A production amount of R-1234yf refrigerant was added to the system (620grams) plus an additional 25 grams to account for pressure transducer instrumentation. This resulted in a total of 645 grams of R-1234yf. Similarly, a production amount of compressor oil was added to the system (150g). The intention was to have a representative A/C system during the collision so that any behaviors observed post-crash would correlate to real life. All other fluids were drained from the vehicle so that there was no interference created when attempting to measure refrigerant concentration with the sensors. A small volume of gasoline was added back into the vehicle so that the engine could be operated for 2-3 minutes prior to being towed into the barrier.

Once at the barrier facility, the vehicle and barrier were configured properly for the scenario identified through CAE. Just prior to towing the vehicle into the barrier, the engine was started and the A/C system was turned on so that the compressor could circulate refrigerant through the system. This created a representative scenario in the A/C system regarding refrigerant temperatures and pressures just prior to the crash event. The ignition remained on for the duration of the test.

Once the A/C system had stabilized, the vehicle tow began and the car was towed into the barrier at 42.5kph.

The goal of this testing was to understand the behavior of the release of R-1234yf during a representative crash scenario. At the point of collision, the exhaust surface temperature was 220°C. While not at maximum temperature, the exhaust surface was well above ambient temperature during this event.

RESULTS & DISCUSSION

Each of the bulleted items identified were evaluated using the methodology described herein. The item relating to exhaust surface temperature was evaluated using thermal characterization. The items related to free space, air, and refrigerant were evaluated through the crash test.

Exhaust Surface Temperature

The results from the thermal characterization testing are shown in [Figure 9](#). The maximum temperatures from the profiles were extracted from the plots and are summarized in [Table 2](#).

Table 2. Maximum exhaust surface temperatures identified on test vehicle during thermal characterization

E9 - Front Takedown Pipe Surface

Peak Temperatures

Continuous Conditions: 580 °C

Excursion Conditions: 645 °C

Extreme Conditions: 705 °C

Average Temperatures

Continuous Conditions: 407 °C

Excursion Conditions: 572 °C

Extreme Conditions: 652 °C

The data shown in [Figure 9](#) and summarized in [Table 2](#) illustrate that the exhaust surface temperatures never exceed the temperature threshold during normal and excursion driving conditions. It is only during extreme driving conditions that the maximum exhaust surface temperature barely peaks over the identified temperature threshold. However, given the fact that the extreme condition is representative of using the vehicle beyond its design capabilities, it was concluded that the test vehicle will not exceed the temperature threshold during its lifetime. Therefore, regardless of the free space, air, and refrigerant conditions existing under hood, the test vehicle will never experience conditions enabling refrigerant release initiated by hot exhaust surfaces. This was a key input into the