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Safety Evaluation of the FuelMaker Home Refueling Concept

Final Report

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Executive Summary

Natural gas is a domestically available alternative fuel. The U.S. Department of Energy supports research and development on infrastructure for natural gas vehicles to help the United States reach its goal of reducing dependence on imported petroleum. Another benefit of natural gas vehicles is that they can reduce emissions of regulated pollutants compared with diesel vehicles. The U.S. Department of Energy supported the work described in this report through its National Renewable Energy Laboratory.

A safety evaluation of the FuelMaker home refueling appliance (HRA) was carried out. The HRA enables compressed natural gas (CNG) vehicles to be refueled inside residential garages. It is installed on the garage wall, it is connected to standard residential natural gas and electric service, and most of its functions are automated to provide time-fill (e.g., overnight) refueling of a CNG vehicle parked in the garage. The FuelMaker HRA is also referred to as "Phill."

The HRA safety evaluation employed standard risk-assessment tools. A process similar to a failure modes and effects analysis (FMEA) was employed to define incident or event scenarios that might lead to circumstances with safety implications. The following categories of HRA incident scenarios were considered:

- Equipment failure (e.g., HRA gas leaks)
- Human errors (e.g., driving out of the garage with the refueling nozzle connected to the vehicle)
- Misuse (e.g., trying to use the HRA to inflate a swimming pool float)
- Maliciousness (e.g., disgruntled neighbor shuts off HRA gas supply)
- External events (e.g., vehicle strikes HRA)

The HRA incident scenarios were used to construct fault trees, and fault tree analysis (FTA) was applied to quantify frequencies of top events such as gas releases. FTA is a standard procedure for graphically representing all the initiating and contributing events that combine to result in a top event. The fault tree branches represent the alternative pathways to that top event. The frequencies and probabilities of all initiating and contributing events were estimated from existing databases, analyses specific to this evaluation, and engineering judgment.

Event tree analysis (ETA) was employed to predict the frequencies of possible consequences of fault tree top events. The primary consequences of concern involve the ignition of a flammable gas-air mixture. For example, if a gas leak were immediately ignited to produce a standing flame, the flame might impinge on a flammable material and result in a structure fire. Or, if leaking gas accumulated to produce a flammable mixture region, and if the mixture were ignited (e.g., by an electric garage door opener), what is termed a "deflagration" could result. A deflagration involves a rapidly moving flame front and an overpressure produced by the expanding combustion gases. The deflagration can range from a localized flash fire, causing no property damage, to an explosion, which may cause significant damage. The magnitude of the overpressure depends on the volume of the flammable gas mixture that accumulated over time.

The basic function of the ETA was to estimate the probabilities of alternative consequences associated with the fault tree top events. For each incident scenario, the frequencies of consequences, such as structure fires or deflagrations, were computed as the products of the top event frequency predicted by that scenario's FTA multiplied by the consequence probabilities predicted by that scenario's ETA.

A number of special investigations and analyses were carried out to develop a more accurate basis for estimating the quantities input to FTA and ETA. CNG vehicle refueling experience was surveyed to determine which kinds of accidents have happened in the past. CNG vehicle fuel system designs were analyzed to support estimation of the probability of leaks and blowdown gas releases from vehicles. Experience with garage-installed gas-fired water heaters was also surveyed. Thirty-three residential garages in various North American locations were surveyed to determine their design and construction characteristics. American Society of Heating and Refrigeration Engineers (ASHRAE) models were applied to estimate infiltration (air inleakage) levels, which are typically characterized as air changes per hour (ACH), from the garage measurements and local weather data. Approximate statistics such as garage volumes, construction materials, and ignition source probabilities were also estimated from the garage survey data.

Gas releases were generally characterized as leaks (typically 0.22 scfm or less, which might not automatically trigger HRA shutdown), direct discharges from the HRA (at approximately 0.67 scfm), or blowdowns (e.g., a rapid discharge of the contents of a CNG vehicle fuel tank). Calculations were carried out to compute the average (i.e., fully mixed) garage gas concentrations for various combinations of leaks, discharges, blowdowns, garage sizes, and garage infiltration or ventilation rates. Detailed computational fluid dynamics (CFD) modeling was employed to predict the time-dependent evolution of three-dimensional garage gas concentration profiles for five cases (i.e., combinations of gas release rates and locations, and infiltration and ventilation levels).

This safety evaluation was carried out in stages. Interim results were reviewed, and, in some cases, HRA design details were refined. For example, initial analyses were carried out based on the assumption that the air flow that cools the HRA compressor (which is driven by a fan inside the HRA at approximately 80 scfm) is fed from and discharged to the inside of the garage. In this situation, the air flow that affects gas concentrations in case of a leak is via infiltration (i.e., the natural wind-driven air flow through openings in the garage). Based partially on these interim results, FuelMaker refined the HRA installation instructions to ensure that the cooling air is discharged outside of the garage. Therefore, when the fan is operating (i.e., because the HRA is on or its gas detector senses a gas accumulation), 80-scfm garage ventilation results.

Eighteen fault trees and event trees characterized the previously discussed incident scenarios, which included various permutations of cooling fan operating (80-scfm ventilation) or not operating (natural infiltration). Some of the misuse scenarios were modeled to recognize that, if an owner was going to misuse the HRA, he or she would be more likely to attempt such misuse within the 1st year after installation, rather than many years later. Although most incident frequencies were characterized in terms of the total number of HRA installations (i.e., cumulative over many years), the misuse frequencies were characterized in terms of the number of HRA installations in the prior year. Figure ES-1 summarizes the predicted fire and deflagration frequencies for all incidents except the noted misuse scenarios; Figure ES-2 summarizes the predicted fire and deflagration frequencies for the misuse scenarios. The frequencies in Figure ES-1 have the units incidents per unit-year, whereas the frequencies in Figure ES-2 have the units incidents per the number of HRAs installed in the prior year.

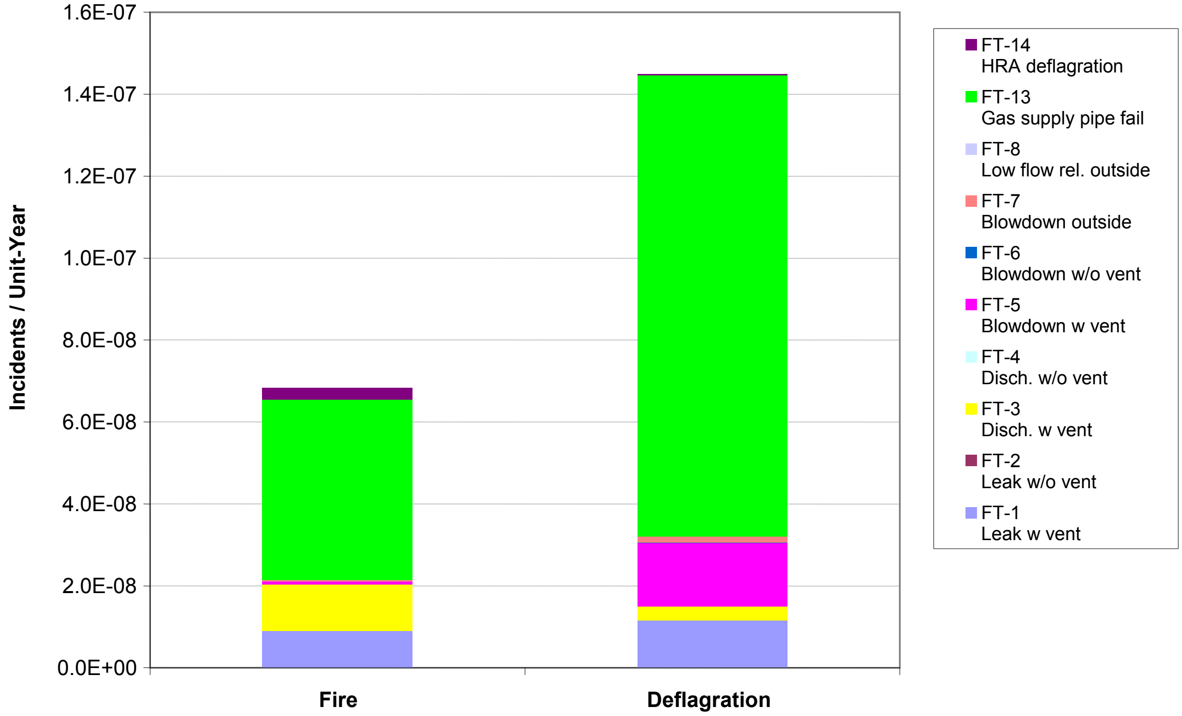

Figure ES-1. Total fire and deflagration frequencies predicted for all HRA incidents except certain misuse scenarios

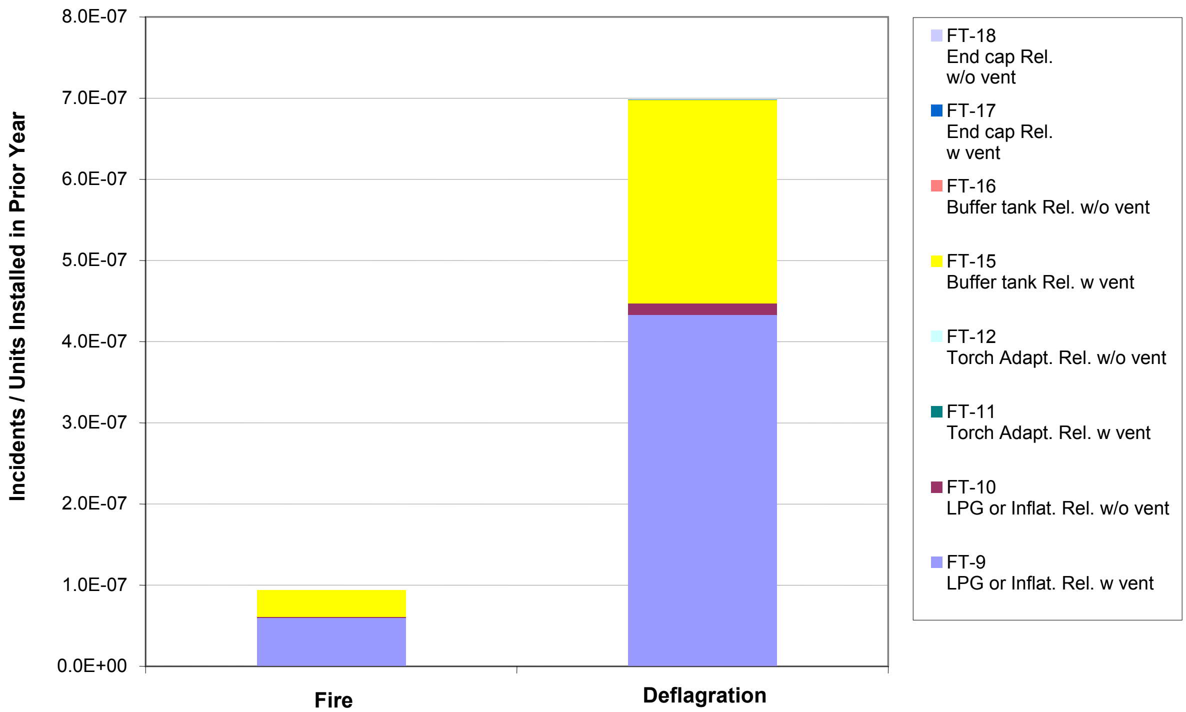

Figure ES-2. Total fire and deflagration frequencies predicted for HRA misuse scenarios

As illustrated in Figure ES-1, the safety evaluation concluded that the non-misuse failure leading to the highest probability of structure fire and deflagration was gas piping failure resulting from a vehicle striking the HRA. Other significant contributors to the predicted frequency of structure fires and deflagrations are a continuous gas leak and a full-flow gas discharge, both with the HRA cooling air fan operating normally. A vehicle tank blowdown into the garage with the cooling air fan in operation contributes significantly to the predicted frequency of deflagrations.

An HRA deflagration due to air entering the appliance contributes to the predicted frequency of structure fires. A deflagration associated with HRA use is predicted to be roughly twice as frequent as a structure fire. The total predicted frequency of a deflagration from all non-misuse causes considered in the analysis corresponds to one predicted deflagration per year after a total of about 7,000,000 HRAs have been installed. The corresponding result for structure fires is that one fire per year is predicted after a total of 14,600,000 HRAs have been installed.

As illustrated in Figure ES-2, the two misuse failures giving rise to the highest incidence of structure fires and deflagrations were attempting to fill a liquid petroleum gas (LPG or propane) bottle or inflatable item and installing a buffer tank (an auxiliary tank attached to the HRA with the intention of providing a faster fill capability). A deflagration associated with HRA misuse was predicted to be more than seven times more frequent than a structure fire. The total predicted frequency of deflagrations from all misuse causes considered in the analysis corresponds to one predicted deflagration per year if about 1,400,000 HRAs were installed in the previous year. The corresponding result for structure fires is one fire per year predicted if about 10,700,000 HRAs were installed in the previous year.

These predicted fire and deflagration frequencies can be compared to the probabilities of other hazardous or fatal events as follows. The frequencies noted above equate to the probability that a single unit installation will experience the consequence (fire or deflagration) in any year after HRA installation for the non-misuse failures or in the 1st year following installation for the misuse failures. In other words, the probability that an installed HRA will cause a deflagration due to all non-misuse failures is 1 in 7,000,000 over a year's use; the probability that an installed HRA will cause a fire due to all misuse failures is 1 in 10,700,000 in the year following installation. Table ES-1 reiterates the estimated annual HRA consequence probabilities and compares them with the annual probabilities of other hazardous or fatal events. This allows the HRA failure and consequence frequencies estimated in this study to be placed into context.

Table ES-1. Probabilities of HRA failure consequences and other hazardous or fatal events

	Probability (1 divided by the value shown per year)
HRA failure event	
Deflagration due to non-misuse failures	7,000,000
Deflagration due to misuse failures	1,400,000
Structure fire due to non-misuse failures	14,600,000
Structure fire due to misuse failures	10,700,000
Other hazardous/fatal events	
Residential structure fire	300
Residential structure fire causing injury	18,700
Residential structure fire causing death	114,000
Being injured in a vehicle crash	95
Being killed in a vehicle crash	6,800
Being struck by lightning	686,000
Being fatally struck by lightning	6,470,000
Being electrocuted by a consumer product	1,880,000

1. Introduction

1.1 Background

The FuelMaker Corporation of Toronto, Canada, is developing an appliance to refuel compressed natural gas (CNG) vehicles in residential garages. This appliance is variously referred to as a Home Fueling Appliance (HFA), a Home Refueling Appliance (HRA), or simply as “Phill.” It is planned that the HRA will be mounted inside residential garages (typically on the wall), receive gas from the utility service (similar to other residential natural gas appliances), and be operated by the homeowner who is also the CNG vehicle owner. A typical scenario will be for the owner to park his or her CNG vehicle in the garage (e.g., upon returning home after work), connect the refueling nozzle and turn on the HRA if refueling is needed. The HRA automatically turns off when the CNG vehicle tank is full, or the owner terminates refueling when he needs to drive the car.

American Honda Motor Company is cooperating with FuelMaker with regard to HRA commercialization as a home refueling strategy for the Honda Civic GX CNG vehicle. HRA development is being supported by government agencies such as the Department of Energy (DOE) and National Renewable Energy Laboratory (NREL), South Coast Air Quality Management District (SCAQMD), California Air Resources Board (ARB), and Technology Partnership Canada. All parties are alert to the safety and risk implications of using HRAs to refuel CNG vehicles inside residential garages.

Additional HRA design and application information is available at the FuelMaker web site, Reference 1.

1.2 Prior and Contemporaneous Work

The work documented here is an extension of a previous preliminary safety evaluation of the FuelMaker HRA (Reference 2). This previous evaluation included consideration of potential safety incident scenarios (which was similar to a Failure Mode and Effects Analysis), a preliminary Fault Tree Analysis, and a framework for an Event Tree Analysis (these analyses will be discussed in more detail in subsequent sections of this report). The preliminary evaluation identified specific uncertainties which needed clarification in order to make the Fault Tree Analysis more accurate and carry out the Event Tree Analysis. Key uncertainties (which are explained in more detail in subsequent sections of this report) included:

- Specific CNG vehicle fuel system design details
- Certain CNG vehicle refueling field experience information
- Residential garage infiltration (i.e., natural ventilation) statistics
- Residential garage gas flow and mixing pattern phenomena
- Additional FuelMaker HRA design and installation details

Each of these uncertainties was addressed in the present work, and the results are documented in this report. Also, FuelMaker has modified the HRA design and installation instructions subsequent to the preliminary safety evaluation (Reference 2). Some of these modifications were made in response to issues identified during the course of this evaluation. Examples of these modifications are briefly discussed on Section 2.3. This report documents a safety evaluation of the FuelMaker HRA design as of approximately June, 2004.

Other prior CNG vehicle risk and safety studies should be noted, although only one study is known to have considered CNG vehicle refueling inside residential garages. The results of this study are documented in a report published by the R. F. Webb Corporation in 1993 (Reference 3). This study focused on the FuelMaker Vehicle Refueling Appliance (VRA), which is an existing FuelMaker product that is often used in residential applications but not inside the garage. The study documented in Reference 3 considered VRA use scenarios including both outdoor and indoor refueling. However, an appliance designed specifically for indoor fueling, such as the HRA, was not considered. Safety analyses were carried out by the TNO Division of Technology for Society (Netherlands Organization for Applied Scientific Research) and PrimaTech Inc. Reference 3 includes separate but similar reports by TNO and PrimaTech.

FuelMaker Corporation has conducted an in-house HRA Failure Modes and Effects Analysis, and they have contracted with Ryerson University (Toronto, Canada) to conduct an HRA safety study. Neither the FuelMaker in-house analysis nor the Ryerson study results were made available to the parties conducting this evaluation. Information regarding the FuelMaker in-house analysis and Ryerson University study is available from FuelMaker, Reference 4.

Contemporaneously with the work documented here, the Department of Energy also sponsored work to investigate codes and standards that are applicable to the FuelMaker HRA, and to develop guidelines for permitting HRA installations. This work was managed by DBHORNE LLC (Reference 5).

1.3 Objective

The overall objective of this project was to carry out an independent safety evaluation of the FuelMaker Home Refueling Appliance considering its application to fuel CNG vehicles inside residential garages. This evaluation was to be based on established Fault Tree and Event Tree Analysis methodologies, which are discussed in subsequent sections of this report. Specific objectives of this project included investigation of the key uncertainties listed in Section 1.2, (which were identified in the prior preliminary HRA safety study, Reference 2), and consideration of recent HRA design and installation revisions.

1.4 Restrictions

FuelMaker provided HRA specification, design, and application information to the parties conducting this safety evaluation through a series of written questions and answers as well as discussions during progress review conference calls (this information and its transmittal are discussed further in Section 2). Certain of this information is restricted by a Confidentiality Agreement, which was executed by FuelMaker and the parties involved in the HRA safety evaluation. This Confidentiality Agreement restricts the information that can be documented in this report. For example, no HRA design details are included. Similarly, the descriptions of HRA components and potential failure modes used in the fault trees and event trees (which are explained in Section 2) are selected so as not to disclose information restricted by the Confidentiality Agreement.

2. Evaluation Approach

2.1 Home Refueling Appliance Design and Application Information

The FuelMaker HRA is a fully integrated self-contained device that is designed to be mounted on the inside wall of a residential garage. It receives standard residential natural gas and electric service, and it enables time-fill (e.g., overnight) refueling of a CNG vehicle parked in the garage. The HRA contains a dryer, a compressor, controls, and safety systems (including a leak detector within a ventilated housing). Compressed gas is delivered to the vehicle through a flexible high-pressure hose (which retracts into the housing) and a NGV 1 Type 3 nozzle. The HRA provides a nominal gas flow rate approximately 0.67 scfm and a maximum outlet pressure of approximately 3,600 psi.

Figure 2-1 shows the HRA housing, and Figure 2-2 shows an example HRA installation inside a residential garage. Additional HRA information is available from the FuelMaker web site, Reference 1.

During the course of this study, FuelMaker revised the HRA design and installation plan so that the fan, which flows air from inside the garage at approximately 80 scfm to cool the compressor and other components of the HRA, discharges that air outside of the garage. This fan is an integral part of the HRA, and it is always on when the HRA is operating. This fan can also be activated by a gas sensor inside the HRA, i.e., if it detects a natural gas concentration exceeding a predetermined percentage of the lower flammability limit (LFL). Therefore, barring any malfunction, the HRA cooling air fan provides forced ventilation of air from inside the garage to outside at approximately 80 scfm when the HRA is operating or when the natural gas concentration at the sensor exceeds a predetermined level.

As discussed in Section 1.4, the parties conducting the safety evaluation documented here were provided with certain confidential HRA design information, which were needed to carry out the analyses. The primary means by which this HRA design information was provided was through a question and answer e-mail exchange between the parties conducting the analyses and FuelMaker staff. Additional HRA design information was communicated during periodic progress review teleconference meetings. It is significant to note that the analysis team did not work from a complete HRA design drawing package or controls instruction code listing, and the analysis did not include any members who were involved in the HRA design process. This analysis differed from many other Failure Modes and Effects and Fault Tree Analyses in these two important respects.

2.2 Overview of Analysis Process

The overall analysis process employed in this project is illustrated in Figure 2-3. This section overviews this process, and details of the various methodologies employed are explained in subsequent sections. In Figure 2-3 the basic process steps are indicated by the three thick arrows, the outputs from each step are shown below the thick arrows, and the various supporting analyses are listed in the boxes on the left.

Photo courtesy FuelMaker Corporation

Figure 2-1. The FuelMaker Corporation Home Refueling Appliance is also referred to as "Phill"

Photo courtesy FuelMaker Corporation

Figure 2-2. The FuelMaker Home Refueling Appliance is designed to enable CNG vehicles to be refueled inside residential garages

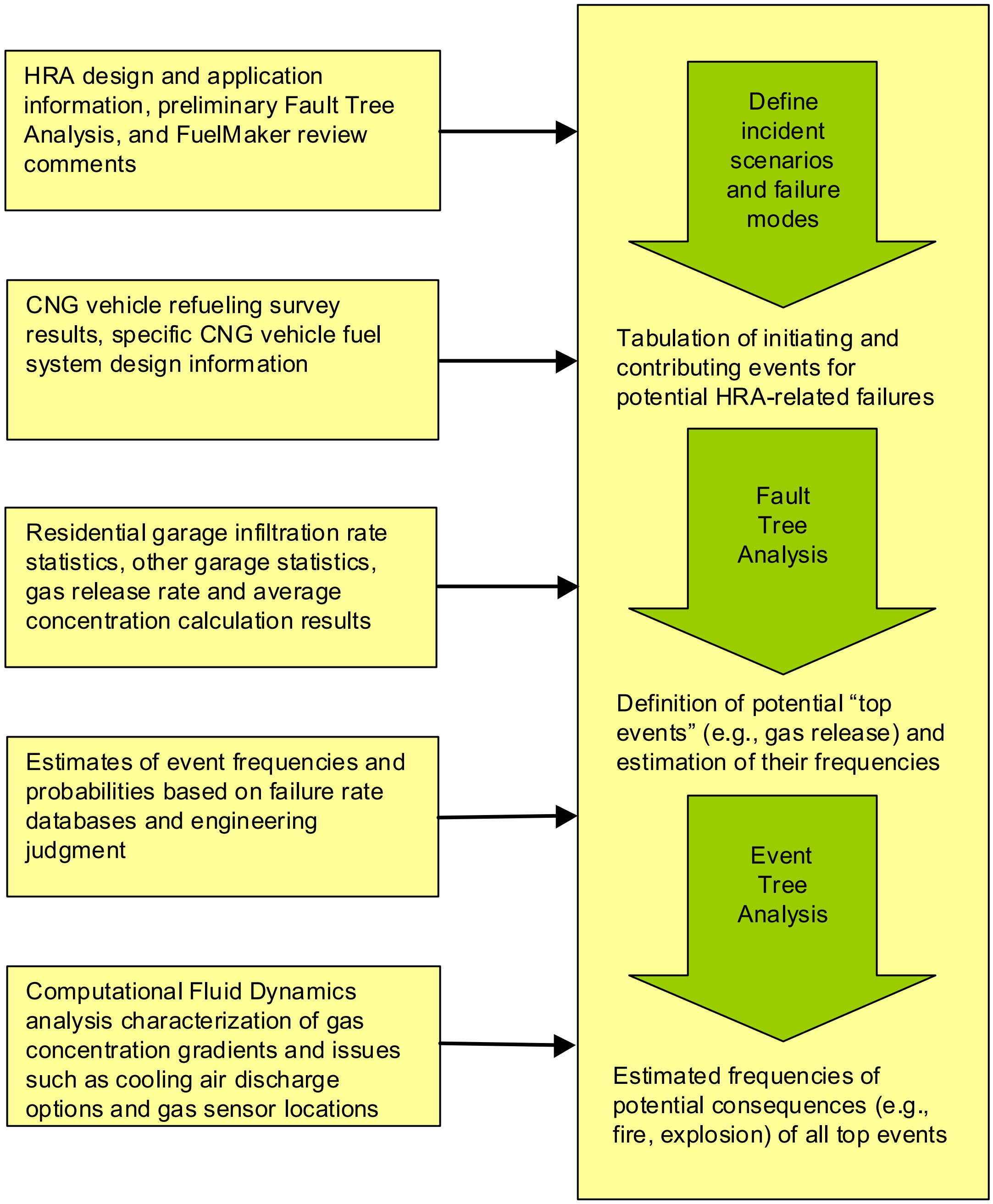

Figure 2-3. Summary of the overall HRA safety evaluation process

The first step in the analysis was to define HRA incident or event scenarios that lead to a circumstance with potential safety implications. Most of these involved some sort of "failure," where failure is broadly defined here to include human error and misuse situations as well as HRA or CNG vehicle component malfunctions. A process similar to a Failure Modes and Effects Analysis (FMEA) was employed to develop these incident scenarios. The FMEA process is documented in many textbooks and reports (e.g., References 6 or 7), and it will not be explained here. Definition of the HRA incident scenarios and failure modes was based on the previously discussed HRA design and application information provided by FuelMaker. Potential

HRA incident scenarios were initially defined as part of the preliminary safety evaluation (Reference 2), and these were revised and expanded as part of the work reported here. More details regarding specific HRA incident scenarios and failure modes are provided in Section 3.2.

The defined HRA incident scenarios and failure modes were applied to construct fault trees. The Fault Tree Analysis (FTA) process is documented in many textbooks and reports, and it will not be explained here. The fault tree branches linked sequences of initiating and contributing events that lead to common top events. It is important to note that the "top events" were defined as events such as gas releases, which have clear safety implications (i.e., "accidents" in lay terms), but the consequences of these top events (e.g., fire, explosion, or nothing, in the case of a gas release) were not included in the FTA. This was done to simplify the overall analysis because many fault tree branches resulted in the same basic top event, and the consequences of each top event depends on many variables. Therefore, using FTA to define top events and event trees to characterize the potential consequences, the total number of permutations is substantially reduced.

Estimates of the frequencies of FTA initiating events and the probabilities of enabling events were based on supporting analyses (e.g., the activities indicated on the left side of Figure 2-3, which will be discussed subsequently), available statistical databases, and engineering judgement. These estimates enabled the FTA to project the frequencies of the top events. Additional details regarding the FTA and event statistics are provided in Section 3.3.

Given the predicted frequencies of the FTA top events, event tree analysis (ETA) can be employed to project the frequencies of alternative outcomes. ETA, which is explained further in Section 3.4, is similar to but simpler than FTA because there are only "or" gates with no "and" gates, and therefore no significant Boolean algebra is involved. However, the relative probabilities of some important FTA top event outcomes are highly dependent on the exact quantitative nature of the top event (e.g., gas release rate) and the residential garage environment (e.g., air infiltration rate and ignition sources present). Because there is very little existing data pertaining to air infiltration and gas mixing rates in residential garages, and because they have a substantial effect on many HRA safety concerns, these issues were given particular attention in this evaluation (Sections 5, 6, and 7). Event tree possibilities were estimated based on these analyses and available statistical databases, and this enabled quantification of the frequencies of the possible consequences (e.g., fire, explosion, no safety consequences) associated with the FTA top events. The event tree analysis results are discussed in Sections 3.4 and 3.5.

2.3 Design, Analysis, and Report Revisions

To some extent, this safety evaluation was carried out in an iterative fashion. In some cases, FuelMaker technical staff reviewed early versions of the fault tree and event tree analyses and made HRA design and/or installation changes that reduced the probabilities of events modeled in the FTA or ETA branches that led to problematic consequences such as fires or explosions. In these cases, the FTA and ETA were redone consistent with the revised HRA design or installation.

The previously mentioned HRA ventilation design and installation change is a good example of such an iteration. It was initially envisioned that the HRA could be installed with the cooling air discharged either inside or outside the garage. When the cooling air is discharged inside the garage, it was determined that the consequences of any gas leak is highly dependent on the natural infiltration of air through the garage. Residential garage infiltration rates are highly variable and uncertain, and so part of the evaluation focused on characterizing these rates (see Section 5). When it was determined that a small fraction of "tight" garages and local wind conditions result in infiltration levels inadequate to ensure that gas leaks or direct discharges cannot form flammable mixtures, FuelMaker revised the HRA design and installation instructions so that the cooling air is to be only discharged outside the garage. This ensures at least 80 scfm of garage ventilation will occur unless there is a malfunction. This also means that the garage infiltration study (Section 5) is less pertinent, although it still applies to cases where some malfunction affects HRA cooling air fan operation.

2.4 Report Organization

The preceding overview of the HRA safety analysis process provides a basis for explaining how this report is organized. The HRA incident scenarios and failure modes, FTA results, and ETA results are presented first in Section 3. This is followed by documentation of various supporting analyses. Section 4 reviews the results of the CNG vehicle and residential garage design information and field experience surveys, Section 5 discusses garage infiltration rate tests and analyses, Section 6 presents garage average gas concentration results, and Section 7 documents the computational fluid dynamics analyses. Overall project conclusions and recommendations are summarized in Section 8. All fault trees and event trees are contained in Appendices A and B, respectively. Other analysis details are documented in Appendices C through F.

3. Failure Modes, Fault Tree, and Event Tree Analyses

3.1 Methodology Overview

As outlined in Section 2.2 and illustrated in Figure 2-3, the HRA safety evaluation process used in this project employed the following sequential steps:

- Define HRA incident or event scenarios that lead to a circumstance with potential adverse safety implications using a process similar to an FMEA. In addition to HRA and CNG vehicle component failures and malfunctions, failures associated with human error and misuse were included incident scenarios. The definition of HRA incident scenarios and failure modes was based on HRA design and application information provided by FuelMaker

- Use the HRA incident scenarios and failure modes to construct fault trees using FTA. Each fault tree leads to a top event, such as a gas discharge in a garage, that has a safety implication, but the potential consequence of the top events, such as a structure fire or deflagration,[1] were not included in the FTA (these were evaluated in the event tree analysis). Calculate the frequencies of the top events from estimated frequencies of initiating events and estimated probabilities of contributing events, which are based on supporting analyses, available statistical databases, and engineering judgement.

- For the collection of top events from the FTA, construct event trees that lead to a collection of defined outcomes (i.e., consequences) that have adverse safety implications, such as structure fire or deflagration. Define the estimated relative probabilities of each branch of each event tree, leading to the estimated probability of each outcome associated with the top event of each fault tree, based on supporting analyses, available statistical databases, and engineering judgement.

In the following, the definition of HRA incident scenarios and failure modes is discussed in Section 3.2, the FTA is discussed and Section 3.3, and the event tree analysis is discussed in Section 3.4. Section 3.5 summarizes the results of the safety analysis supported by the fault tree/ event tree analyses.

3.2 HRA Incident Scenarios and Failure Modes

A process similar to a FMEA (References 6 and 7) was carried out to analyze HRA design features and use (and misuse) possibilities in order to define a large number of potential incident scenarios and HRA failure modes that might lead to top events with safety implications. To

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[1] "Deflagration" as used here refers to the rapid combustion, with a subsonic flame front, of a natural gas and air mixture volume for which the gas concentration is between LFL and UFL. Methane-air deflagrations can produce overpressures that are adequate to destroy a residential garage and perhaps some or all of an attached home. However, the overpressures in a garage are judged to generally be inadequate to cause the methane-air deflagration to progress to a detonation (i.e., supersonic flame front and blast wave), which produces much higher overpressures. The word "explosion" can refer to either a deflagration or detonation, and so the word deflagration is generally used here to make it clear that this is the type of explosion being referred to.

illustrate, a natural gas leak is an example of such a top event, because it might lead to a fire or deflagration if it creates a mixture richer than the lower flammability limit (LFL) that encounters an adequate-energy ignition source.

This tabulation of incident scenarios and HRA failure modes was initiated during the preliminary HRA safety assessment (Reference 2), and it was substantially refined as new information was added as part of this study. Approximately 100 HRA incident scenarios were defined.

The following information was tabulated for each incident scenario: the initiating event, contributing events, top event, scenario category, explanations or uncertainties pertaining to the event sequence, and reference to the corresponding fault tree. The HRA incident scenarios fell into the six categories discussed in the following subsections.

3.2.1 Equipment Failure

Incident scenarios were classified as equipment failures if the initiating event and/or primary contributing event was an HRA (or CNG vehicle) component failure. Examples include hose leaks or ruptures, malfunctions of HRA valves or control systems, and failure of the CNG vehicle receptacle reverse-flow check valves. Conceivable failures that might result in air ingress into the HRA so as to create the opportunity for a deflagration inside of the HRA were also considered in this category. All equipment failure scenarios required multiple contributing event failures in order to result in a clearly problematic top event.

3.2.2 Human Errors

Many incident scenarios had human errors as the primary contributing events. Driving the CNG vehicle away with the refueling nozzle still connected to the receptacle is the classic example, and many of these scenarios involved this error. The HRA is equipped with breakaway device compliant with NGV 4.4 and NFPA 52, and so various other contributing events must occur in conjunction with a connected drive away in order to result in a problematic top event. Debris that affects the ability of the receptacle check valve to seat is another example of human error (e.g., because the user failed to ensure that the coupling was clean).

3.2.3 Misuse

Many incident scenarios classified as misuse were also considered. These included scenarios such as: trying to use the HRA to inflate a tire or swimming pool float, trying to use the HRA to fill a propane tank (e.g., for a gas grill) or to refuel a propane vehicle, or attempting to modify the HRA by adding a buffer tank to provide a fast-fill capability.

3.2.4 Maliciousness

Some scenarios had malicious acts as the initiating or primary contributing events. An example is a disgruntled neighbor seeking to shut off the gas or electric supply to the HRA. For all maliciousness scenarios, no credible contributing events were identified that could lead to problematic top events.

3.2.5 External Events

A few incident scenarios were classified as external events because they involved things like the house catching on fire, an earthquake, or a vehicle striking a wall-mounted HRA. "Disaster" external events were not analyzed in detail because it was judged that the HRA response would be similar to the response of other residential gas appliances.

3.3 Fault Tree Analysis

All HRA incident scenarios that resulted in top events with safety implications were used to construct fault trees. Fault trees are graphical representations of initiating and contributing events that combine to result in a top event (e.g., an "accident"). The various branches of fault trees generally represent the alternative pathways to the top event. Fault tree construction provides a convenient visual representation of the failure scenarios, and it also facilitates the Boolean algebra that computes top event frequencies from initiating event frequencies and contributing event probabilities. Many FTA software applications are available that automate these functions, and FTA details are discussed in various safety engineering textbooks and handbooks.

The sequences of events discussed in Section 3.2 usually formed the branches of the fault trees. Table 3-1 summarizes the 18 fault trees developed, their top events, and some pertinent remarks. Recall from Section 2 that the final safety evaluation assumed that, per current FuelMaker HRA installation specifications, the HRA cooling air discharge is plumbed to vent to the outside. However, there are various failure and other scenarios in which the cooling air fan will not be in operation, or in which the outside discharge vent becomes completely blocked preventing the outside discharge. For this reason, each gas release event has two fault trees associated with it; one with the cooling air fan in operation ventilating the garage with its 80 scfm discharge flowrate, and one with no cooling air fan forced ventilation. With no forced ventilation, gas concentrations inside the garage will be determined by the gas release rate and the garage's infiltration characteristics, as captured by the term air changes per hour (ACH), further discussed in Sections 5 and 6. Both of the two fault trees associated with each gas release event are listed in Table 3-1.

The fault trees assembled corresponding to the list in Table 3-1 are given in Appendix A. An example fault tree is shown and discussed below.

For most of the fault trees, the initiating events, which are shown as ovals in the fault trees in Appendix A, have the units of frequency: events per unit per year (i.e., number of times / unit-year, where the "per unit" is generally understood and not noted). For example, the initiating event for some fault trees is simply the act of refueling the CNG vehicle, which was assumed to have a frequency of 100/year. All the contributing events, which are shown as diamond shapes in the fault trees in Appendix A, have probability units (i.e., unity or less). The top events have frequency units (number of times / unit-year), which are the product of the initiating event frequencies times a Boolean logic combination of the contributing event probabilities, which are affected by the fault tree branches, "and" gates, and "or" gates. "And" gates are shown as the flat-bottomed (mailbox end view) shapes in the Appendix A fault trees. The frequency of an "and" gate top event is the product of the frequency and probabilities of events leading to the gate. "Or" gates are shown as the rounded triangular shapes in the Appendix A fault trees. The frequency of an "or" gate top event is the sum of the frequencies of all events leading to the gate.

Table 3-1. Summary of 18 Fault Trees and their Top Events

Fault Tree Number	Summary	Remarks
FT-1	A continuous gas leak (approximately 0.22 scfm) into the garage with the HRA cooling air discharging outside	The top event is a 0.22 scfm leak with 80 scfm ventilation
FT-2	A continuous gas leak (0.22 scfm) into the garage with the HRA on but with no cooling air fan ventilation	The top event is a 0.22 scfm leak with only garage volume x air changes per hour (ACH) infiltration
FT-3	A continuous full-flow gas discharge (0.67 scfm) into the garage with the HRA cooling air discharging outside	The top event is a 0.67 scfm discharge with 80 scfm ventilation
FT-4	A continuous full flow gas discharge (0.67 scfm) into the garage with the HRA on but with no cooling air fan ventilation	The top event is a 0.67 scfm discharge with only garage volume x ACH infiltration
FT-5	A vehicle fuel tank blowdown gas release inside the garage with the HRA off and cooling air discharging outside (activated by the HRA gas detector)	The top event is a spectrum of blowdown possibilities with 80 scfm ventilation
FT-6	A blowdown gas release inside the garage with HRA off and no cooling air fan ventilation	The top event is spectrum of blowdown possibilities with only garage volume x ACH infiltration
FT-7	A blowdown gas release outside the garage through the HRA cooling air vent to the outside	The top event is spectrum of blowdown possibilities through the HRA vent
FT-8	A low flow discharge or slow blowdown outside the garage through the HRA cooling air vent to the outside	The top event is spectrum of low flow discharge or slow blowdown possibilities through the HRA vent
FT-9	A gas release inside the garage due to HRA use to fill an LPG bottle or inflatable with the HRA cooling air discharging outside	A misuse scenario, the top event is a spectrum of LPG bottle or inflatable releases with 80 scfm ventilation
FT-10	A gas release inside the garage due to HRA use to fill an LPG bottle or inflatable but with no cooling air fan ventilation	A misuse scenario, the top event is a spectrum of LPG bottle or inflatable releases with only garage volume x ACH inflation
FT-11	A gas release inside the garage due to the attempt to fit a torch to the HRA, with cooling air discharging outside	A misuse scenario, the top event is a gas release from failed adapter fitted to the HRA hose, with 80 scfm ventilation
FT-12	A gas release inside the garage due to the attempt to fit a torch to the HRA, with no cooling air fan ventilation	A misuse scenario, the top event is a gas release from failed adapter fitted to HRA hose, with only garage volume x ACH infiltration
FT-13	A gas release inside the garage because the gas supply line is broken, due to a vehicle impact with the HRA with failure of the supply pipe breakaway, or a gas supply overpressure	This scenario assumes that the HRA is off, but the garage door is open, and someone may or may not shut off the gas supply

Table 3-1. Summary of 18 Fault Trees and their Top Events (concluded)

Fault Tree Number	Summary	Remarks
FT-14	Deflagration in the HRA due to air ingress into the appliance	This scenario assumes that the cooling air fan is off following any HRA deflagration, and that the gas supply piping may or may not fail
FT-15	A release of gas inside the garage from a buffer tank which has been fitted to the HRA due to pressure relief valve (PRV) failure or tank rupture, with cooling air discharging outside	A misuse scenario, the top event is a buffer tank discharge (through the tank PRV or due to rupture) with 80 scfm ventilation
FT-16	A release of gas inside the garage from a buffer tank which has been fitted to the HRA due to PRV failure or tank rupture, with no HRA cooling air fan ventilation	A misuse scenario, the top event is a buffer tank discharge (through the tank PRV or due to rupture) with only garage volume x ACH infiltration
FT-17	A release of gas inside the garage due to HRA end cap overpressure because too long of a hose extension has been added, with cooling air discharging outside	A misuse scenario, the top event is gas release from the HRA end cap inside the garage (due to PRV failure), with 80 scfm ventilation
FT-18	A release of gas inside the garage due to HRA end cap overpressure because too long of a hose extension has been added, with no cooling air fan ventilation	A misuse scenario, the top event is gas release from the HRA end cap inside the garage (due to PRV failure), with only garage volume x ACH infiltration.

Note that, with this methodology, the frequencies of top events depend only on how many units are installed, and not on how long they have been operating.

The FTA team judged that some of the fault tree initiating and contributing events should not have the units probability x number of times / unit-year. In particular, for the misuse scenarios, it was judged that someone would be more likely to attempt the HRA misuse sooner rather than later, e.g., if they haven't tried to use the HRA to inflate a beach ball in the first year or two after having the opportunity, they probably wouldn't attempt it at all. For the four misuse scenarios (each with two corresponding fault trees – with and without forced ventilation – FT-9, 10, 11, 12, 15, 16, 17, and 18 in Table 3-1), the initiating event is purposely assumed to be one unit installed per year, the adjacent contributing event is the probability that someone will attempt the misuse of that unit installed in that year, and this causes the top event to have the units: number of times / units installed in a year. While this difference in the frequency units of different fault trees makes the analysis more accurate, it also makes the FTA and ETA results more difficult to report and understand.

The frequencies of the fault tree initiating events and probabilities of the contributing events were estimated from available references and databases pertaining to component failure and human error statistics (References 8 through 13), the CNG vehicle design and experience survey discussed in Section 4, and engineering judgment. In some cases these estimates were based on failure or error statistics for generically similar (but not identical) components and situations.

These fault tree event frequency and probability estimates are given in Table A-1 in Appendix A, which also includes a short discussion of the rationale for each estimate.

As an example, Figure 3-1 shows the fault tree leading to a continuous gas leak into the garage with the HRA cooling air fan not operating, FT-2. As shown in the figure, the three major branches leading to the continuous gas leak into the garage are an in service hose leak; an out of service hose leak; and a piping, HRA component, or vehicle component leak. Various initiating and contributing events lead to each of these branch top events, with those leading to the piping / component leak shown the tab E tree denoted FT-1E, which is the set of events that lead to a piping / component leak for the corresponding fault tree with the HRA cooling air fan operating and discharging to the outside (FT-1).

The contributing event labeled “HRA on & fan off” deserves some explanation. Whenever the HRA is in operation, the cooling air fan is also supposed to be running. However, the cooling air fan can operate with the HRA off. Specifically, whenever the appliance’s gas detector detects a

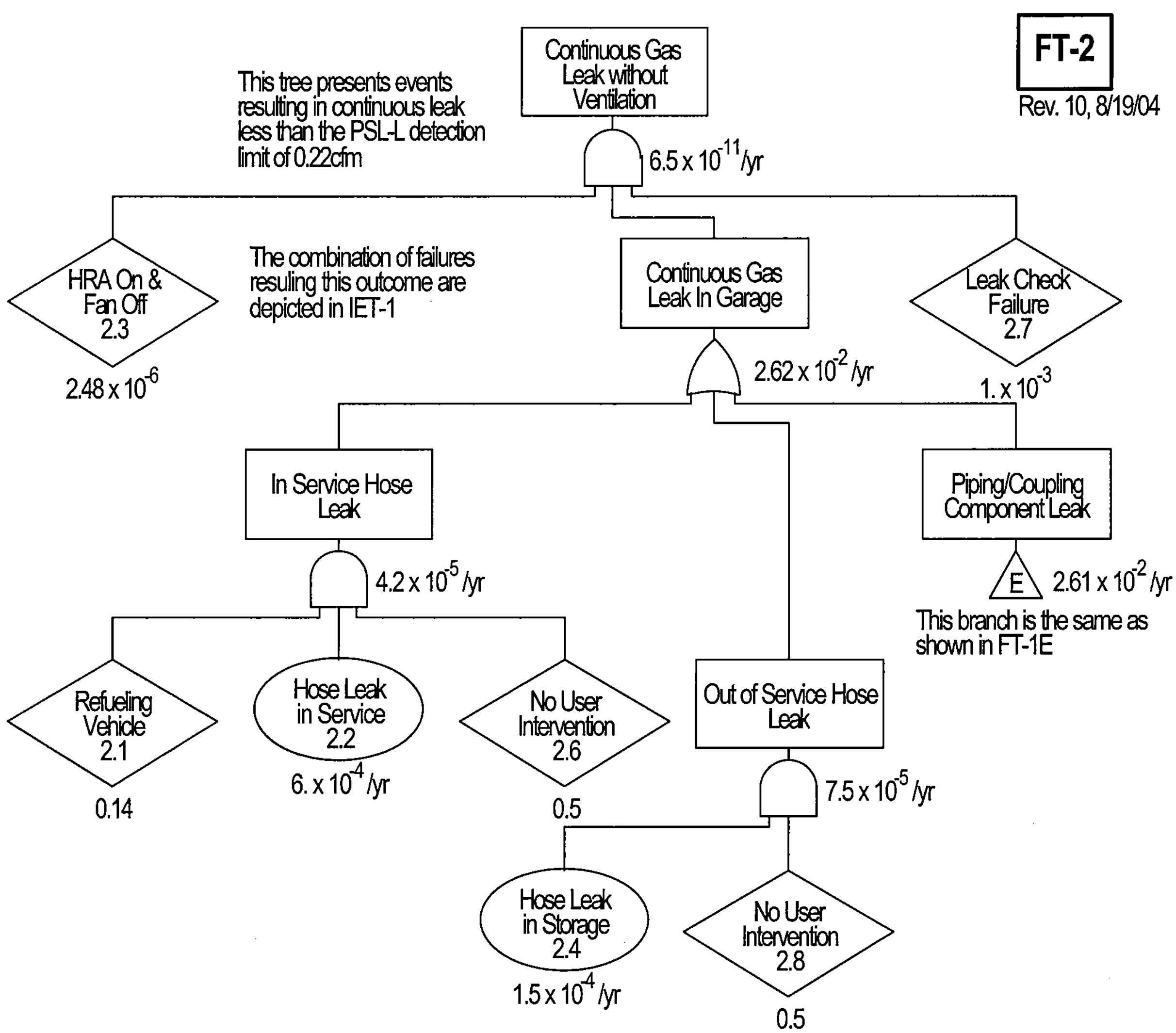


Figure 3-1. Example fault tree, FT-2

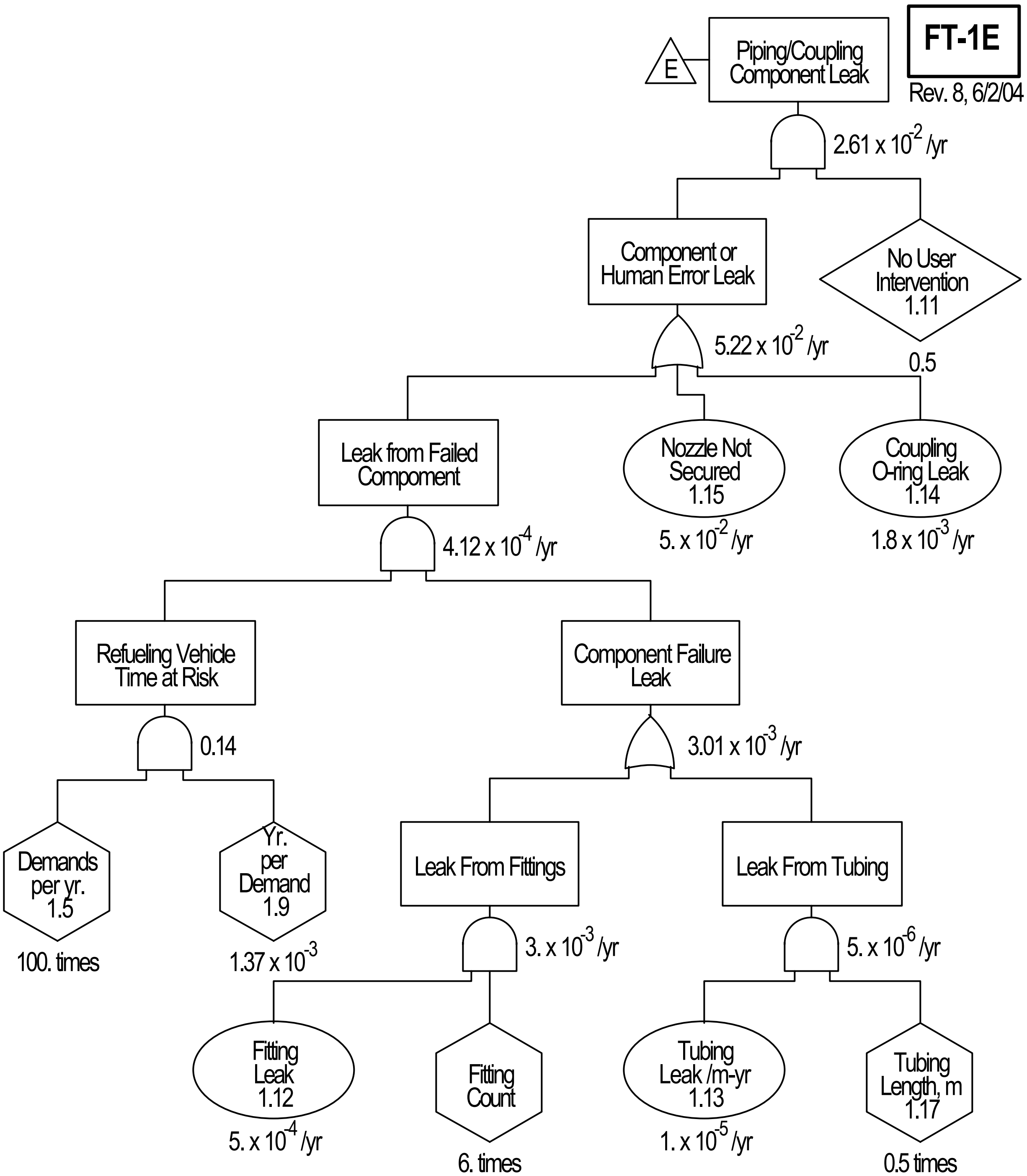


Figure 3-1. Example fault tree, FT-2

methane concentration greater than a predetermined setpoint, the cooling air fan turns on to ventilate the garage in an attempt to prevent a further gas concentration increase. So, because the HRA cooling air fan can operate both with or without the HRA itself in operation, there are several cooling air fan ventilation failure permutations. These include:

- A gas release occurs, but the gas concentration does not reach the gas detector trip point
- A gas concentration exceeds the detector trip point, but the gas detector fails
- The fan motor fails, but the cooling air flow sensor fails and does not stop operation of the HRA

These permutations were handled via the use of what are termed intermediate event trees (IETs) in the FTA process. Three IETs were defined in this analysis, corresponding to the three gas release magnitudes considered in the study, a gas leak of 0.22 scfm (termed IET-1), a full flow gas discharge of 0.67 scfm (IET-2), and a vehicle tank blowdown(IET-3). Section 6 discusses these release rates and the resulting estimated average garage concentrations. The IETs are also given in Appendix A. The concept of event trees and their construction is discussed in Section 3.4.

The IET for the continuous gas leak (IET-1) in Appendix A results in an estimated probability that the HRA is operating, but the cooling air fan is not operating, of 2.48×10^{-6} (the sum of the probabilities of the two "release without ventilation" branches in IET-1). When combined with the frequency of the continuous gas leak in garage event in Figure 3-1, the estimated frequency of a continuous gas leak in garage without ventilation (the top event in FT-2, shown in Figure 3-1) is 6.50×10^{-11} events/unit-yr. The estimated frequencies for all fault tree top events are summarized in Table 3-2. Note that, as discussed above, frequencies for non-misuse failures are expressed as failures/unit-yr, while frequencies for misuse failures are expressed as failures/units installed per yr.

Table 3-2. Fault tree top event frequencies

Non-misuse Failures		Misuse Failures	
Fault Tree Number	**Estimated Top Event Frequency (failures/unit-yr)**	**Fault Tree Number**	**Estimated Top Event Frequency (failures/units installed per yr)**
FT-1	2.59×10^{-5}	FT-9	4.01×10^{-6}
FT-2	6.50×10^{-11}	FT-10	4.88×10^{-8}
FT-3	1.61×10^{-6}	FT-11	1.87×10^{-11}
FT-4	4.05×10^{-12}	FT-12	4.70×10^{-17}
FT-5	2.33×10^{-8}	FT-15	1.16×10^{-6}
FT-6	2.83×10^{-10}	FT-16	3.29×10^{-11}
FT-7	1.47×10^{-7}	FT-17	1.69×10^{-9}
FT-8	1.14×10^{-8}	FT-18	2.05×10^{-11}
FT-13	7.35×10^{-7}		
FT-14	1.04×10^{-8}		

Figures 3-2 and 3-3 are simple bar charts that summarize the results of the FTA in terms of the frequencies of the top events of each of the 18 fault trees summarized in Table 3-2. Note the logarithmic frequency scales in both of these charts. As previously discussed, the fault trees produce top event frequencies of two types (i.e., with two different units). The top event

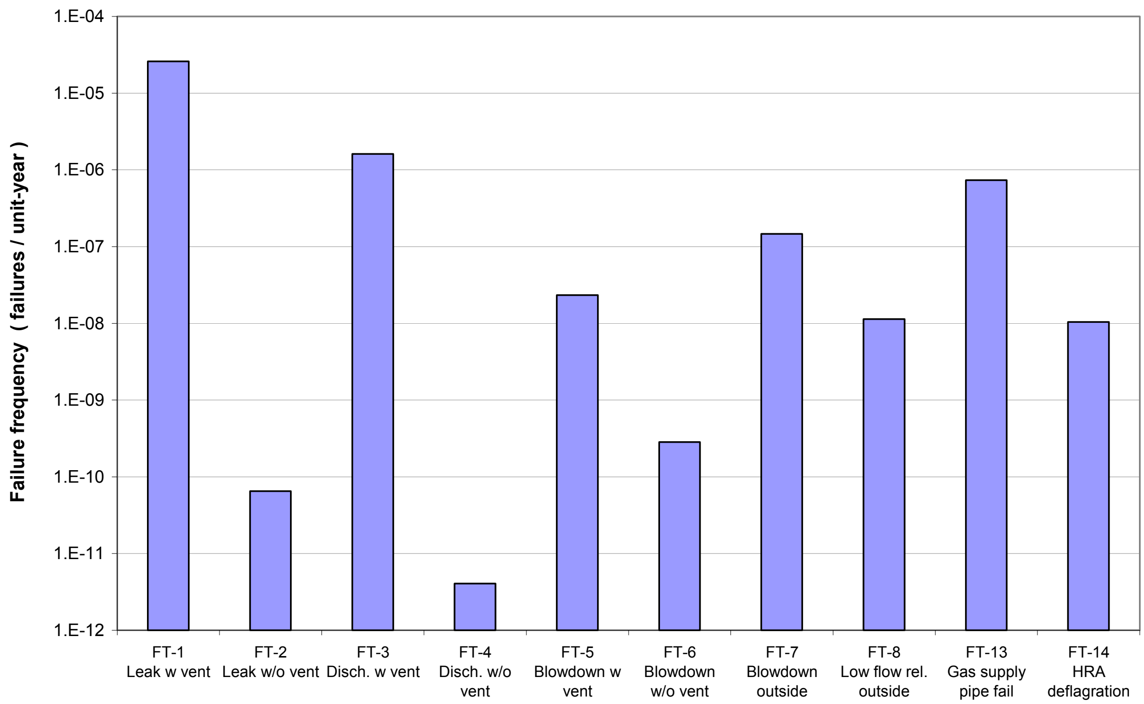


Figure 3-2. Fault tree analysis results: top events with frequencies expressed as failures/unit-year

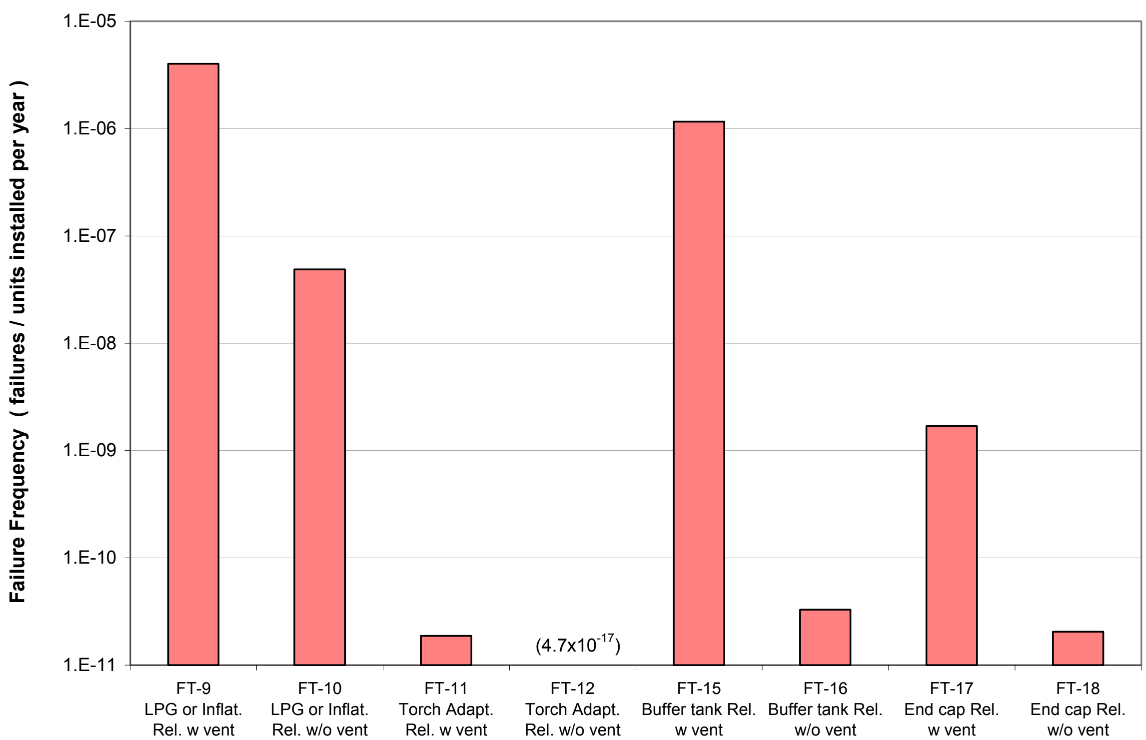


Figure 3-3. Fault tree analysis results: top events with frequencies expressed as failures/units installed per year

frequencies shown in Figure 3-2 have the units failures / unit-year (where we have loosely characterized all fault tree top events as "failures"). For example, a top event with a frequency of 10^{-3} failures/unit-year means that one HRA will experience this failure in 1,000 years, or, if 1,000 HRA units are installed, one will fail in a year. The top event frequencies shown in Figure 3-3 have the units failures/units installed per year. For example, a top event with a frequency 10^{-6} failures/units installed per year means that one HRA unit will fail if a million units were installed during the prior year, or, if 1,000 HRA units were installed in a year, the probability of a failure would be 10^{-3} in the next year.

Figure 3-2 shows that HRA leaks with ventilation (cooling air fan operating) are predicted to be the most frequent non-misuse top event. They are predicted to occur at a rate of roughly 2.6×10^{-5}/unit-year. All other top event frequencies are an order of magnitude or more lower. The predicted leak with ventilation frequency corresponds to one predicted failure per year after a total of about 39,000 HRAs have been installed. Figure 3-3 indicates that the two most frequent misuse top events are the rupture of a LPG bottle or toy being inflated with an HRA with ventilation (once for every 250,000 HRA units installed in the prior year) and a gas release from a buffer tank added to the HRA with ventilation (once for every 860,000 HRA units installed in the prior year). The predicted frequencies of other misuse failures are more than an order of magnitude lower.

Recall that failure frequency is not directly related to adverse safety implications because the consequences of some top events may have much more severe safety implications than the consequences of other top events. That is the subject of the event tree analysis discussed in Section 3.4.

3.4 Event Tree Analysis

As applied in this study, the FTA predicted the frequencies of top events (such as gas releases) but not the consequences (e.g., potential fires or deflagrations). As explained in Section 2.2 and illustrated in Figure 2-3, event tree analysis (ETA) was applied to each top event to predict the resulting consequence frequencies.

Event trees "grow" in the opposite direction relative to fault trees. Each event tree starts with the top event from a fault tree (e.g., a continuous 0.22-scfm HRA leak into the garage with the HRA cooling air fan not operating). From these top events, the event trees branch into alternative outcomes or consequences. Each branch point is an "or" gate (unlike fault trees, event trees do not have "and" gates). Further the probabilities of each of the two branches leaving an "or" gate must sum to one. Additional discussion of event tree construction and conventions accompanies the description of an example event tree, below.

Much of the garage infiltration characterization, average gas concentration calculations, and computational fluid dynamics analyses described in Sections 5, 6, and 7 were carried out for the purpose of establishing the bases for estimating event tree probabilities. For example, the potential for a given gas release to produce a fire or deflagration is obviously a critical event tree issue. This depends on many factors in addition to the release rate, e.g., whether or not the HRA cooling air fan is on or off, the elapsed time, garage size, garage infiltration rate, gas mixing and diffusion phenomena, likelihood and location of ignition sources, and flammability of surrounding materials. Each of these and other factors were taken into consideration and available data combined with engineering judgment were applied to estimate the probabilities associated with each event tree "or" gate.

The event trees for each of the 18 fault tree top events are included in Appendix B. Table B-1 in this Appendix summarizes the rationale and data sources for the probability estimates associated with each of the "or" gates for each of the event trees.

The function of the event trees will be illustrated by using ET-2, shown in Figure 3-4, as an example. The origin of ET-2 is the top event from fault tree FT-2 (discussed in Section 3.3): a

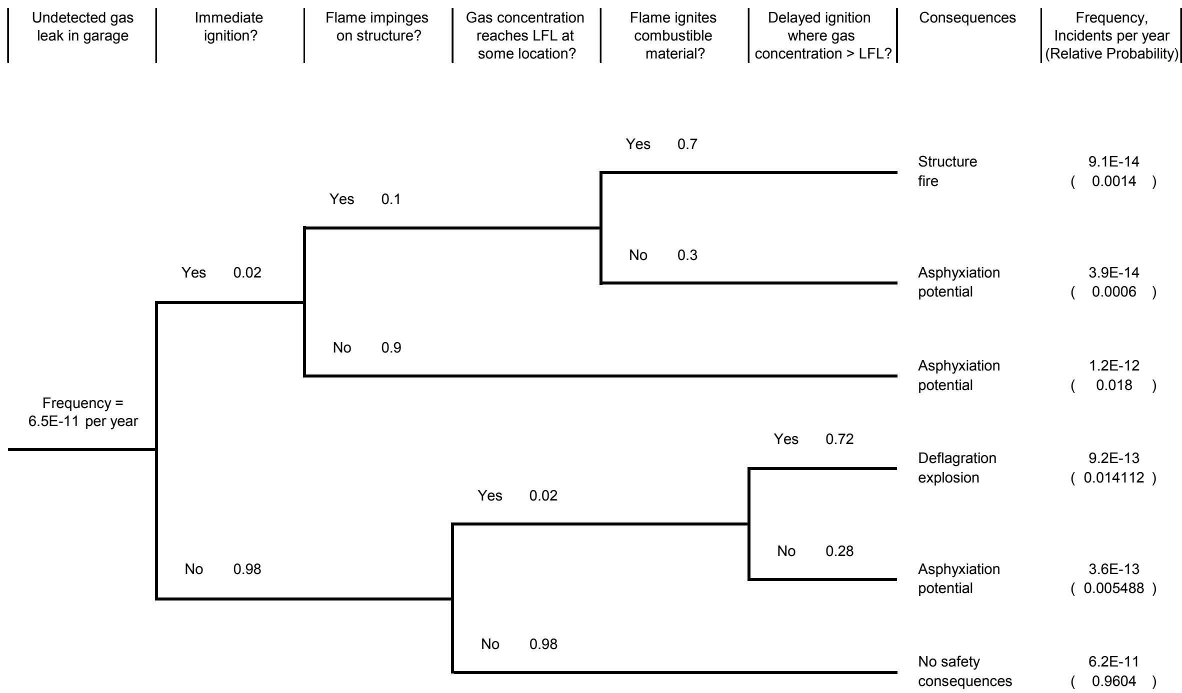


Figure 3-4. Example event tree, ET-2

continuous HRA leak of approximately 0.22 scfm inside the garage with the HRA cooling fan not operating. FT-2 predicts this to occur with a frequency of 6.50×10^{-11}/unit-year. The branches and probabilities of ET-1 are as follows:

- Immediate ignition? The gas release may immediately ignite and burn as a standing flame at the point of discharge. However, the likelihood of a suitable ignition source being located in this relatively small volume with a gas concentration ≥LFL is judged to be very small, and so the "Yes" probability was estimated as 0.02.

- Flame impinges on structure? If the discharge ignites immediately, it may impinge on a structure (e.g., the garage wall). However, a 0.22-scfm release would not produce a long flame (relative to garage dimensions), and only certain discharge locations and angles would result in the flame reaching the structure. Based on a rudimentary consideration of these variables, the "Yes" probability was estimated as 0.1.

- Flame ignites combustible material? If the discharge ignites immediately and the resulting flame impinges on a structure, it might ignite a combustible material to produce a "structure fire" consequence as indicated in Figure 3-4. The garage survey statistics to be discussed in Section 5 were applied to estimate a "Yes" probability of 0.7. Therefore, the estimated frequency of a structure fire due to a 0.22-scfm HRA discharge in a garage is:

$$6.50\text{x}10^{-11}\text{/ unit-year x } 0.02 \text{ x } 0.1 \text{ x } 0.7 = 9.10\text{x}10^{-14}\text{/unit-year}$$

- (Restarting from the immediate ignition? "No" branch) Gas concentration reaches LFL at some location? This important probability is estimated from the garage survey and infiltration results discussed in Section 5, the average gas concentration calculations discussed in Section 6, and the computational fluid dynamics analyses discussed in Section 7. Combining elements of these supporting analyses, as outlined in Table B-1, the resulting "Yes" probability was estimated to be 0.02.

- Delayed ignition where gas concentration > LFL? The garage survey statistics (Section 5) indicated that approximately 90% of garages have ignition sources such as electric garage door openers or gas water heaters. We estimated that roughly 80% of these would have adequate energy (>0.29 mJ) and be located where the gas concentration was >LFL. The resulting "Yes" probability is 0.72. Therefore, the estimated frequency of a deflagration due to a 0.22-scfm gas leak in a garage is:

$$6.50\text{x}10^{-11}\text{/unit-year x } 0.98 \text{ x } 0.02 \text{ x } 0.72 = 9.17\text{x}10^{-13}\text{/unit year}$$

- The three ET-2 branches that did involve a gas release but did not result in a deflagration or structure fire are labeled "Asphyxiation potential" in Figure 3-4 because it is conceivable that enough oxygen could be displaced to asphyxiate a person who might happen to be in the garage. However, this is extremely unlikely for two reasons. By law (Reference 14), the natural gas must be odorized so that a leak can be detected by a person with a normal sense of smell when the concentration reaches 20% of the LFL (i.e., 1%). The gas concentration would have to be more than 20 times this high before asphyxiation was even an issue, and the smell would be incredibly strong at that point. The second reason is that the asphyxiation concentration is much higher than the LFL, and so (except for garages with no ignition sources) a garage would be likely to deflagrate before it asphyxiated someone inside.

- One ET-2 branch in Figure 3-4 involves a gas discharge that does not ignite immediately and does not produce a concentration >LFL. This "no safety consequences" outcome has the highest frequency at $6.24\text{x}10^{-11}$/unit-year.

The gate probabilities for the other event trees were estimated by processes similar to the preceding example for ET-2. All probabilities and their rationale are summarized in Table B-1.

3.5 Results Summary

Table 3-3 summarizes the results of the HRA ETA in terms of the estimated frequencies of each consequence considered for each fault tree top event (i.e., each failure scenario). As previously

Table 3-3. Summary of consequence frequencies predicted by the Event Tree Analysis

		Deflagration	Structure Fire	Asphyxiation Potential	Gas Burns at Vent	No Safety Consequences	(Neglected Consequences)	Total1
Frequencies: Incidents per Unit-Year:								
ET-1,	Continuous 0.22-scfm leak in garage with ventilation	1.2×10^{-8}	9.1×10^{-9}	2.7×10^{-7}	—	2.6×10^{-5}		2.6×10^{-5}
ET-2,	Continuous 0.22-scfm leak in garage without ventilation	9.2×10^{-13}	9.1×10^{-14}	1.6×10^{-12}	—	6.2×10^{-11}		6.5×10^{-11}
ET-3,	Continuous 0.67-scfm discharge in garage with ventilation	3.4×10^{-9}	1.1×10^{-8}	7.3×10^{-8}	—	1.5×10^{-6}		1.6×10^{-6}
ET-4,	Continuous 0.67-scfm discharge in garage without ventilation	8.7×10^{-13}	5.7×10^{-14}	6.8×10^{-13}	—	2.4×10^{-12}		4.1×10^{-12}
ET-5,	Blowdown in garage with ventilation	1.5×10^{-8}	7.5×10^{-10}	5.5×10^{-9}	—	1.7×10^{-9}		2.3×10^{-8}
ET-6,	Blowdown in garage without ventilation	2.0×10^{-10}	9.1×10^{-12}	6.8×10^{-11}	—	7.6×10^{-12}		2.8×10^{-10}
ET-7,	Blowdown through HRA vent outside	1.4×10^{-9}	2.9×10^{-10}	—	7.0×10^{-9}	1.3×10^{-7}		1.5×10^{-7}
ET-8,	Low flow release through HRA vent outside	5.4×10^{-11}	1.1×10^{-11}	—	5.6×10^{-10}	1.0×10^{-8}		1.1×10^{-8}
ET-13,	Gas supply pipe failure due to vehicle strike or other	1.1×10^{-7}	4.4×10^{-8}	5.2×10^{-7}	—	6.2×10^{-8}		7.4×10^{-7}
ET-14,	Air ingress causing HRA deflagration	3.7×10^{-10}	2.8×10^{-9}	7.5×10^{-9}	—	2.8×10^{-9}		1.0×10^{-8}
Total[1]		1.4×10^{-7}	6.8×10^{-8}	8.6×10^{-7}	7.6×10^{-9}	2.7×10^{-5}		2.8×10^{-5}
Frequencies: Incidents per units installed prior year:								
ET-9,	LP bottle or inflatable bursts in garage with ventilation	4.3×10^{-7}	6.0×10^{-8}	2.0×10^{-6}	—	1.4×10^{-6}		4.0×10^{-6}
ET-10,	LP bottle or inflatable bursts in garage with ventilation	1.4×10^{-8}	7.3×10^{-10}	2.5×10^{-8}	—	8.8×10^{-9}		4.9×10^{-9}
ET-11,	Attempt to attach torch with ventilation	1.6×10^{-14}	6.5×10^{-14}	8.9×10^{-13}	—	1.8×10^{-11}		1.9×10^{-11}
ET-12,	Attempt to attach torch without ventilation	6.1×10^{-18}	3.3×10^{-19}	6.7×10^{-18}	—	3.4×10^{-17}		4.7×10^{-17}
ET-15,	Attempt to attach buffer tank with ventilation	2.5×10^{-7}	3.2×10^{-8}	2.5×10^{-7}	—	6.3×10^{-7}		1.2×10^{-6}
ET-16,	Attempt to attach buffer tank without ventilation	1.9×10^{-11}	3.3×10^{-12}	9.7×10^{-12}	—	7.4×10^{-13}		3.3×10^{-11}
ET-17,	Added hose(s) with ventilation	4.6×10^{-10}	1.3×10^{-10}	9.8×10^{-10}	—	1.3×10^{-10}		1.7×10^{-9}
ET-18,	Added hose(s) without ventilation	8.8×10^{-12}	1.5×10^{-12}	9.4×10^{-12}	—	7.7×10^{-13}		3.8×10^{-11}
Total[1]		7.0×10^{-7}	9.3×10^{-8}	2.3×10^{-6}		2.1×10^{-6}		5.2×10^{-6}

[1]Totals may be affected by round-off issues.

discussed, two types of top event frequencies were considered in the FTA, and therefore two types of consequence frequencies are listed in Table 3-3.

Table 3-3 shows that all of the event trees (which correspond with all of the fault trees) have most of the consequences (outcomes) in common; the most important of which are deflagrationand structure fire. The asphyxiation potential consequence is a collection of outcomes where gas is leaked or discharged but no burning or combustion results. As previously discussed, it is exceedingly unlikely that any one would ever actually be asphyxiated in any of these scenarios, and so this consequence can be neglected in comparison to the potential deflagration and structure fire consequences. Similarly, the no safety consequence outcome can also be neglected.

Figures 3-5 and 3-6 summarize the contributions to predicted structure fire and deflagration frequencies for events that are characterized by the units of incidents / unit-year and incidents / units installed in prior year, respectively.

Figure 3-5 shows that, for the non-misuse failures, a deflagration associated with HRA use is predicted to be roughly twice as frequent as a structure fire. The most likely cause of either structure fires or deflagrations is predicted to be a gas release resulting from a gas supply pipe failure due to the HRA being struck by a vehicle and the supply pipe breakaway fails. Other significant contributors to the predicted frequency of both structure fires and deflagrations are a continuous gas leak and a full flow gas discharge, both with the HRA cooling air fan operating normally (i.e., with ventilation). A vehicle tank blowdown into the garage with the cooling air fan in operation provides a significant contribution to the predicted frequency of deflagrations; an HRA deflagration due to air ingress provides some contribution to the predicted frequency of structure fires. The total predicted frequency of a deflagration from all non-misuse causes considered in the analysis corresponds to one predicted deflagration per year after a total of about 7,000,000 HRAs have been installed. The corresponding result for structure fires is that one fire per year would be predicted after a total of 14,600,000 HRAs have been installed.

Figure 3-6 shows that, for the misuse failures, deflagrations are predicted to be over seven times more frequent that structure fires. The attempt to fill an LPG bottle or inflatable and a gas release from an added buffer tank are predicted to be the misuse scenarios that precipitate the most frequent both fires and deflagrations. The total predicted frequency of a deflagration from all misuse causes considered in the analysis corresponds to one predicted deflagration per year if about 1,400,000 HRAs were installed in the previous year. The corresponding result for structure fires is that one fire per year would be predicted if about 10,700,000 HRAs were installed in the previous year.

These consequence frequencies can be compared to the probabilities of other hazardous or fatal events as follows. The consequence frequencies noted above equate to the probability that a single unit installation will experience the consequence in a year for the non-misuse failures or in the first year following installation for the misuse failures. In other words, the probability that an installed HRA will cause a deflagration due to all non-misuse failures is 1 in 7,000,000 over a year’s use; the probability that an installed HRA will cause a structure fire due to all misuse failures is 1 in 10,700,000 in the year following installation.

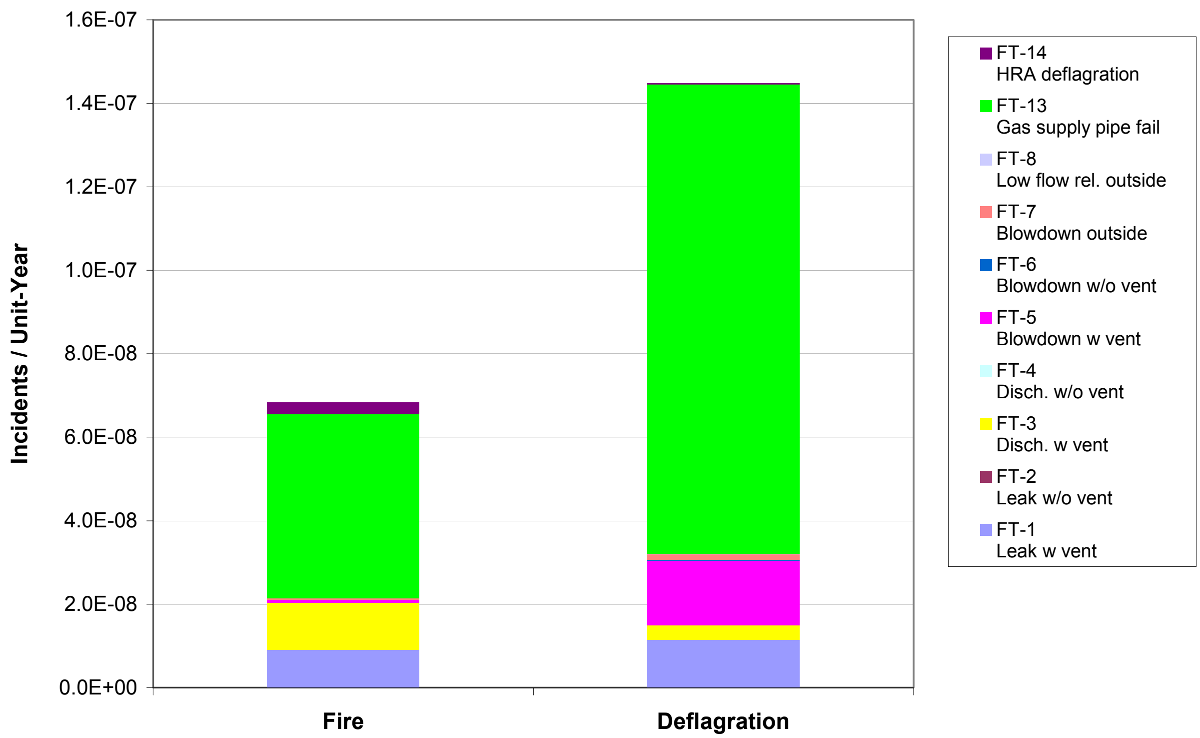


Figure 3-5. Consequence frequencies predicted by the FTA and ETA that have the units of incidents/unit-year

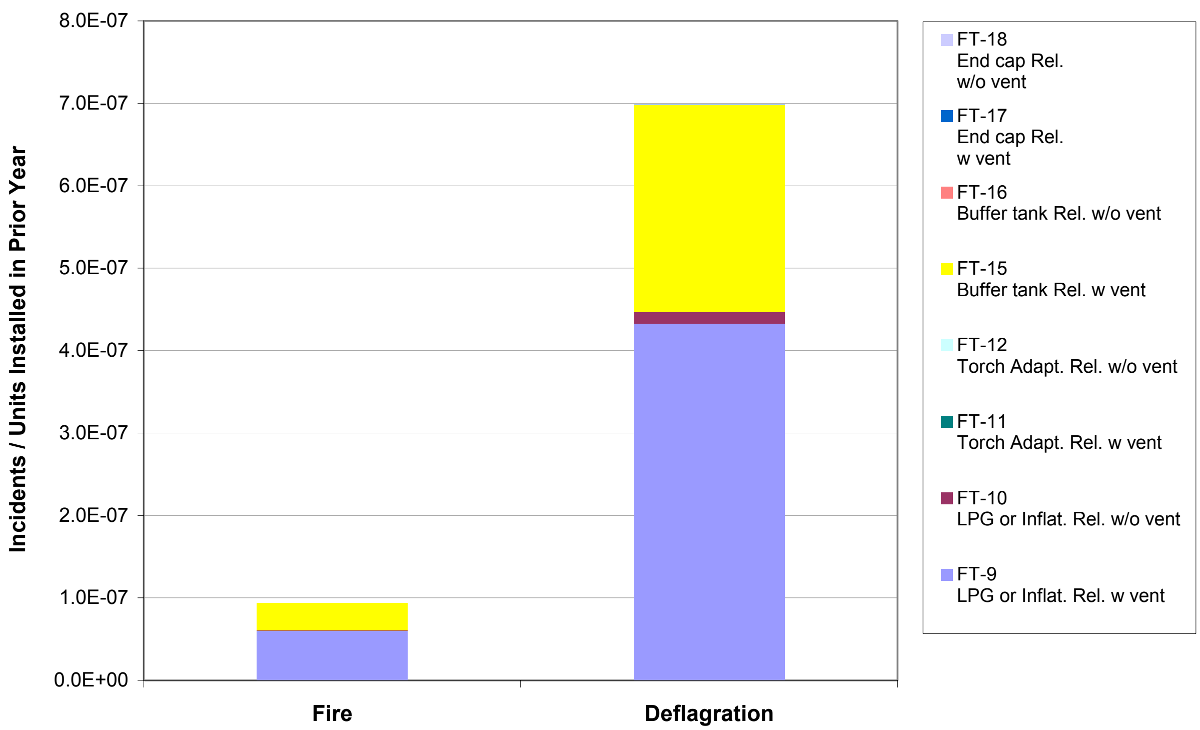


Figure 3-6. Consequence frequencies predicted by the FTA and ETA that have the units of incidents/units installed in prior year

Table 3-4 reiterates the annual HRA consequence probabilities and compares them to the annual probabilities of other hazardous or fatal events. (Recall that probabilities for the non-misuse failure consequences are associated with any year after an HRA installation; those for misuse failure consequences are associated only with the year following the HRA installation.) The probabilities of these other hazardous or fatal events were taken from Consumer Product Safety Commission (CPSC, References 15 and 16), Census Bureau (Reference 17), National Highway Traffic Safety Administration (NHTSA, Reference 18), and National Weather Service (NWS, Reference 19) data for the U.S.

Table 3-4. Probabilities of HRA failure consequences and other hazardous or fatal events

	Probability, 1 in the table value per year	Note
HRA failure event		
Deflagration due to non-misuse failures	7,000,000	
Deflagration due to misuse failures	1,400,000	
Structure fire due to non-misuse failures	14,600,000	
Structure fire due to misuse failures	10,700,000	
Other hazardous/fatal event		
Residential structure fire	300	1
Residential structure fire causing injury	18,700	2
Residential structure fire causing death	114,000	2
Being injured in a vehicle crash	95	3
Being killed in a vehicle crash	6,800	3
Being struck by lightning	686,000	4
Being fatally struck by lightning	6,470,000	4
Being electrocuted by a consumer product	1,880,000	5

1. CPSC estimates there were 337,300 unintentional residential structure fires in 1999 (Reference 15), the Census Bureau estimates there were 102,803,000 occupied housing units in 1999 (Reference 17); the ratio is 300
2. CPSC estimates there were 14,550 injuries and 2,390 deaths caused by unintentional residential structure fires in 1999 (Reference 15), NHTSA states the resident population in 1999 was 272,691,000 (Reference 18); the ratios are 18,700 and 114,000
3. NHTSA documents 3,033,000 injuries and 41,116 fatalities in motor vehicle crashes in 2001 (Reference 18) in a resident population of 284,797,000; the ratios are 95 and 6,800
4. NWS documents 415 incidents of people being struck by lightning in 2001, with 44 fatalities (Reference 19); with the 2001 resident population in note 3, the ratios are 686,000 and 6,470,000
5. CPSC estimates that there were 150 consumer product-related electrocutions in 2000 (Reference 16), NHTSA states that that the resident population in 2000 was 282,125,000 (Reference 30); the ratio is 1,880,000

Additional conclusions drawn from the FTA and ETA results discussed in Section 8.

4. Surveys of Design Information and Field Experience

4.1 Overview

The preliminary study discussed in Section 1.2 reached some preliminary conclusions based on component failure statistics from databases documenting the failure frequencies of components similar to those used in CNG vehicles and CNG fueling stations. However, these statistics were not derived from analyses of actual HRA components or actual CNG vehicle refueling practices. Further, preliminary conclusions were reached based on assumptions regarding CNG vehicle fuel system characteristics. Accordingly, among the recommendations of the interim study were to attempt to better establish the failure frequencies associated with actual CNG vehicle experience and to better define the design characteristics of actual CNG vehicles. This was accomplished in this study by surveying actual vehicle refueling appliance (VRA) users, CNG vehicles users, and fueling station operators to document their actual experience with component failures leading to natural gas fuel releases. Results of these surveys are discussed in Section 4.3. Also, information on the specific designs of vehicle fuel systems used in representative light-duty vehicles was developed through discussions with vehicle manufacturers and reviews of vehicle service and parts literature. Results of this design information development effort are discussed in Section 4.2 immediately following.

In addition, the results the initial safety evaluation performed in this project (in this initial evaluation the FTA/ETA assumed that the HRA compressor cooling air discharge was into the garage) concluded that one of the two greatest contributors to the predicted frequencies of structure fires and deflagrations was a gas supply pipe failure due to a vehicle striking the HRA. Initial study reviewers believed that the predicted consequence frequencies were too high, given the perceived frequency of fires and deflagrations caused by failed water heaters or vehicle strikes of water heaters. To address this concern, an effort to research information and data regarding garage-installed water heater hazards, accidents, and practices was undertaken. Results of this survey effort are discussed in Section 4.4.

4.2 CNG Vehicle Design Issues

The interim report (Reference 2) identified the fact that, while no HRA failures could produce a prolonged high-volume discharge of gas into the garage, a failure of the CNG vehicle fuel system during or subsequent to refueling could in fact result in such a potentially dangerous high-volume gas release. The interim study included an approximate analysis of a potential CNG vehicle blowdown. The CNG vehicle fuel system configuration assumed for the interim study analysis was based on readily available specifications for an aftermarket refueling receptacle. An objective of the present study was to repeat the analysis using more representative original equipment manufacturer (OEM) CNG vehicle fuel system component specifications. These specifications are discussed here, and the blowdown analysis is documented in Section 6.2. A parallel objective was to more accurately estimate the probability of events that might precipitate such a blowdown, and work in this regard is discussed in Section 4.3.

Two OEM LNG vehicles were selected as being representative: the Honda Civic GX and the Ford CNG Crown Victoria. Owner's manuals, parts catalogs, service manuals, and special service bulletins for these two vehicles were reviewed. Honda and Ford personnel familiar with these two CNG vehicles were interviewed by telephone (References 20 and 21). An SAE paper that describes Honda's CNG vehicle fuel system design theory (Reference 22) was also reviewed.

This research identified a number of relevant facts pertaining to these CNG vehicles' fuel systems between the fuel tank and refueling receptacle. Both the Civic GX and CNG Crown Victoria have two reverse-flow check valves. One check valve is in the refueling receptacle, per NGV1 design. For the CNG Crown Victoria, the fuel tank solenoid valve acts as a second check valve. When it is not energized, it is closed to outflow (but it can be opened by inflow, e.g., during refueling). For the Civic GX, the second check valve is inside the CNG fuel tank. It is integrated with the minimum-area orifice, which is discussed subsequently. This research identified the fact that Ford has had problems with receptacle check valves on various CNG models. Ford has changed designs and component suppliers for CNG receptacles, and they have issued service bulletins.

The Honda and Ford CNG fuel system designs both include purposely located minimum-area orifice restrictions, which control the thermal response during fast filling. In particular, these orifices ensure that the check valves are not the minimum-area flow restrictions where ice or hydrates might form due to the Joule-Thomson cooling effect. The Honda system design theory is explained in Reference 22, and we have assumed that the information in this reference applies to the Civic GX. Figure 4-1 shows the details of the Honda orifice and check valve in the CNG fuel tank. This figure was taken from Reference 22 and the Civic GX owners' manual.

Table 4-1 summarizes our understanding of the Honda Civic GX and Ford CNG Crown Victoria fuel systems with respect to check valves and orifice sizes. The Civic GX orifice diameter, which is based on information in Reference 22, was used for the blowdown analysis documented in Section 6.2. The fact that there are two reverse-flow check valves affected our estimates of the component failure probabilities in the fault tree analyses (Section 3.3).

4.3 CNG Vehicle Refueling Field Experience

To allow the better definition of the failure frequencies of CNG vehicle fuel system components that could result in natural gas releases during refueling events, a telephone survey of VRA users and other personnel involved with CNG vehicles and fueling stations was completed to gain information on their specific experience with fuel system component failures and gas releases associated with refueling events. The emphasis of this survey was documenting the frequency of receptacle and check valve failures. Results of these surveys are discussed in the following subsections.

4.3.1 VRA Users Survey

Eight VRA users who had reported vehicle fuel leaks in a prior survey conducted as part of the interim study were contacted to supply information on their experience with gas releases associated with CNG vehicle refuelings using VRAs. Four responded with information. All four reported receptacle check valve leaks. The responses are summarized in the following.

4.3.1.1 Port of Los Angeles

The Port of Los Angeles (POLA) operates a fleet of 18 CNG vehicles, mostly Ford pickup trucks and vans, plus a few Honda vehicles. All have OEM vehicle fuel systems. Most vehicles are refueled every other day. The time fill VRA at the port typically performs 10 vehicle refuelings per day, 21 work days per month, for an average of 210 refuelings per month.

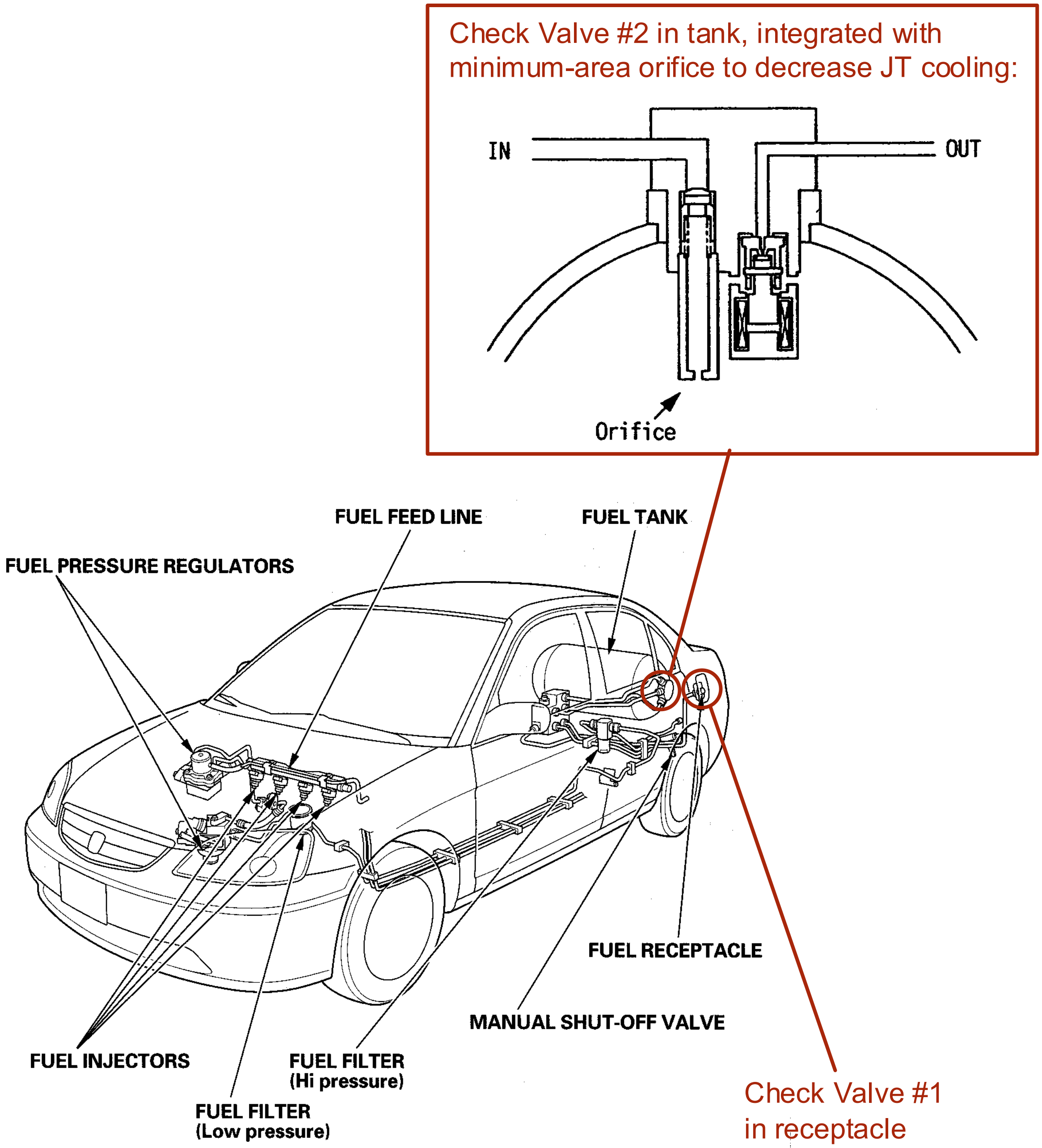


Figure 4-1. The Honda CNG vehicle fuel system design includes an orifice and check valve in the fuel tank

Table 4-1. Pertinent information regarding the Honda Civic GX and Ford CNG Crown Victoria fuel systems

Honda Civic GX	Two reverse flow check valves	Min. orifice dia. = 0.098 in (2.5 mm)
Ford CNG Crown Victoria	Two reverse flow check valves	Min. orifice dia. = 0.107 in (2.7 mm)

The port experienced five Ford vehicle check valve failures over a two year period ending in August 2003, although none resulted in a complete fuel tank blowdown. The leaks resulting from the check valve failure were perceptible by sound (hissing) and receptacle frosting. The port has also experienced receptacle o-ring removal while removing the refueling nozzle after refueling their Honda vehicles.

4.3.1.2 Miramar Marine Corps Air Station

The U.S. Marine Corps operates a fleet of 120 CNG vehicles at the Miramar Marine Corps Air Station. The fleet is comprised mostly of Ford sedans and vans, although a few Chevrolet bifuel sedans, Bluebird buses, and Dodge vans are included in the fleet. All but fewer than 10 vehicles have OEM fuel systems. The rest are aftermarket CNG conversions. The vehicle refueling station has both fast fill and time fill dispensers. Typically six vehicles per day are refueled using the fast fill dispenser, one per day using the time fill dispenser.

The Air Station experienced one check valve failure in its 120 vehicle fleet in the one year period ending in August 2003. This failure occurred during a fast fill refueling. However, again, this failure did not result in a tank blowdown. The Air Station has also experienced removal of the receptacle o-ring after refueling, leading to a gas leak evident by noise and odor. The o-ring is reinserted into the receptacle when this occurs. In addition, the Air Station had two drive away incidents while the vehicle was still connected to the dispenser over the 18 month period ending in August 2003.

4.3.1.3 Sacramento Housing Authority

The Sacramento Housing Authority operates a fleet of 35 CNG vehicles. Six of these, three Ford vehicles and 3 Dodge vehicles, have experienced check valve leaks. Based on the time period when the incidents occurred, the Authority attributes these leaks to debris left in the station refueling lines after the fueling station was expanded. The contractor performing the expansion evidently did not completely flush the fuel lines, leaving dirt in them. The leaks were perceptible by odor, though no noise was experienced. The Authority representative reported no check valve leak incidents had occurred during the six-month period just prior to the August 2003 interview. Like the above two users, the Authority has also experienced receptacle o-ring removal incidents. The o-ring comes off when the fueling nozzle is removed too quickly, leading to a gas leak during the next vehicle refueling. However, the Authority also notes that the frequency of o-ring removal problem decreases with user experience.

4.3.1.4 Alabama Gas Corporation

Alabama Gas Corporation operates a fleet 400 CNG vehicles. Out of this fleet, the company has experienced 12 to 15 check valve leaks in their GM trucks. They were common initially, and associated with user personnel failing to replace the receptacle dust cap after a refueling, allowing debris to enter the receptacle leading to a leak in a subsequent refueling. The incidence of leaks declined as user personnel developed experience. These leaks were perceptible by noise and by nozzle/receptacle frosting on humid days.

4.3.2 General CNG Vehicle Experience

A number of individuals with general experience in CNG vehicle use, fleet operation, and refueling station operation other than specific VRA users were surveyed to gain more overall information on the incidence of receptacle check valve leak and fuel tank blowdown incidents during vehicle refuelings. Highlights of the information developed in this survey are as follows.

Both time fill and fast fill operations have advantages and disadvantages with respect to affecting the frequency of check valve leaks. In fast fill operations, the potential for ice or hydrate formation in the vehicle refueling line is greater, and this can lead to ice or hydrate particles clogging the check valve and preventing it from properly seating after the refueling is completed. Moreover, in a fast fill operation, the receptacle check valve is pushed essentially completely open, increasing the potential for sticking in this position. Also, the high gas velocities accompanying the fast fill operation tend to push any upstream debris further into the vehicle refueling line, leading to an increased probability of check valve leakage due to deposited debris preventing complete valve closure. In contrast, during time fill operations, the check valve would not be placed in a fully open position. In this partially closed position, the valve could act as a debris filter, and fail to properly seat when contaminated with any deposited debris.

Categories of debris that can cause check valve leaks include ice or hydrates formed during fast fill operations, pieces of worn receptacle o-ring material, and other debris that enters the receptacle opening if vehicle users do not properly replace the receptacle dust cap after refueling.

The general observation of many of the individuals surveyed was that earlier aftermarket CNG conversions appear to be more prone to receptacle leaks than OEM CNG vehicles.

A local distribution company (LDC) located on the U.S. east coast was surveyed. This company operates 12 refueling stations that service 80 CNG vehicle fleets totaling 600 to 700 light duty vans, pickup trucks, and automobiles, including 130 vehicles in the LDC’s own fleet. Each fleet vehicle needs to be refueled nominally 10 times per month, so the LDC services 6,000 to 7,000 refuelings per month over its 12 station system.

This LDC has experienced no vehicle fuel tank blowdown events, at least in the five years ending in 2003. However, during a recent cold winter (2002 – 2003), 40 receptacle gas leaks occurred. The representative was unsure whether the leaks were related to ice or hydrate formation, but did acknowledge that no leaks were experienced since the weather turned warmer later in 2003. The LDC has had problems with receptacle o-rings blowing out, a problem also experienced by the VRA users, as noted in Section 4.3.1. A vehicle driveway with the dispenser refueling line still connected to the vehicle occurs about once per month over the 12 station system.

An individual familiar with the Atlanta CNG market, which has about 100 CNG refueling stations servicing a customer base of over 1,000 vehicles, was that one check valve failure was experienced per month. These failures were invariably associated with fast fill operations, with very few to no failures associated with time fill operations. This individual also reported his awareness of a single vehicle storage tank blowdown incident that occurred in 1995. Details of this incident are as follows.

The vehicle involved was a Ford Taurus equipped with an aftermarket CNG conversion (bifuel GFI kit with a manual shutoff valve on a single tank). The vehicle had just completed a fast fill refueling (dispenser capacity of about 100 cfm) totaling about 5 gallons of gasoline equivalent (GGE) at a final fuel tank pressure of 3,000 psi, and the dispenser had shut off. The vehicle user turned the manual 3-way valve to the off position, then to the vent position to bleed the pressure off the fill hose. As soon as the as the valve was placed in the vent position, the sound of high pressure gas flowing through the hose again became apparent, with gas being released to the atmosphere from the dispenser emergency vent at the top of the fueling canopy. The noise was very loud and a strong gas odor was quickly noticed. The noise and gas discharge continued even after pushing the emergency stop (ESD) buttons at the station. All persons present moved away from the vehicle and fueling island after pushing the ESD, and the fire department and LDC safety personnel were summoned. After five to seven minutes the discharging gas noise began to subside, until it gradually stopped altogether. By the time the fire department arrived only the odor of gas remained, with no further signs of a gas discharge or leak apparent. When the vehicle user was informed that it was safe, he disconnected the fill hose and attempted to drive away. However, the vehicle fuel tank was completely empty. After investigation, it was determined that no failure associated with the refueling station or its compressor had occurred. Instead, it was found that the vehicle receptacle check valve had completely failed, stuck in the open position. The entire contents of the full vehicle fuel tank had discharged to atmosphere through the dispenser's vent hose, a tank blowdown event. Fortunately no gas ignition occurred and no personnel injuries were sustained. As noted above, this is the only, single event of this type in the Atlanta area of which the knowledgeable individual reporting it is aware.

4.4 Water Heater Impact Information

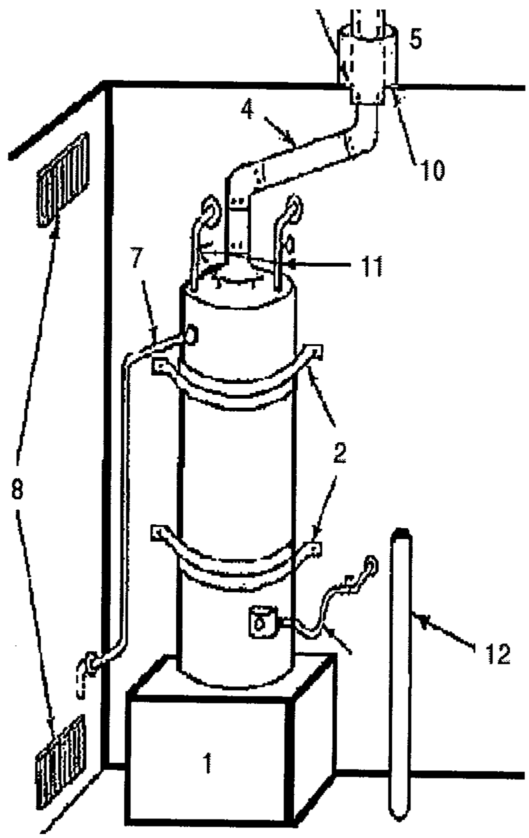
As discussed in Section 4.1, information pertaining to garage-installed natural gas fueled water heaters was researched to determine what can be learned about potential vehicle impacts. This research was motivated by an interim FTA/ETA result indicating that vehicle-HRA impacts that might rupture the gas supply line account for a significant fraction of the total predicted fire and deflagration frequencies. Some of the inputs to this portion of the FTA and ETA were rough estimates, and an objective was to determine if there is a basis for more accurate estimates. In particular, reviewers suggested that information and data regarding garage-installed gas water heaters may be available and pertinent. This section summarizes the results of this brief garage-installed water heater research.

This research revealed that there is considerable statistical data and many research reports pertaining to flammable liquid (e.g., gasoline) vapors in residential garages being ignited by gas water heaters. Data and reports regarding fires caused by lint accumulation and overheating in garage-installed natural gas clothes dryers are also available. However, none of these reports or data sources included any information regarding impacts of vehicles with garage-installed gas appliances.

While no statistical data were identified, general and anecdotal information indicates that vehicle impacts with garage-installed water heaters are of serious concern in some situations. Three examples of this general and anecdotal information are summarized in the following paragraphs.

National Fire Protection Association (NFPA) Standard 54 (The National Fuel Gas Code, Reference 23), Part 5-19 (which addresses installation of gas utilization equipment in residential garages), Subpart (b) states: "Such equipment shall be located or protected so it is not subject to physical damage by a moving vehicle." It is concluded that this subsection would not be part of NFPA 54 if vehicle inputs with garage-installed gas appliances were a non-issue.

Many but not nearly all local building codes address the possibility of bollards being installed in residential garages to protect water heaters from vehicle impacts if the water heater is located where such impacts are possible. Figure 4-2, which is abstracted from the City of San Mateo, California, Building Division documents, is an example of such a local code.



12. Pipe Bollard: If the water heater is located in the path of travel of a vehicle then a protective 3" pipe bollard may be required to be installed so as to protect the water heater from damage. Pipe is to be 3' above floor and set into a 2' deep concrete foundation and filled with mortar (new construction only).

Figure 4-2. Example from local building code pertaining to garage-installed water heaters (Reference 24)

Reference 25 is an example of a home construction expert's advice responding to an inquiry regarding the necessity of bollards to protect garage-installed water heaters from vehicle impact. A portion of this advice states "…from the standpoint of truly adequate protection, the installation of a steel post (known as a bollard) would be a worthwhile upgrade. Furthermore, some building departments have required the placement of a bollard, regardless of the raised platform. The justification for this proactive mandate is well considered. Raised platforms generally consist of wood framing and drywall. This construct would easily give way when impacted by a 10-mile-an-hour car or truck. In that event, the water heater could fall, causing the gas pipe to rupture, with varying consequential possibilities. On the other hand, you might be driving a four wheel drive SUV, with a bumper that is higher than the raised platform. In that event, careless parking procedures would enable that bumper to assertively engage the base of the water heater with equally adverse results. Although a bollard may not be required by the building department in your area, an upgrade would be highly advisable."

These examples suggest that vehicle impacts with garage-installed water heaters have been a concern in some situations. However, they contain no statistical data, and the relation of garage-installed water heater vehicle impacts to potential garage-installed HRA vehicle impacts is largely conjectural.

5. Residential Garage Infiltration Rates

5.1 Objective and Approach

The preliminary HRA safety evaluation (Reference 2) quickly identified the critical importance of the garage infiltration[2] rate, because it strongly affects the likelihood that a given HRA-related gas leak might cause the gas concentration to exceed the lower flammability limit (LFL) in some region in the garage. Unfortunately, while infiltration rates in the normally occupied portions of homes are well characterized in the literature, infiltration rates in residential garages are not.

The infiltration air flow rate (I) through a building or a room within a building has units such as standard cubic feet per minute (scfm). However, infiltration is usually characterized by the air changes per hour (ACH) of a building or room, which is the infiltration air flow rate in scfh (or in scfm times 60 min/hr) divided by the volume (V) of the building or room in cubic feet:

$$ACH = \frac{I}{V}$$

What little residential garage infiltration data is available in the literature covers a broad range, and this has forced prior considerations of CNG and hydrogen vehicle refueling in residential garages to approach the subject in a parametric fashion. For example, the TNO study (in Reference 3) cited in Section 1.2 states that the number of air changes per hour (presumably for a residential garage) can vary from 0.5 to 2, but no literature sources are referenced. The PrimaTech study (also in Reference 3) appears to copy the TNO study, and states that the number of air changes per hour can vary from 0.5 to 2.0, without indicating their information source. A more recent University of Miami study of hydrogen-fueled vehicle safety (Reference 26) used 0.2 to 2.92 air changes per hour in their analyses. These numbers were based on consideration of an ASHRAE standard (Reference 27, which is primarily for occupied residences, but includes a recommendation of 100 scfm per car for residential garages) and experiments by GEOMET (Reference 28, which addresses electric vehicle recharging inside residential garages).

Because residential garage infiltration rates are so critically important to HRA safety, and because so little data were available regarding this subject, an objective of this evaluation was to carry out some simple analyses and measurements to generate a very preliminary and approximate indication of the statistical range of residential garage ACH levels. Our basic approach to accomplishing this objective is summarized below, and details as well as quantitative results are provided in subsequent sections:

- We developed a garage questionnaire survey form and we asked 33 friends and colleagues in the United States and Canada to examine and measure their garage, fill out the form, and

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[2] The American Society of Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE) defines infiltration as the uncontrolled flow of air through unintentional openings. ASHRAE defines ventilation as the flow of air through intentional openings (natural ventilation) or induced by mechanical means (forced ventilation).

return it to us. The form was designed to be simple enough so that people would not be discouraged from filling it out, yet comprehensive enough so that it provided the information we needed to estimate the ACH of their garage. The residential garage survey is discussed further in Section 5.2 and Appendix C.

- We applied existing correlations to develop a methodology for estimating approximate garage ACH levels from the data on the survey forms and typical wind velocities from available weather databases. The methodology is summarized in Section 5.3, and details of the methodology are documented in Appendix D.

- We measured the air infiltration rates in three garages using the tracer gas decay method. These measurements were compared with the ACH estimates based on the survey forms and approximate methodology. The tracer gas decay method, the three garage measurement results, and comparisons with estimates are presented in Section 5.4.

- An approximate residential garage ACH population distribution graph based on the above measurements and analyses, tabulation of pertinent ACH statistics (mean, median, etc.), and graphs of other garage statistics (e.g., volume population distribution) are presented in Section 5.5.

The residential garage infiltration rate information generated in this fashion was used to estimate certain event tree probabilities that involved, for example, the likelihood that a gas release inside a garage will form a flammable mixture. Based partially on the interim results of this analysis, FuelMaker modified the HRA installation plan so that the 80-scfm compressor cooling air flow is always discharged outside the garage as discussed in Section 2.1. This changed the role of the garage infiltration information reported in this section. Infiltration was previously the primary garage air flow mechanism affecting mixture ratios in case of a gas release inside the garage. After the HRA installation plan change, 80-scfm ventilation became the primary garage air flow mechanism affecting mixture ratios, and infiltration applies only if the HRA fan does not operate for one of the reasons characterized by the intermediate event trees as discussed in Section 3.3.

5.2 Garage Survey

A garage questionnaire survey form was developed for the purpose of collecting the information needed to estimate air infiltration rates and ACH. The strategy was to distribute these survey forms to owners or renters of homes with garages in a variety of geographic locations, to ask them to complete the form based on some simple observations and measurements, to input data from the forms into an approximate ACH methodology (described in Section 5.3), and to organize the results to provide an approximate statistical distribution of residential garage ACH levels. It was also determined that, as long as ACH-related garage data were being collected, other information of interest to this project (e.g., wood or masonry garage construction, ignition sources in the garage) would also be collected.

The Residential Garage Infiltration Survey Form categories were:

- Purpose
- What we are asking you to do

- Example
- Location
- Sketch
- General configuration
- Dimensions
- Garage "vehicle" door(s)
- Garage "people" door(s)
- Garage windows
- Intentional ventilation openings
- Wind conditions/shielding
- Ignition sources
- Other
- Return and questions

An objective was to make the survey form easy to understand and fill out (so as not to discourage recipients) while ensuring that it provided all the information that we needed to estimate the garage ACH. A number of compromises were made to achieve this objective. For example, we asked for the basic width, depth, and height (to lowest ceiling) of rectangular shaped garages, but we did not ask for peaked ceiling/roof dimensions (which would have required a stepladder). Instead, we asked if the ceiling/roof was slightly or significantly peaked or sloped, and we estimated the additional garage volume accordingly.

The garage survey forms were formatted so that they could be filled out electronically on a computer or printed out and filled out with a pen or pencil. They could be returned to us by mail, FAX, or e-mail. The form content and format was subject to a number of review and revision cycles before finalization. An example Residential Garage Infiltration Survey form is included in Appendix C.

Garage survey forms were completed by the participants in this project, and we also distributed forms to friends and colleagues. An effort was made to achieve a reasonable geographic distribution, but heavy concentrations in regions near the project participants was unavoidable, e.g.: the San Francisco Bay Area (TIAX-Cupertino and St. Croix Research), the Los Angeles area (TIAX-Irvine), the New England area (ioMosaic), and the Toronto area (FuelMaker). A total of 33 garage survey forms were received and analyzed. Figure 5-1 shows the geographic locations of the garages for which survey forms were received. It should be emphasized that 33 is not an adequate population for precise statistical analyses, our geographic coverage was nonuniform, and the fact that the survey form recipients were friends and colleagues of the project participants probably introduced some biases. However, the goal was simply to improve on existing garage ACH distribution information, and a comprehensive high-precision survey was inconsistent with the project scope.

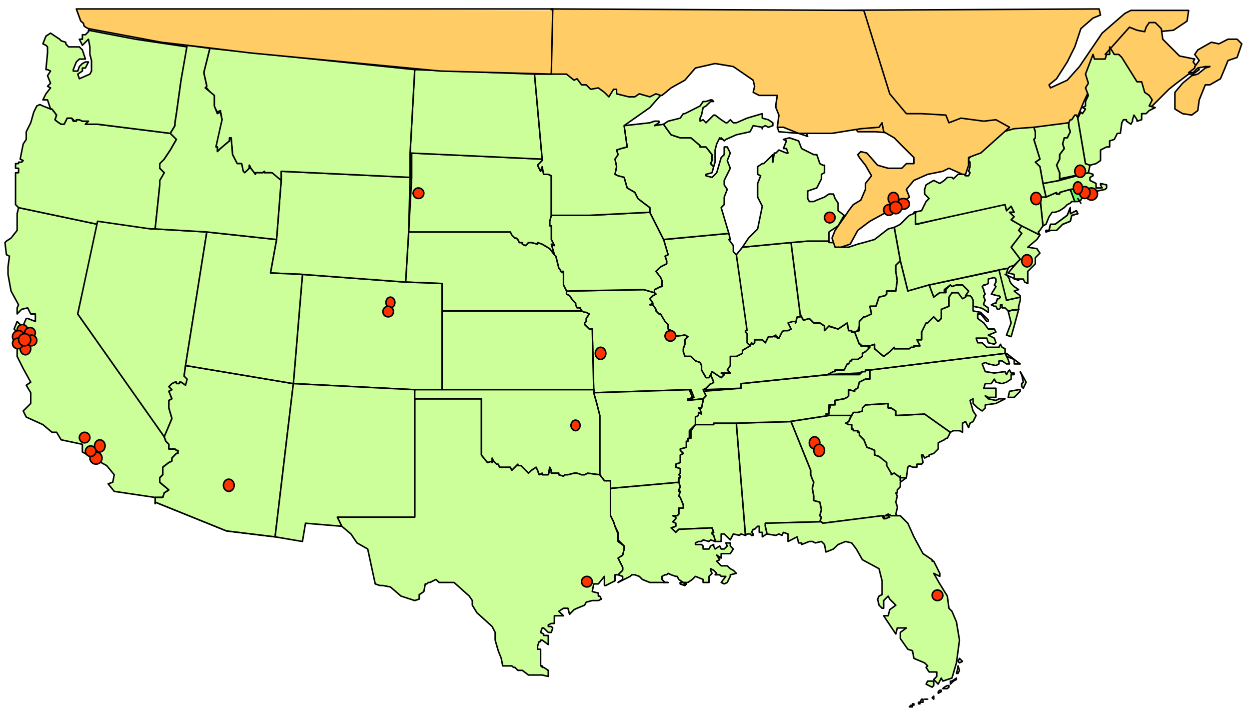

Figure 5-1. Geographic locations of the 33 residential garages surveyed

5.3 Garage Infiltration Rate Estimation

Air infiltration rates and ACH levels were estimated from the garage survey results using models that have been developed for building energy audit purposes. The models and our estimation methodology are described in detail in Appendix D and summarized here.

The main semi-empirical model we applied is one developed by the Lawrence Berkeley Laboratory (LBL) and published in the ASHRAE Fundamentals Handbook (Reference 29). The basic equation and our approach to evaluating its various terms is summarized below:

$$Q = L\left(C\Delta T + Bv^2\right)^{0.5}$$

Where:

Q = The infiltration rate (also denoted as I; can be converted to ACH)

L = The total effective leakage area (our approach to evaluating this important term is summarized in the following text)

C = A stack coefficient that depends on the number of stories of the garage structure (a table of values is provided in the ASHRAE Handbook)

ΔT = The average indoor-outdoor temperature difference (we used the ASHRAE tabulation of geographic temperature data, and we assumed that ΔT is approximately one-half of the “mean daily temperature range”)

B = The wind coefficient or “shielding factor” (a table of shielding factor values is provided in the ASHRAE Handbook, and the 5 options on the survey form correspond to the 5 shielding factors tabulated by ASHRAE)

v = The average wind speed in the vicinity of the garage at the time of interest (we used ASHRAE tabulations of geographic wind data, and we evaluated v as the average prevailing wind velocity)

The garage survey form (Appendix C) includes the number of “people” doors, windows, and ventilation openings. We used ASHRAE guidelines for estimating the leakage area (L) contributions of the people doors and windows, and we calculated the effective leakage area of any vents based on the measurements provided on the survey form. The dominant contribution to the effective leakage area for most garages is from the “vehicle” door or doors. The garage survey form provides the garage car door dimensions. It also provides the gap dimensions (measured or estimated) if the gaps are obvious, or notation that they fit tightly (gaps too small to measure) or have weather stripping if that is the case. We used what is referred to as the “Baker Method” (Reference 30) to estimate the effective garage car door leakage area from these data. In effect, the Baker Method is a means of relating the geometry of an opening to its discharge coefficient. The details associated with the application of the Baker Method are provided in Appendix D.

The estimated garage total effective leakage area, L, is simply the sum of all of its components. Given this value of L and all the other terms described above, the garage infiltration rate, Q, can be calculated. The garage volume was calculated from the information on the survey forms, and this enabled calculation of ACH.

The garage infiltration rates and ACH values calculated in this fashion should be regarded as approximate averages. They are approximate because many factors were not accounted for or averaged out in the correlations used (e.g., the angle between the prevailing wind direction and the garage openings was not part of the model) and estimation was involved in filling out and interpreting the survey forms. The results represent average infiltration rates and ACH values because calculations were based on average local wind speeds and temperatures (i.e., the ACH distributions associated with local wind speed statistical distributions were not considered).

Section 5.4 describes actual measurements of ACH for three garages and discusses the comparison of the measurements with estimates based on the methodology described above. Section 5.5 summarizes the distribution of ACH estimates for the 33 garages surveyed as well as other garage survey results.

5.4 Garage Infiltration Rate Measurements

It was originally planned to make at least one direct measurement of the air infiltration rate in a residential garage and to compare this with our prediction to validate (or revise) the methodology. However, because we were able to use NREL equipment and take advantage of measurement know-how developed under other NREL projects, we were able to measure infiltration rates in three garages. The measurement methods, garages, results, and comparisons with predictions are summarized in this section.

The tracer gas decay method was used to measure the air infiltration rates in the garages. This is a standard method for building infiltration or air exchange measurement, and it is described in the ASHRAE Fundamentals Handbook (Reference 29) as well as various American Society for Testing and Materials (ASTM) publications. The method involves injecting a small quantity of tracer gas into the space of interest, allowing the gas to mix with the air in the space, and recording the concentration of gas in the space over time. The gas concentration will decay with time as fresh air leaks into the space and gas-air mixture leaks out of the space.

The tracer gas concentration decay rate can be related to the air infiltration rate by simple mass balance considerations. A closed-form solution results for the case where the infiltration rate does not vary with time, and the garage ACH is equal to the natural logarithm of the original-to-measured gas concentration ratio divided by time. The physics and equations involved are similar to average gas concentrations in garages with HRA leaks, which are discussed in Section 6.

The tracer gas method developed under various NREL building energy programs uses sulfur hexafluoride (SF_6) as the tracer gas, because it is inert, nontoxic, nonreactive, and easily detected. SF_6 contained in small pressure vessels (Figure 5-2) is released to provide an initial concentration of about 5 to 10 ppm (this initial concentration is not critical to the measurement accuracy). The mixing of SF_6 in the garage space is aided by a very small fan that has a negligible effect on the garage ACH. Sampling lines are placed in the garage interior, and the lines draw the sample out of the space (typically under a door) and to the measurement instrumentation. The instrumentation used for these measurements was an NREL Bruel kjaer photo-acoustic spectrometer (Figure 5-3). A wind-speed anemometer is located as high as practical near the structure (e.g., on the roof of the house associated with one of the garages measured, as shown in Figure 5-4). Thermocouples are used to measure the temperature inside of the structrure space as well as the exterior temperature. The gas concentration, wind speed, and temperatures are recorded as functions of time using a data acquisition system.

The locations and characteristics of the three garages for which infiltration measurements were made are listed in Table 5-1. The house in Spring, Texas (near Houston) is used by NREL for various building energy studies. It has an attached two-car garage. The infiltration test equipment and personnel were already in this area, so this garage was selected as the first one to be tested. Figure 5-5 is a photograph of the Spring, Texas, house, and Figure 5-6 shows the inside of the garage.

On the day when the Spring, Texas, garage infiltration measurements were made, the wind speed was exceptionally low. The measured wind speed varied from zero to 3.7 mph, and the average was about 1.4 mph. For comparison, the previously cited ASHRAE database indicates that Houston has an average prevailing wind speed of 12.7 mph. Figure 5-7 shows the measured

Figure 5-2. The SF_6 tracer gas is released into the garage to provide a starting concentration of 5 to 10 ppm

Figure 5-3. The NREL Bruel kjacer photo-acoustic spectrometer is used to measure the SF_6 concentration

Figure 5-4. An anemometer is usually installed high on the building roof to measure wind speed

Table 5-1. Garages for which air infiltration measurements were made

Location	Home and Garage Type	Volume	Garage Characteristics	Remarks
Spring, Texas (near Houston	One-story single-family house with attached 2-car garage	3,040 ft^3	Two paneled and overhead-retracting garage “car” doors have significant air gaps	This home is used for NREL building energy studies
Fremont, California (between Oakland and San Jose)	Three-story condominium with 2-car garage on bottom floor	4,076 ft^3 (includes utility area)	One paneled and overhead-retracting garage “car” door has significant air gap at top	Garage has substantial wind shielding due to adjacent 3-story condominiums
San Jose, California	One-story single-family house with attached 2-car garage	3,770 ft^3	One paneled and overhead-retracting garage “car” door is well sealed by vinyl flaps	Vent opening was sealed off for most of the test to provide a low ACH case

Figure 5-5. The first garage infiltration measurement was made at this Spring, Texas, house

Figure 5-6. The Spring, Texas, house is a new home with an attached two-car garage

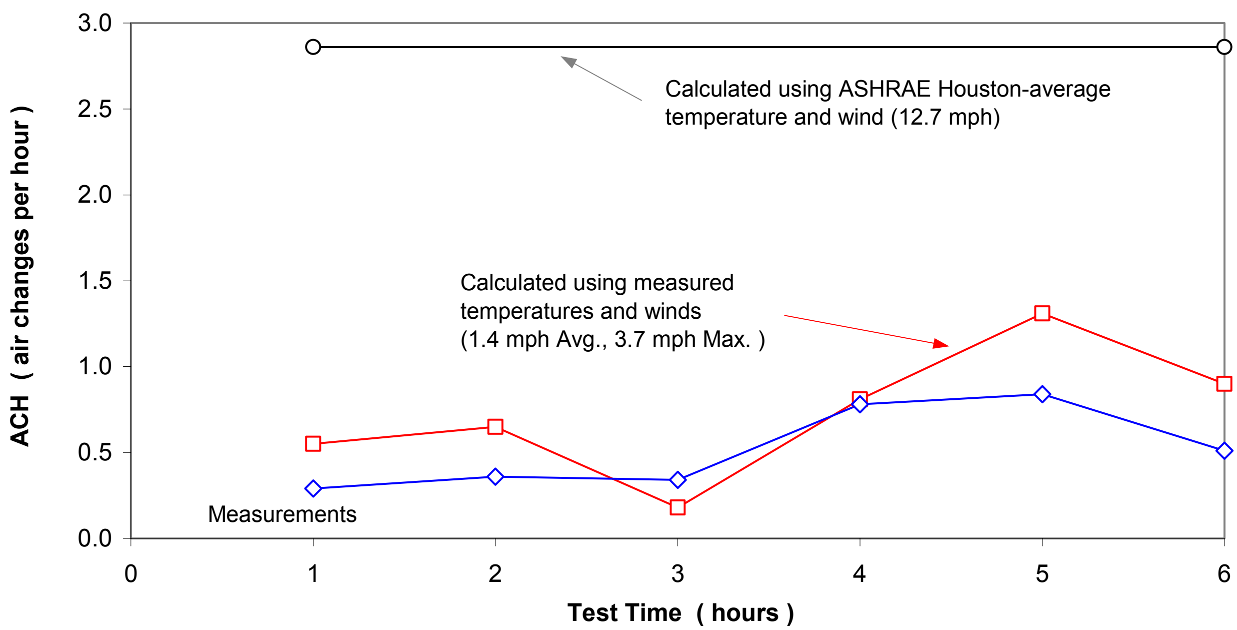

Figure 5-7. Spring, Texas, garage ACH measurement compared with predictions using measured wind speed and Houston-average wind speed

ACH as a function of time over a 6-hour period when the wind speed was at least high enough to produce meaningful data. This is compared with the ACH calculated using the methodology explained in Appendix D, inputs from the completed survey form for the Spring, Texas, garage, and the actual wind speed measured with the anemometer. Figure 5-7 also shows the calculated ACH based on the Houston-average wind speed of 12.7 mph.

Figure 5-7 indicates that the agreement between the measurement and the calculation is surprisingly good considering the exceptionally low wind speed and the very approximate nature of the calculation methodology. The measurement was somewhat less than 0.5 air changes per hour during the first three hours and somewhat more (but less than 1 air change per hour) during the subsequent three hours. This relatively low ACH is strictly due to the very low wind speed. The calculation using the Houston-average wind speed is about 2.8 air changes per hour. This indicates that this is a relatively "leaky" garage, and this is due to the relatively large (approximately 3/8 inch) gaps around the garage "car" doors.

Two measurements were then made for garages in the San Francisco Bay Area. Figure 5-8 shows the garage on the ground-level floor of the three-story condominium in Fremont, California. The basic characteristics of this garage and condominium are listed in Table 5-1. A noteworthy characteristic of this garage is the substantial wind shielding because of the "canyon-like" environment associated with the configuration of this condominium complex (Figure 5-9). It was originally anticipated that this would be a relatively low-leakage garage, but it was subsequently observed that, while most of the garage "car" door fit tightly, there was a substantial air gap along the top of the door.

Figure 5-10 shows the measured ACH and wind speed for the Fremont, California, garage over a four-hour period. This is compared with the calculated ACH based on the measured wind speed and the average prevailing wind speed (4.6 mph) published by ASHRAE for San Jose, California. Figure 5-10 shows that the measured wind speed was roughly half of the San Jose average until late in the test, when it decreased substantially. The figure also indicates that there were substantial fluctuations in the measured ACH (which is actually also a calculation, based on tracer gas concentration measurement differences, as previously discussed) during the first hour of the test. However, the overall conclusion from Figure 5-10 is that the calculated and measured ACH are in quite good agreement.

For the third garage ACH measurement, it was desired to test a relatively low-leakage garage in order to check the calculation methodology in the low-ACH regime. We identified a house in San Jose with an attached two-car garage (Table 5-1 and Figure 5-11) that had recently had a new garage door installed. The new upward-retracting hinged-panel garage door was sealed with vinyl flaps (Figure 5-12), which appeared to ensure low leakage (i.e., a relatively low contribution to the "L" term in the equation discussed in Section 5.3). This particular garage also had a small vent opening near the ground on one side, which we sealed during most of the measurement period.

The ACH and wind speed measured over an eight-hour period for the San Jose garage are shown in Figure 5-13. This figure also shows the ACH prediction based on the measured wind speed and the San Jose average prevailing wind speed of 4.6 mph. Note that the measured wind speed increased during the first five hours of the test and then fluctuated near an average of

Figure 5-8. The ACH of this condominium garage in Freemont, California, was measured

Figure 5-9. The Fremont, California, garage had substantial wind-shielding due to the "canyon-like' configuration of the condominium complex

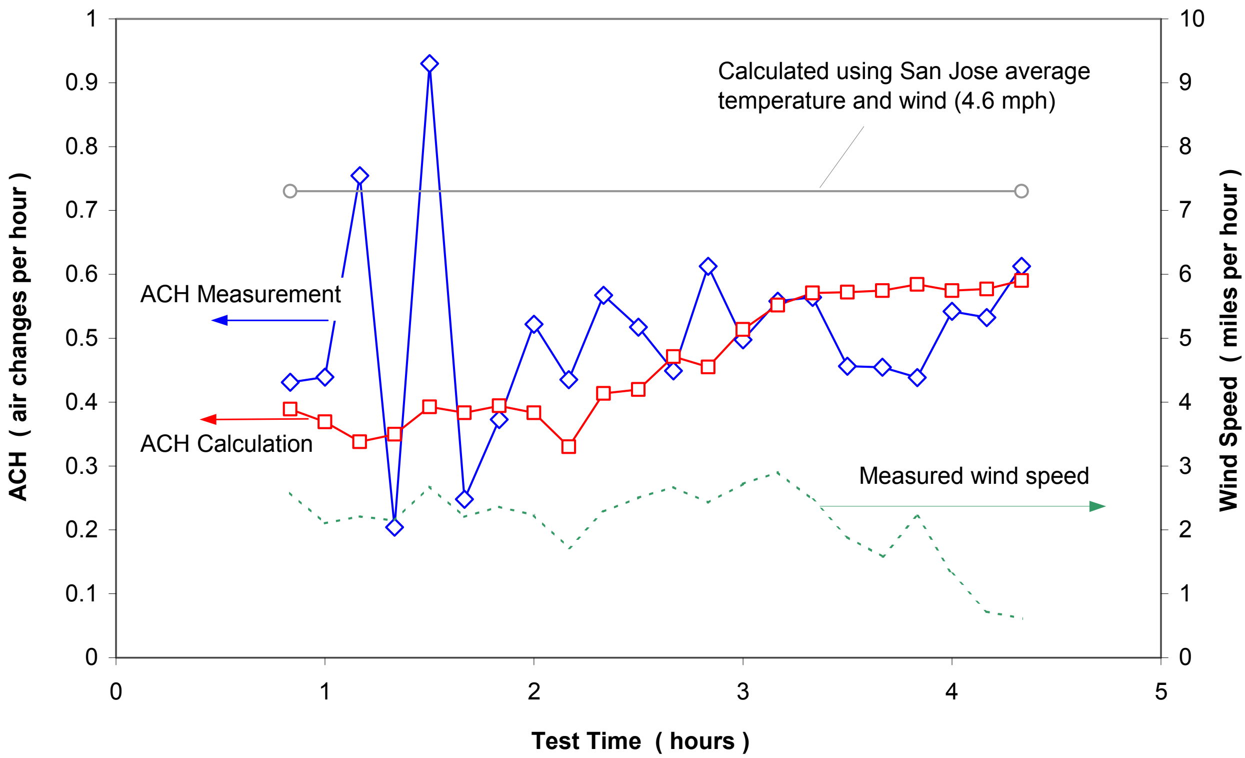

Figure 5-10. Fremont, California, garage ACH and wind speed measurements compared with ACH predictions using measured wind speed and San Jose average wind speed

Figure 5-11. The ACH of this attached two-car garage in San Jose, California, was measured

Figure 5-12. The San Jose garage was selected because the door was sealed by vinyl flaps, which were anticipated to provide a low ACH

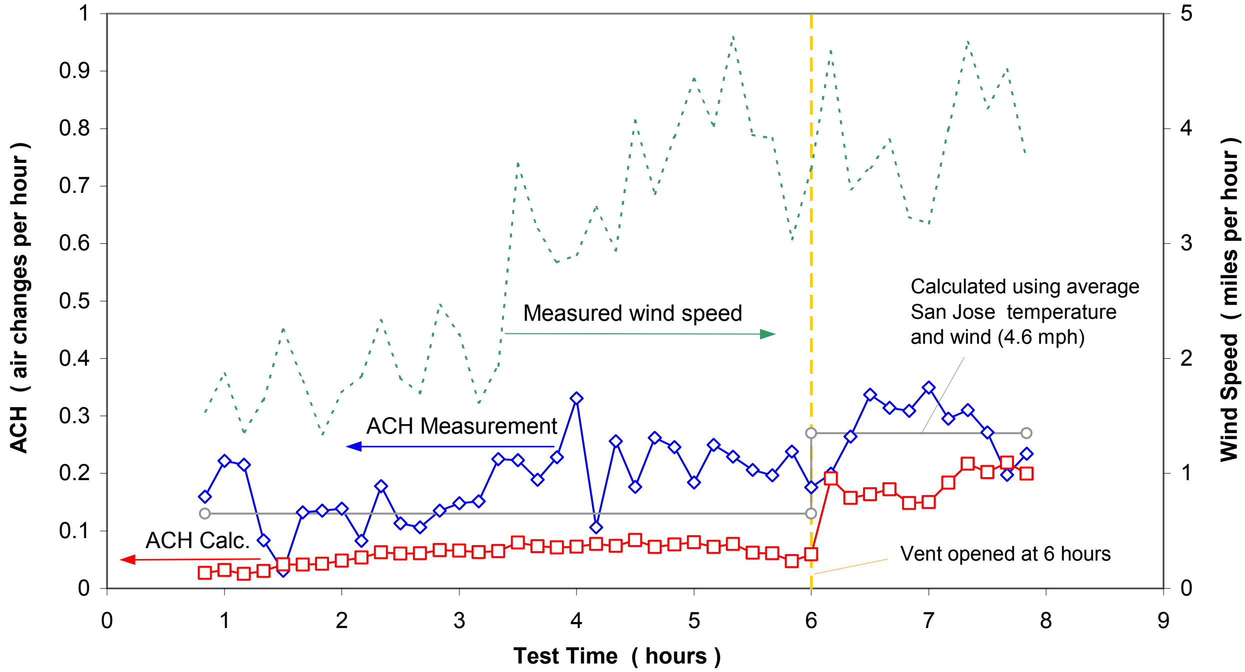

Figure 5-13. San Jose, California, garage ACH and wind speed measurements compared with ACH predictions using measured wind speed and San Jose average wind speed

approximately 4 mph (i.e., near the average published by ASHRAE). Because this test was over a relatively long time period and measurements during the first few hours appeared to be consistent, we decided to remove the seal from the vent (which was approximately 4 inch x 5 inch) at six hours in order to obtain data for this configuration.

Figure 5-13 shows that, with the vent sealed, the calculated ACH significantly underpredicts the measurement. When the vent was unsealed, the measured ACH increases as expected, but the predicted ACH increases by a higher percentage. The results are that the calculated ACH more nearly predicts the measurements after the vent is unsealed. We speculate that the reason for the ACH underprediction may be associated with air leakage paths that we did not see and account for when evaluating the "L" term in the equation discussed in Section 5.3. This garage had obviously been modified a number of times, and there were areas where openings in the interior sheet rock may have been in communication with openings in the exterior siding, for example.

In summary, the tracer gas method was used to measure the air infiltration rates of three residential garages, which represented a range of "leakage" characteristics and other factors. The measured ACH levels were compared with predictions using the methodology discussed in Section 5.3. For two of the three garages, the predictions were in very good agreement with the measurements. For the third garage, the measured ACH was substantially underpredicted while the vent was sealed, and slightly underpredicted when the vent was unsealed. We concluded that the methodology should not be expected to predict ACH more accurately than a factor of roughly two, due to the many approximations involved. Given the approximate nature of the prediction methodology, we regarded it to be suitably validated by the ACH measurements.

5.5 Garage Infiltration Rate Statistics

Figure 5-14 shows the distribution of ACH values for the 33 garages for which survey forms were completed (the locations of these garages were indicated in Figure 5-1). These ACH values were calculated using the methodology discussed in Section 5.3 and Appendix D, i.e., they are based on the information in the survey forms and the average prevailing winds and temperature ranges at the nearest city listed in the ASHRAE weather database. The ACH values are graphed as a population distribution in Figure 5-14, i.e., the vertical scale indicates the percentage of garages with ACH values higher than the ACH value on the horizontal scale.

The calculated ACH values range from a low of 0.028 (for a very large garage in Mesa, Arizona, with weather stripping around the door) to a high of 5.92 (for a small garage in Brampton, Ontario, with a very loose-fitting one-piece swing-up door). As indicated in Figure 5-14, the average ACH was 1.0 and the median ACH was 0.54. The tenth and ninetieth percentile ACH values are 2.62 and 0.113, respectively (based on linear interpolation between data points). Correlation of the computed ACH values with the garage characteristics from the survey forms indicates that, in general (with some exceptions), the garages fall into the three ACH ranges summarized in Table 5-2.

The residential garage ACH statistics summarized in Figure 5-14 are needed to estimate various event tree probabilities, as discussed in Section 3.4. Other residential garage statistics, which are potentially pertinent to the HRA event tree analyses, were also abstracted from the survey forms.

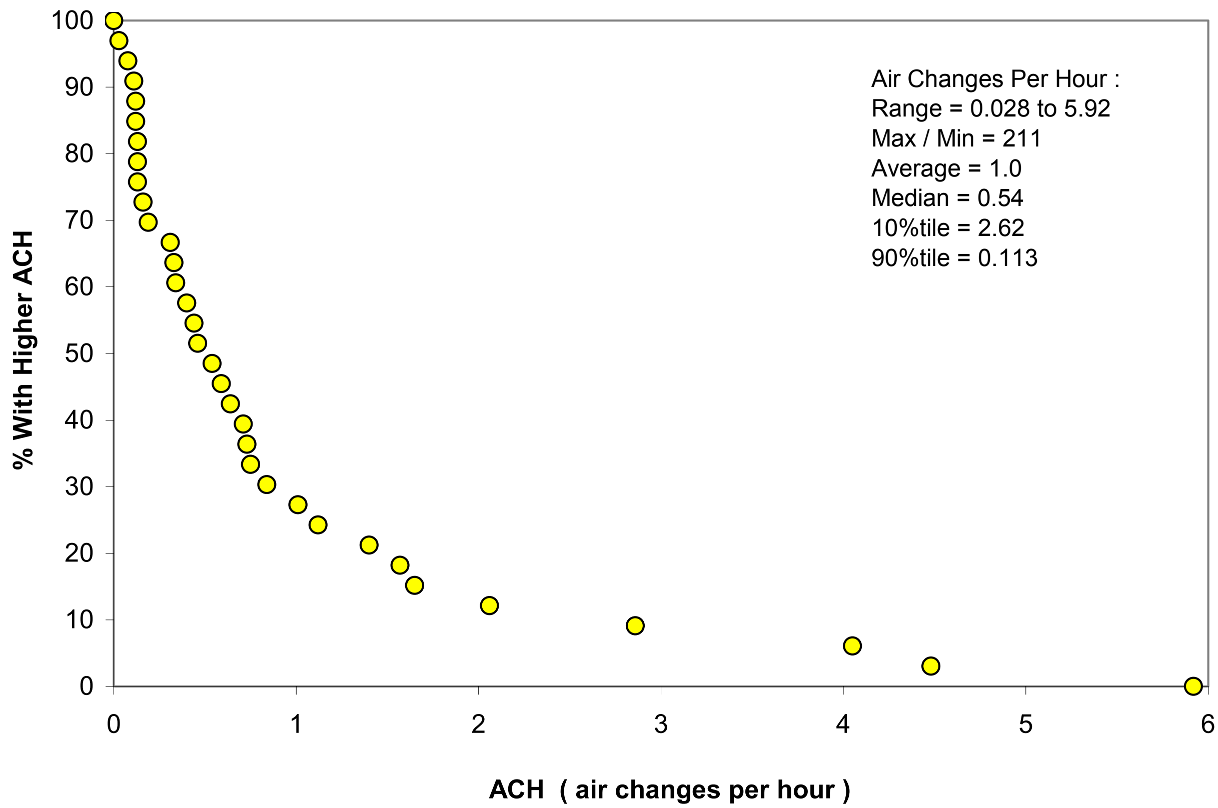

Figure 5-14. Population distribution of calculated ACH values for the 33 residential garages surveyed

Table 5-2. With a few exceptions, the garages generally fell into three groups

Garage Characteristics	ACH Range	% of Garages
Doors weather-stripped, no vents	< 0.25/hr	~33%
Tight doors, no vents	0.25/hr –1/hr	~33%
Gaps around doors, or vents	>1/hr	~33%

For example, Figure 5-15 shows the population distribution of the interior volume of the 33 surveyed garages. Note that the interior volume does not include any subtraction for objects in the garage (e.g., vehicles, appliances, stored items) that might decrease the effective volume. As indicated in Figure 5-15, the average and median garage volume are 4,640 ft^3 and 4,260 ft^3, respectively. The tenth and ninetieth percentile volumes are 6,270 ft^3 and 1,990 ft^3, respectively. The 14,400 ft^3 garage data point in Figure 5-15 is the previously mentioned unusually large garage in Mesa, Arizona.

Figure 5-16 and 5-17 are bar charts that summarize some other potentially pertinent residential garage statistics. Figure 5-16 shows that, as expected, the majority (79%) of the surveyed

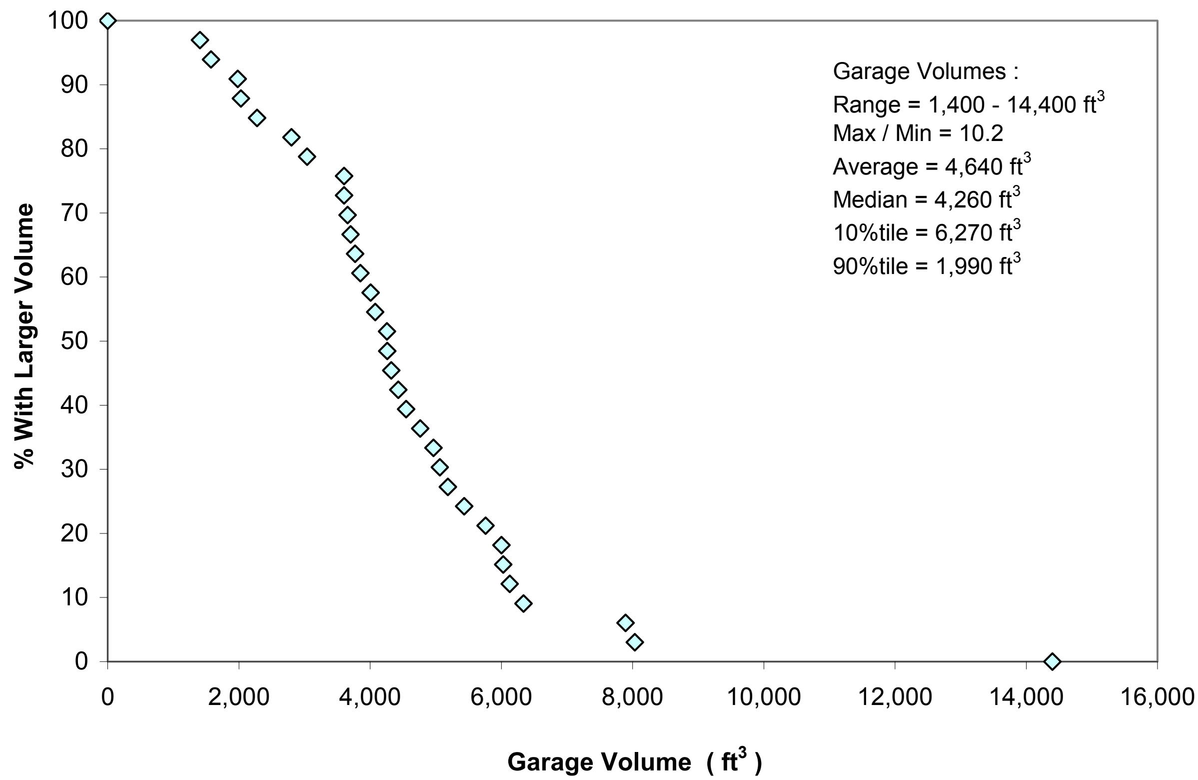

Figure 5-15. Population distribution of interior volumes of the 33 surveyed residential garages

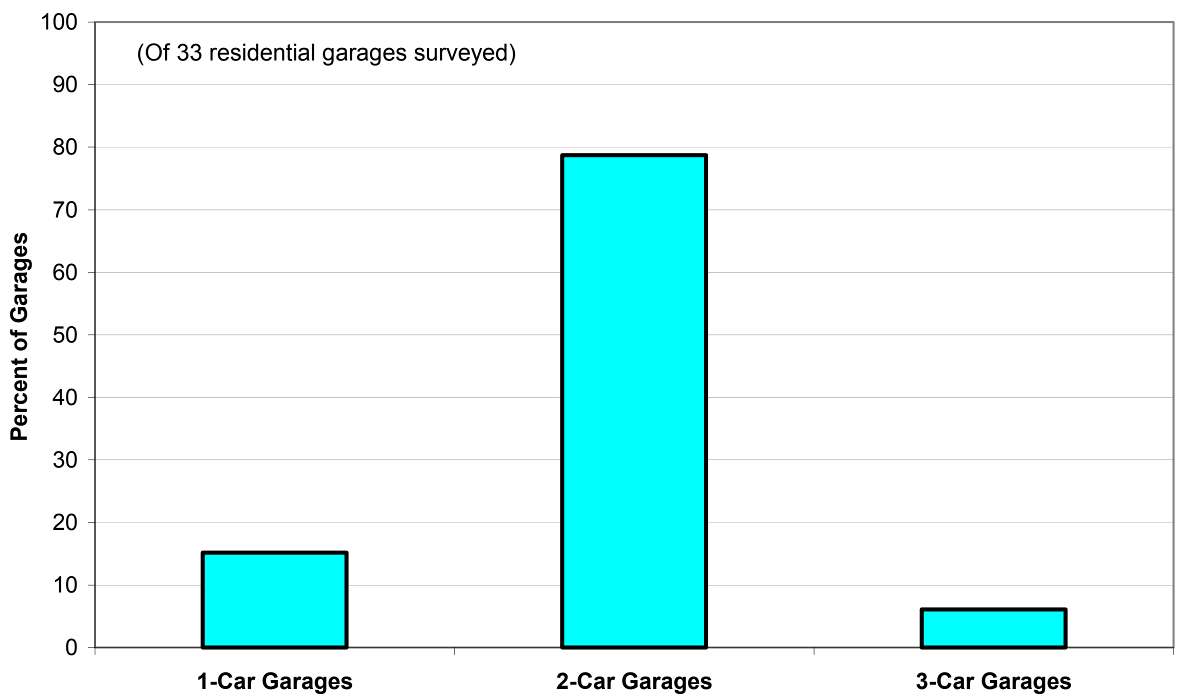

Figure 5-16. The great majority of the garages surveyed were 2-car garages

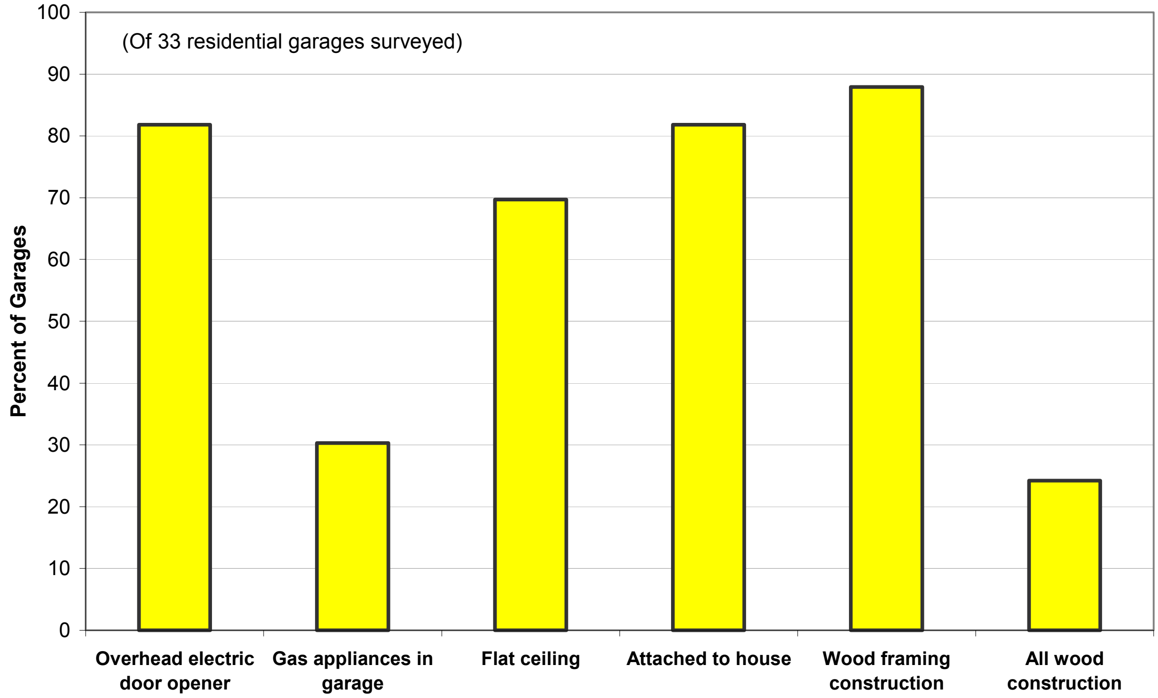

Figure 5-17. The garage survey results yielded other approximate statistics that may be pertinent to HRA applications

garages are two-car garages. Most of the garages have potential ignition sources, e.g., overhead electric garage door openers (82%) or natural gas appliances (30%). Approximately 88% of the garages have wood framing and 24% are all-wood construction. Leaked gas accumulation around the electric garage door opener may be affected by the fact that 70% of the garages have flat ceilings, and the fact that approximately 82% of the garages are attached to houses may affect the consequences of a worst-case deflagration scenario.

It is important to note that the residential garage survey results presented here may not be from a statistically significant or valid population, and they should not be regarded as archival data for future studies. Their only purpose was to promptly provide approximate data on which to base certain HRA event tree probability estimates.

6. Average Gas Concentrations from Leaks and Discharges in Garages

6.1 Analysis Purpose and Methodology

Many of the incident scenarios and fault tree branches lead to top events involving gas leaks or discharges inside the residential garage in which the HRA is installed. In order to provide some initial guidance for the event trees (Section 3.4) that characterize the consequences of these top events, a rudimentary gas leak and discharge analysis was carried out. This analysis computed the average (i.e., fully mixed) gas concentration in the garage for various scenarios. The average gas concentration provides a useful baseline and an accurate indication of the actual gas concentration for many (but not all) situations. More comprehensive computational fluid dynamics analyses, which accounted for concentration gradients associated with diffusion and mixing, are discussed in Section 7.

Figure 6-1 is a simple illustration of three types of gas releases associated with HRA use in a residential garage. Type 1 releases include any release of gas inside the garage that originates from the HRA (i.e., gas release could be from the housing, hose, or nozzle). Type 2 releases are gas releases from the CNG vehicle in the garage. Type 3 releases are gas releases from the HRA vent, which is outside of the garage. This analysis focused on Type 1 and Type 2 gas releases. Two types of Type 1 gas releases from the HRA were considered: direct discharges and leaks. Direct discharges might result from simultaneous malfunctions that cause the HRA to pump natural gas directly into the garage at it maximum flow rate of roughly 0.67 scfm. HRA leaks are assumed to produce gas discharge rates of 0.22 scfm or less.

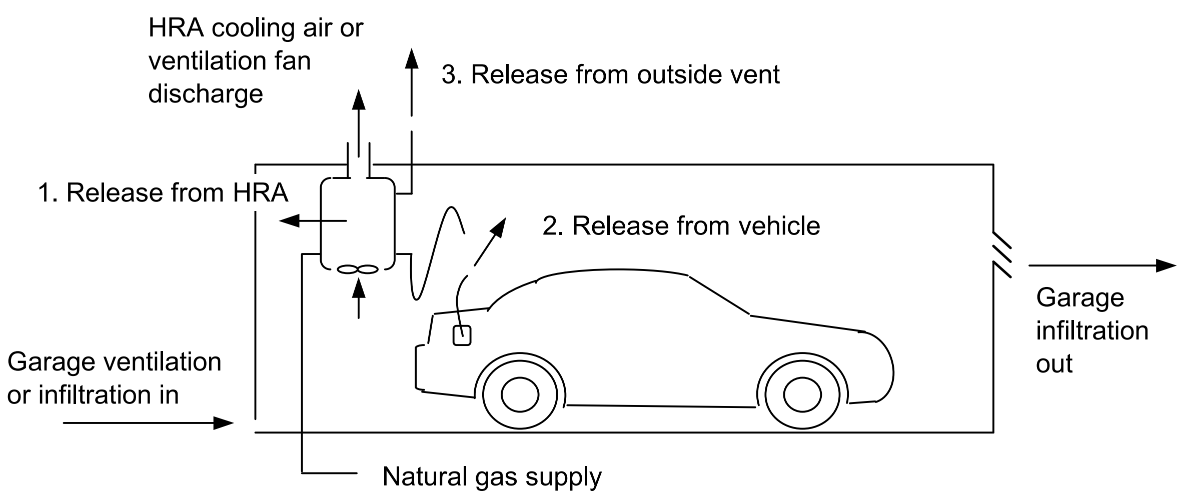

Figure 6-1. Mass balance on garage-mounted HRA indicating three gas release modes

Figure 6-1 also illustrates two types of air flow through the garage: infiltration and ventilation. As previously discussed, ASHRAE (Reference 29) defines the natural flow of air through a structure (e.g., through small openings such as gaps around doors) as infiltration. The flow of air through intentional openings (i.e., vents) is defined as ventilation. Ventilation may be either natural or forced (e.g., with a fan). Both infiltration and ventilation are of interest for a garage-installed HRA. As detailed in Section 5, infiltration rates of residential garages vary by more than two orders of magnitude. As discussed in Section 2.1 and illustrated in Figure 6-1, the HRA cooling air fan induces garage ventilation of roughly 80 scfm in two situations: (1) when the HRA is operating, the air flow cools the compressor, (2) when the gas detector senses a predetermined natural gas concentration (even if the HRA is not operating).

In summary, the average gas concentrations were calculated for three types of gas releases inside the garage and two types of air flows:

- Gas release: leaks (characterized as 0.22 scfm), direct discharges (characterized as 0.67 scfm), and vehicle blowdown (discussed in Section 6.2)
- Air flow: ventilation (for 80 scfm and a range of garage sizes) and infiltration (for a range of ACH rates and garage sizes)

6.2 CNG Vehicle Blowdown Release Analysis

A specific type of CNG vehicle gas release was considered: blowdown of the vehicle fuel tank contents inside the garage. All incident scenarios and fault tree branches leading to vehicle fuel tank blowdown top events included vehicle receptacle check valve failure contributing events (e.g., stuck open or leaking). CNG vehicle fuel tank blowdown includes a spectrum of possibilities corresponding to different fuel tank volumes and starting pressures, and depending on whether the discharge is directly from the receptacle or throttled back through the hose and perhaps through some of the HRA. Gas-release rate calculations were carried out for two representative blowdown conditions to provide input for garage average gas concentration calculations (Section 6.3).

The CNG vehicle fuel tank blowdown conditions were based on a hypothetical Honda Civic GX. A key factor affecting the gas flow rate for a blowdown situation is the minimum orifice size in the flow path, which was discussed in Section 4.2. Two starting conditions were assumed: fuel tank full at 3,600 psi, and fuel tank near 25% full at 900 psi. Table 6-1 lists the key assumptions and the calculation methodology is summarized below.

Table 6-1 Key assumptions associated with CNG vehicle fuel tank blowdown gas release calculation

Item or Quantity	Assumption or Value	Basis or Remarks
CNG composition	100% methane	Adequate accuracy
Gas properties	NIST	Non-ideal gas effects important
Fuel tank capacity	968 scf	Honda Civic GX tank approximately 8 gge
Initial tank pressures	3,600 psig 900 psi	Completely full Approximately 25% full
Initial tank temperature	60°F	Nominal
Effective choked-flow throat area	0.006 in^2	80% of Honda minimum orifice area
Heat transfer to tank during initial blowdown	2 Btu/sec	Avoids liquefaction due to decompression cooling

The blowdown was modeled as a choked flow process until the gas velocity at the minimum area was no longer sonic, and then it was modeled as pipe flow with nominal assumptions for pipe and fitting friction effects. Because over 99% of the gas is discharged while the flow is choked, the pipe flow assumptions are relatively unimportant. The blowdown calculation stepped through time while iteratively solving the appropriate mass and energy balance equations. The mass balance is simply that the gas mass in the tank at any time is equal to the mass initially in the tank minus the gas discharged prior to that time. The energy balance at any given time is:

$$d\frac{(Mu)}{dt} = \dot{Q} - \dot{m}h$$

where:

- M = The mass of gas in the tank
- u = The internal energy per unit mass of the gas in the tank
- t = time
- $\dot{Q}$ = The rate of heat transfer to the tank
- $\dot{m}$ = The gas mass flow rate out of the tank
- h = The enthalpy per unit mass of the gas flowing out of the tank

A discharging gas tank cools as it does work on the environment, and the resulting temperature difference causes heat transfer from the environment to the tank. This heat transfer rate ($\dot{Q}$ in the above equation) was assumed to initially increase to 2 Btu/second, because that is the approximate minimum required to avoid liquefaction of some of the gas in the tank during the blowdown, and then to decrease to zero as the tank temperature approached the ambient temperature. The natural gas was assumed to be 100% methane, and methane properties were modeled using the NIST-based Cryodata GASPAK computer program (Reference 31), which provides good accuracy in the non-ideal gas regime of interest here.

The minimum Honda Civic GX fuel system flow area, which would be the throat during a choked-flow blowdown situation, was assumed to be the 0.098-inch diameter orifice in the CNG tank, which was discussed in Section 4.1 and illustrated in Figure 4-1. The effective throat area of this orifice was assumed to be 80% of its actual area to account for boundary layer and other effects. The resulting assumed effective choked-flow throat area was 0.006 in^2 as indicated in Table 6-1.

Figure 6-2 shows the time-dependent gas release rates for the two CNG vehicle fuel tank blowdown situations summarized in Table 6-1, i.e., a Honda Civic GX starting at 900 psi and 3,600 psi. The points where the flow becomes unchoked are indicated in Figure 6-2. In each case, more than 99% of the gas has been exhausted by the time the flow becomes unchoked, which justifies the approximate way the fuel system flow path friction characteristics were estimated. Figure 6-3 shows the computed blowdown gas release rates plotted in log-log coordinates so that they can be compared to the much smaller HRA release rate of 0.67 scfm and assumed leak rate of 0.22 scfm. The logarithmic time scale enables the blowdown event, which lasts for less than 15 minutes, to be compared to the typical refueling time of 8 hours (which is a representative time period during which the HRA might leak).

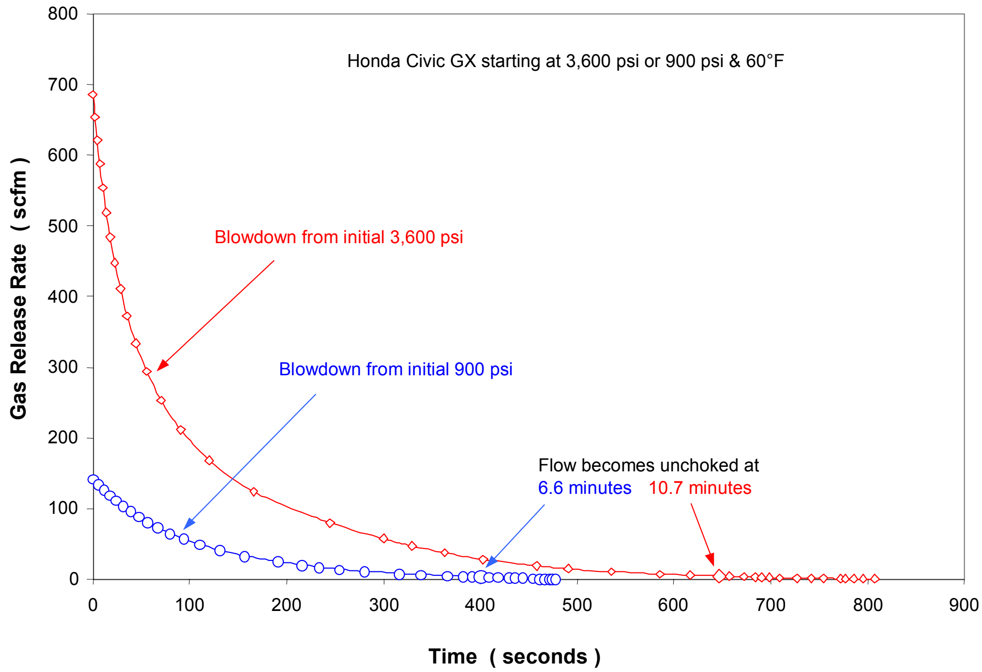

Figure 6-2. Calculated CNG vehicle fuel tank blowdown gas release for conditions listed in Table 6-1

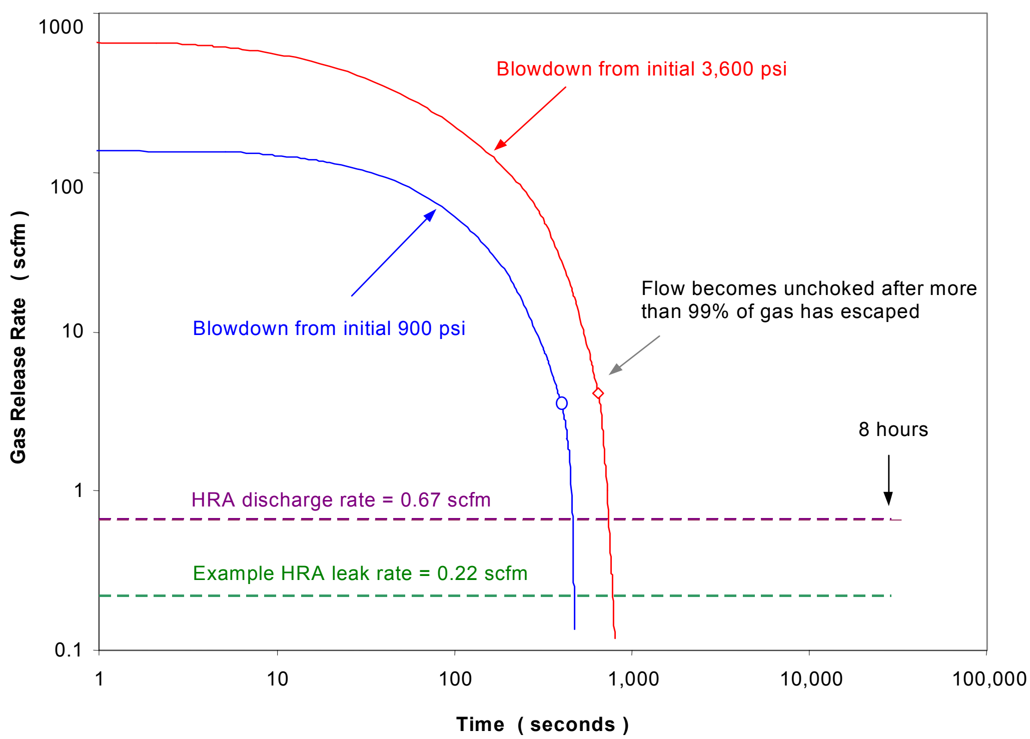

Figure 6-3. Comparison of calculated vehicle blowdown and assumed HRA discharge and leak rates (note logarithmic scales)

6.3 Garage Average Gas Concentrations Following Blowdowns, Discharges, and Leaks

The range of potential HRA discharge and leak rates or CNG vehicle blowdown rates established in Sections 6.1 and 6.2 provides the basis for calculating the corresponding average gas concentrations in residential garages with various air infiltration or ventilation rates. These concentrations can be compared to the natural gas lower flammability limit (LFL) of approximately 5%, and they can be used in conjunction with the computational fluid dynamics analysis results (Section 7) to estimate certain event tree probabilities.

The average gas concentration (also called bulk or fully mixed concentration) neglects diffusion and mixing phenomena, which produce gas concentration gradients. While these gradients can be very important (e.g., the local gas concentration near a leak will be much higher than the concentration near a distant ignition source), a bulk analysis is useful for establishing bounding regimes. Concentration gradients associated with diffusion, mixing, and other phenomenon are fully accounted for in the computational fluid dynamics analyses reported in Section 7.

The time-rate-of-change of the average gas concentration in a garage following initiation of the gas release derives from mass balance considerations. If the mass of air plus gas inside the garage is assumed to be constant (which is a reasonable assumption while the gas concentration is less than or near the flammability limit), the gas concentration is given by:

$$V\frac{dC}{dt} = R - (R + I)C$$

where:

V = The garage volume (e.g., ft^3)
C = The volume fraction of gas in the garage (C × 100 = gas concentration %)
R = The gas volumetric release rate (e.g., scfm)
I = The garage infiltration volumetric inflow rate (e.g., scfm)

Note that the previously discussed garage air changes per hour is simply ACH = I/V (where I is multiplied by 60 if necessary to make this unit scfh). For $R << I$ and constant infiltration and gas release rates, the solution of this equation is:

$$C = \frac{R}{I}\left(1 - e^{-It/V}\right)$$

For long times, the asymptotic solution is simply:

$$C_{maximum} = \frac{R}{I}$$

The gas concentration reaches 90% of its maximum (asymptotic) level when:

$$t_{90\%} = \frac{2.3}{ACH}$$

The average natural gas concentration histories in residential garages were calculated for the previously discussed leak, discharge, and blowdown rates and for variations in garage ventilation and infiltration rates. The mass conservation equation was solved using a simple time-step algorithm, because the closed-form solution is inapplicable for the blowdown cases. Time-dependent garage average gas concentrations were calculated for three garage sizes to characterize 80-scfm ventilation situations and five garage size and ACH combinations to characterize the infiltration-only situation (i.e., HRA cooling air fan off). In actuality, when the HRA cooling air fan is on, air flows through the garage via infiltration as well as ventilation. However, ventilation and infiltration were characterized separately in order to focus more precisely on causes and effects.

The three garage ventilation cases analyzed were:

- 80 scfm and a median garage volume
- 80 scfm and a tenth percentile garage volume
- 80 scfm and a ninetieth percentile garage volume

Note that each of these causes represents a different number of air changes per hour, because ACH depends on the garage volume as well as the air flow rate. The median, tenth percentile, and ninetieth percentile garage volumes were discussed in Section 5.5. Figure 6-4 shows the computed average natural gas concentration histories in a median-volume garage (4,260 ft^3) with

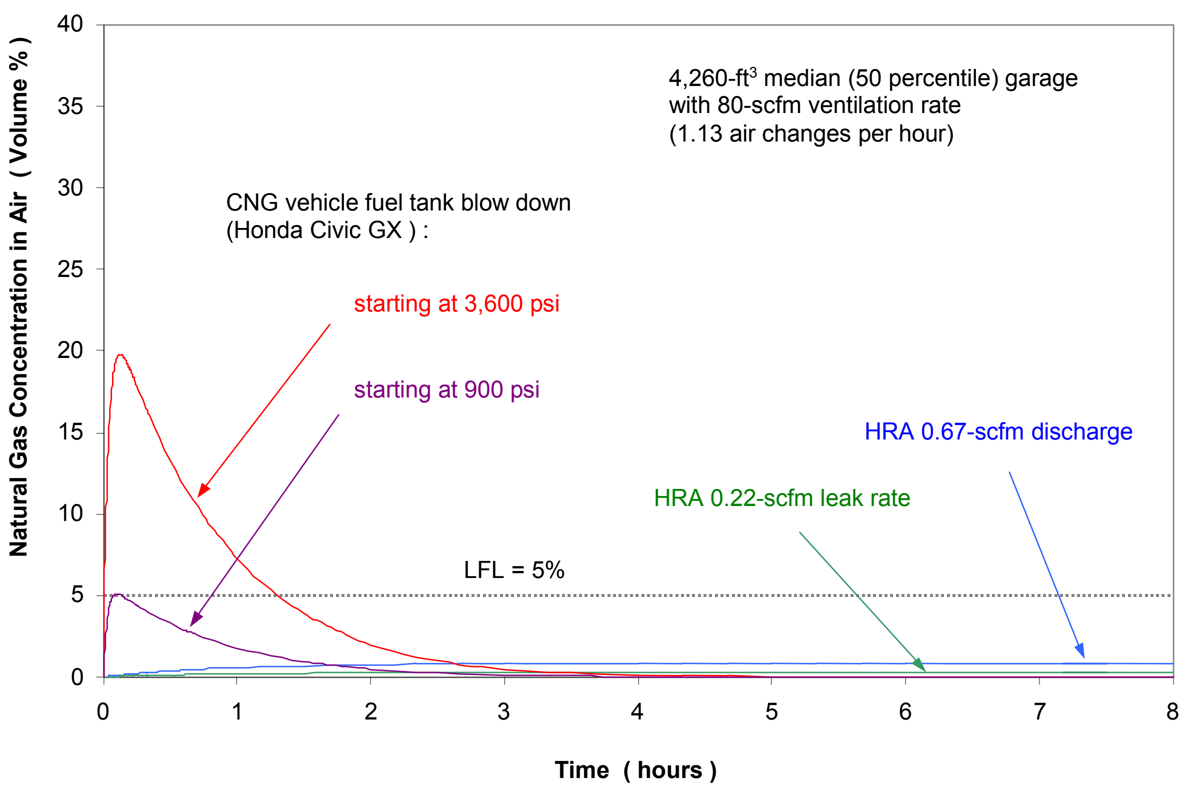

Figure 6-4. Average gas concentration histories for the considered blowdown, discharge, and leak scenarios in a median-volume garage with 80-scfm ventilation

80 scfm ventilation for the considered blowdown, discharge, and leak situations. In this case, a blowdown release from a CNG vehicle full fuel tank would cause the average gas concentration to abruptly exceed the LFL (by as much as a factor of four) and remain above the LFL for more than one hour. A blowdown release from a CNG vehicle fuel tank filled to 900 psi would produce an average gas concentration that peaks at approximately LFL and decays to less than a third of the LFL in one hour. For these conditions, the maximum average gas concentrations produced by a 0.22-scfm leak or a 0.67-scfm discharge are approximately 0.3% and 0.8%, respectively, which are substantially less than the 5% LFL. Graphs of average gas concentrations for all three of the previously listed 80-scfm ventilation and garage volume combinations are contained in Appendix E.

The five garage infiltration cases analyzed were:

- Median garage volume and median ACH
- Median garage volume and tenth percentile ACH
- Median garage volume and ninetieth percentile ACH
- Tenth percentile garage volume and median ACH
- Ninetieth percentile garage volume and median ACH

The median, tenth percentile, and ninetieth percentile garage volume and ACH estimates were discussed in Section 5.5. Figure 6-5 shows the computed average natural gas concentration

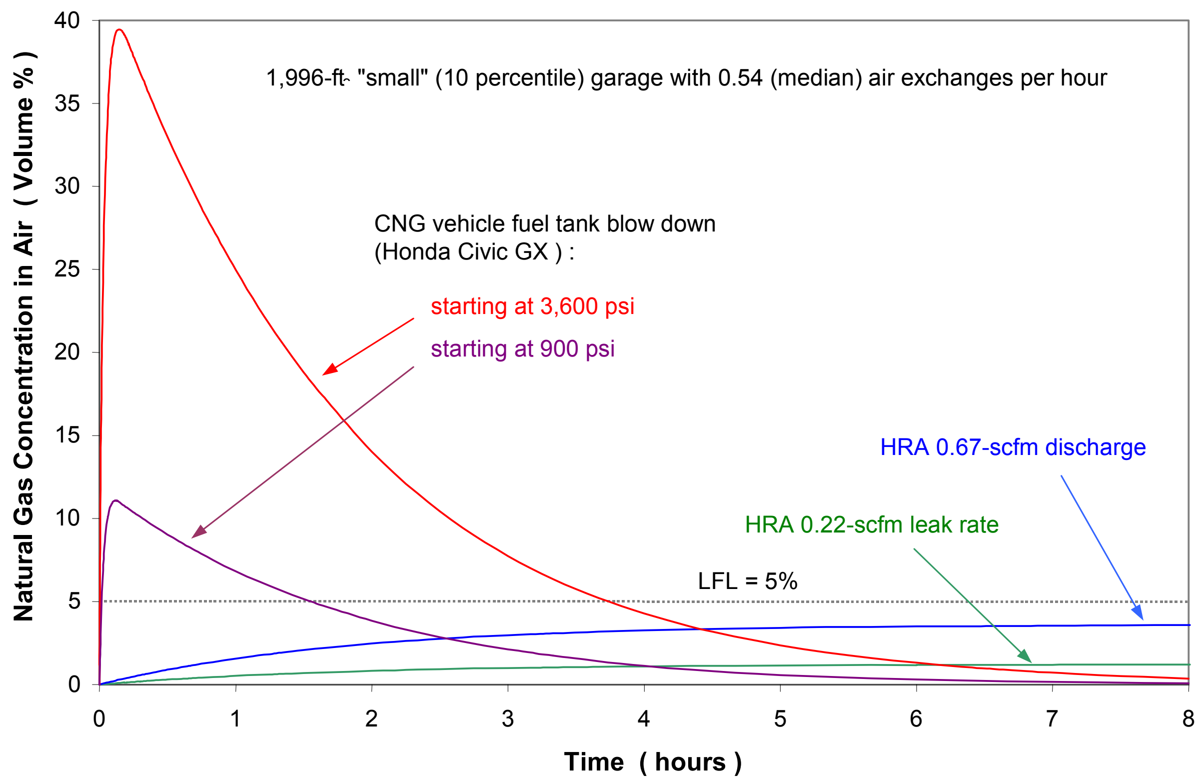

Figure 6-5. Average gas concentration histories for the considered blowdown, discharge, and leak scenarios in a tenth percentile ("small") garage with a median ACH

histories in a tenth percentile "small" garage (1,996 ft^2) with a median ACH (0.54 air changes per hour) for the considered blowdown, discharge, and leak situations. In this case, a blowdown of a CNG vehicle full fuel tank would cause the average gas concentration in the garage to abruptly exceed the LFL. The maximum average gas concentration exceeds the LFL by almost a factor of eight, and nearly four hours lapse before the average gas concentration is less than the LFL. A blowdown from a CNG vehicle fuel tank filled to 900 psi would also produce an average gas concentration that exceeds the LFL for approximately 1.5 hours. Also, for these assumed conditions, the average gas concentration produced by a 0.67 scfm HRA discharge would eventually (after many hours) reach 3.7% (75% of the LFL). A 0.22-scfm leak would eventually result in an average gas concentration of 1.2% (25% of the LFL). Graphs of average gas concentrations for all five of the previously listed garage infiltration cases (i.e., ACH and garage volume combinations) are contained in Appendix E.

Key conclusions from the average gas concentration analysis results detailed in Appendix E are:

- When the HRA 80-scfm cooling fan is operating:
  - The 80-scfm produces approximately 1.1 air changes per hour in a median-volume garage, 0.8 air changes per hour in a ninetieth percentile ("large") garage, and 2.4 air changes per hour in a tenth percentile ("small") garage
  - Neither a 0.22-scfm leak nor a 0.67-scfm discharge will produce an average gas concentration that is a significant fraction of the LFL
  - The average gas concentration produced by a CNG vehicle fuel tank blowdown depends more on the garage volume than the ventilation or infiltration rate. The average gas concentration will abruptly exceed the LFL unless the CNG vehicle fuel tank is nearly empty at the start of the blowdown.
- When the HRA 80-scfm cooling fan is not operating and the only air flow in the garage is due to natural infiltration:
  - A 0.67-scfm HRA discharge will produce an average gas concentration equal to the LFL in about eight hours in a median-volume garage with a tenth percentile ACH (0.113 air changes per hour)
  - A 0.22-scfm HRA leak will not produce an average gas concentration equal to the LFL for any of the conditions considered (an ACH less than 0.07 air changes per hour would be required for a 0.22-scfm leak to cause the average gas concentration to exceed the LFL in a median-volume garage, and this would take more than 30 hours)
  - A CNG vehicle full fuel tank blowdown causes the average gas concentration in the garage to significantly exceed the LFL for all the garage volume and ACH combinations considered.

It is important to re-emphasize that the results presented here are restricted to average natural gas concentrations in a residential garage, and the effects of concentration gradients associated with diffusion and mixing are considered in Section 7.

7. Estimation of Garage Natural Gas Concentrations by Computational Fluid Dynamics Analyses

7.1 Analysis Approach and Cases Considered

Computational fluid dynamics (CFD) modeling was employed to predict the time-dependent evolution of natural gas concentration profiles inside a representative garage for a number of combinations of gas release rate, garage infiltration rate, and HRA cooling air discharge scenarios. The HRA cooling air fan rejects the heat generated by the compressor and other heat sources in the appliance such as the electronic controls. The main inputs to the modeling effort were taken from the garage characterization effort discussed in Section 5, along with the gas release rates associated with HRA failures that were discussed in Section 3. Five calculation cases were defined with characteristics as follows:

- Case 1
  - Median garage infiltration
  - Undetected gas leak at the fuel tank refueling receptacle
  - HRA fan discharging into the garage, HRA heat rejected into the cooling air
- Case 2
  - Median garage infiltration
  - Undetected gas leak at the fuel tank refueling receptacle
  - HRA fan discharging through a vent to the outside air, HRA heat rejected into the cooling air
- Case 3
  - Low garage infiltration
  - Undetected gas discharge from the HRA hose breakaway valve directed away from the HRA
  - HRA fan discharging into the garage, HRA heat rejected into the cooling air
- Case 4
  - Low garage infiltration
  - Undetected gas discharge from the HRA hose breakaway valve directed away from the HRA
  - HRA fan discharging through a vent to the outside air, HRA heat rejected into the cooling air
- Case 5
  - Low garage infiltration
  - Undetected gas discharge from the HRA hose breakaway valve directed away from the HRA
  - HRA fan off having failed, HRA heat rejection through the HRA walls

As noted previously, the initial safety evaluation performed in this project was based on discharging the HRA cooling air into the garage interior. In fact, one purpose of the CFD modeling effort was to evaluate the effect on predicted garage gas concentrations of discharging the HRA cooling to the outside. It was subsequently decided that FuelMaker would require the discharge of the cooling air outside as part of the HRA installation specifications. Thus, of the calculation cases defined, only Cases 2, 4, and 5 are useful in the context of the final safety evaluation completed and documented in this report. However, all five cases are discussed in this section to illustrate the relative importance of requiring outside discharge of the cooling air compared to allowing for its discharge into the garage interior.

With this in mind, Cases 1 and 2 represent nominal failure scenarios with a typical, median garage and a higher probability top event failure (gas leak, see the discussion of the fault tree analysis in Section 3). They differ only in the HRA installation procedure; installed with the cooling air discharge directly from the top of the HRA into the garage interior, or installed with the cooling air vented to outside of the garage through a duct passing through the garage wall from the rear of the HRA. Cases 3 and 4 represent more worst case failure scenarios with a relatively well-sealed garage and a lower probability top event failure (continuous gas discharge). Again, these cases differ only in the HRA installation specifics (where HRA cooling air is discharged). Case 5 represents a near worst case failure scenario with the relatively well-sealed garage and no garage volume convection via the HRA cooling air fan.

Model input assumptions were as follows:

- Garage infiltration
  - Median: ACH of 0.48/hr with the HRA not in operation (Cases 1 and 2)
  - Low: ACH of 0.19/hr with the HRA not in operation (Cases 3, 4, and 5)
- Gas release rate
  - Gas leak: 0.22 scfm (Cases 1 and 2)
  - Gas discharge: 0.67 scfm (Cases 3, 4, and 5)
- HRA cooling fan air flowrate: 80 cfm (Cases 1 through 4)
- HRA heat rejection rate
  - Cases 1 and 2: 675 W
  - Cases 3, 4, and 5: 550 W

The rationale for the selection of the above calculation parameters is as follows. The median garage infiltration rate corresponding to an ACH of 0.48/hr was near the median garage ACH arising out of the garage characteristics survey discussed in Section 5. The low garage infiltration rate corresponding to an ACH of 0.18/hr was calculated as that which resulted in a steady state average garage gas concentration from a gas discharge of 0.67 scfm into the garage with no forced ventilation (such as that associated with discharging 80 cfm of HRA cooling air outside) of just under the methane LFL of 5%. The garage survey discussed in Section 5 indicated that about 70% of garages have ACH greater than 0.2/hr (are "leakier"). The gas leak rate of 0.22 scfm is representative of an HRA leak, as discussed in Section 6. The gas discharge rate of 0.67 scfm is the vehicle refueling rate of the HRA, and, thus, represents the rate of gas release from the appliance continuing to pump gas through a hose rupture or undetected breakaway event, also discussed in Section 6. The cooling fan air flowrate is that of the HRA. The HRA heat rejection rate for Cases 3, 4, and 5 corresponds to the rate when the compressor pumps to atmospheric pressure, 550 W. The HRA heat rejection rate for Cases 1 and 2 of 675 W is the average of the 550 W and the heat rejection rate when the compressor is pumping to a nearly full vehicle CNG fuel tank at 3,600 psi, 800 W.

The model garage was defined to be a typical two car garage. The median garage in the garage survey discussed in Section 5 had a volume of 4,260 ft^3. The model garage volume of 4,500 ft^3 was selected for dimensional simplicity, that being a garage with interior dimensions of 20 ft wide by 25 ft deep by 9 ft high (ceiling height). The garage was assumed to contain two vehicles having dimensional characteristics corresponding to a Ford Taurus. Swain (Reference 26) modeled a helium leak into a single car garage in a parallel modeling/experimental effort evaluating a hydrogen leak into the garage. In the experimental setup, a plywood mockup of a Ford Taurus was constructed of planar sections of plywood. The dimensions of this assembly of planar sections was used in the modeling work, and facilitated the definition of the calculational grid. The same dimensions of the assembly of planar sections was used in the CFD analyses performed in this project for the same reason, ease of calculational grid definition.

The HRA location was placed in accordance with the FuelMaker installation guidelines, which specify that the appliance base be located at least 5 ft above the garage floor. The HRA was mounted on a garage sidewall at this height 10 ft into the garage from the vehicle door. Figure 7-1 is an isometric view of the garage geometry showing the placement of the vehicles and the appliance, the vehicle door, and an assumed door into the dwelling space. Also shown in the figure is a calculational space exterior to the vehicle door. This calculational space is needed to allow the flow fields in the garage interior to communicate with the "outside." More detail on the garage geometry used for the CFD calculations is given in Appendix F.

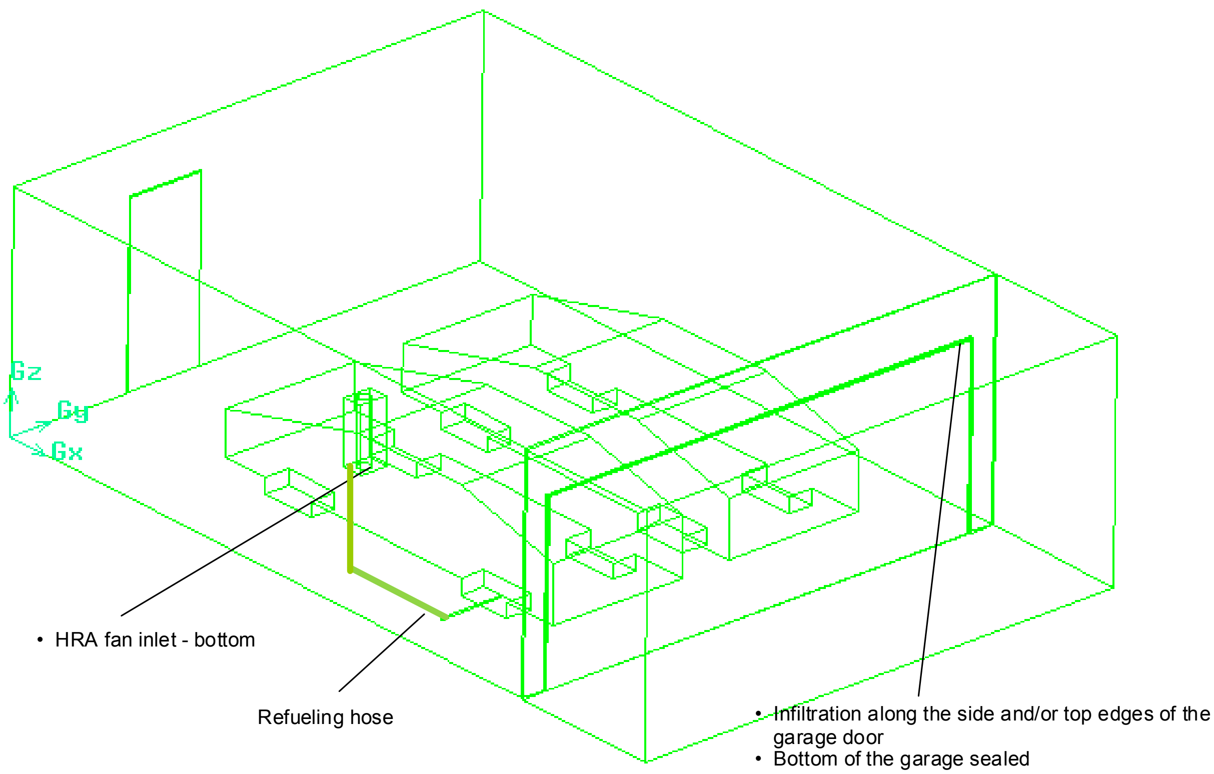

Figure 7-1. Garage geometry for the CFD calculations

For all calculation cases, all infiltration was assumed to occur through gaps of equal size along the sides and top of the vehicle door. The dimensions of this gap and the resistance to airflow through the gap were varied to give the infiltration rate that corresponds to the target ACH values for the calculation cases noted above. The target ACH values are noted as being with the HRA not in operation in the above. The gap dimensions and resistance to airflow was not varied from the respective appliance off values. With the convection associated with the cooling fan in operation, the actual ACH for a given calculational case can change from the appliance-off value. This is especially true for the cases in which the cooling air is discharged to the outside. For cases with the HRA cooling air discharged into the garage, the cooling air intake is at the base of the appliance, and the discharge is out the top of the appliance, both through 4-in openings. For cases with cooling air discharged outside the garage, the discharge was through rear of the appliance near the top of the appliance, again through a 4-in vent.

For all calculations:

- Natural gas was assumed to be 100% methane
- No external wind was assumed (i.e., there was no forced air convective velocity in the calculational space external to the garage door)
- The garage interior and exterior (the calculational space external to the garage door) were at the same initial temperature of 70°F; the exterior was held at 70°F
- The garage walls were assumed to be isothermal at 70°F

All CFD calculations were performed using FLUENT 6.0. Full transient case calculations were completed. Details of the computational grid definitions to support the calculations are given in Appendix F.

A set of steady state calculations was performed prior to doing the full transient calculations for Cases 1 and 2. This set of steady state calculations was used to establish the garage door gap width and airflow restriction associated with the infiltration that corresponded to the target pre-HRA installation ACH. This target ACH was near the median ACH arising out of the garage survey discussed in Section 5. This survey indicated the median ACH of the garages in the survey was 0.54/hr. The gap width and airflow restriction selected for the Case 1 and 2 calculations resulted in an ACH of 0.48/hr before HRA installation. A second set of steady state calculations was performed prior to completing the full transient calculations for Cases 3, 4, and 5. This set of calculations was used to establish the door gap width and airflow restriction associated with the infiltration that gave a calculated steady state average garage gas concentration of just less than 5% for a gas discharge of 0.67 scfm into the garage with no forced ventilation. The gap width and airflow restriction selected for the transient calculations resulted in a steady state average garage concentration of 4.8%, with an ACH of 0.18/hr, as noted above.

All transient calculations were carried out for a period of 14 hours. This was felt to be the longest period of time a refueling vehicle could possibly be left unattended. This period corresponds to a vehicle owner initiating a refueling at say 5:00 pm and not reentering the garage until 7:00 am the next morning. Assessing the evolution over time of garage natural gas concentration profiles was the focus of the transient CFD calculations. Results of the transient calculations for the two general gas release scenarios, a gas leak (calculation Cases 1 and 2) and a gas discharge (Cases 3, 4, and 5) are discussed in the following subsections.

7.2 Garage Concentrations Resulting from a Gas Leak

As noted above, the gas leak failure scenarios had a gas leak of 0.22 scfm emanating from the vehicle fuel tank refueling receptacle while the HRA refueling hose was attached to the vehicle. The leak was into a typical garage with infiltration characteristics (ACH) associated with the median arising out of the garage survey discussed in Section 3.

Figure 7-2 shows the predicted average garage methane concentrations over time for the two gas leak cases evaluated. The steady state garage average concentration for Case 1, with the HRA cooling fan discharging into the garage interior, is 0.61%. Figure 7-2 shows that this is essentially reached at the end of the transient calculation period of 14 hours of continuous gas leak. The steady state garage average concentration for Case 2, with the HRA cooling fan discharged outside of the garage, is a reduced 0.29%. This average concentration is essentially reached after about 6 hours. The decreased steady state concentration for Case 2 is due to the increased infiltration caused by venting the HRA cooling air outside. By so doing, the garage ACH is increased to 1.0/hr.

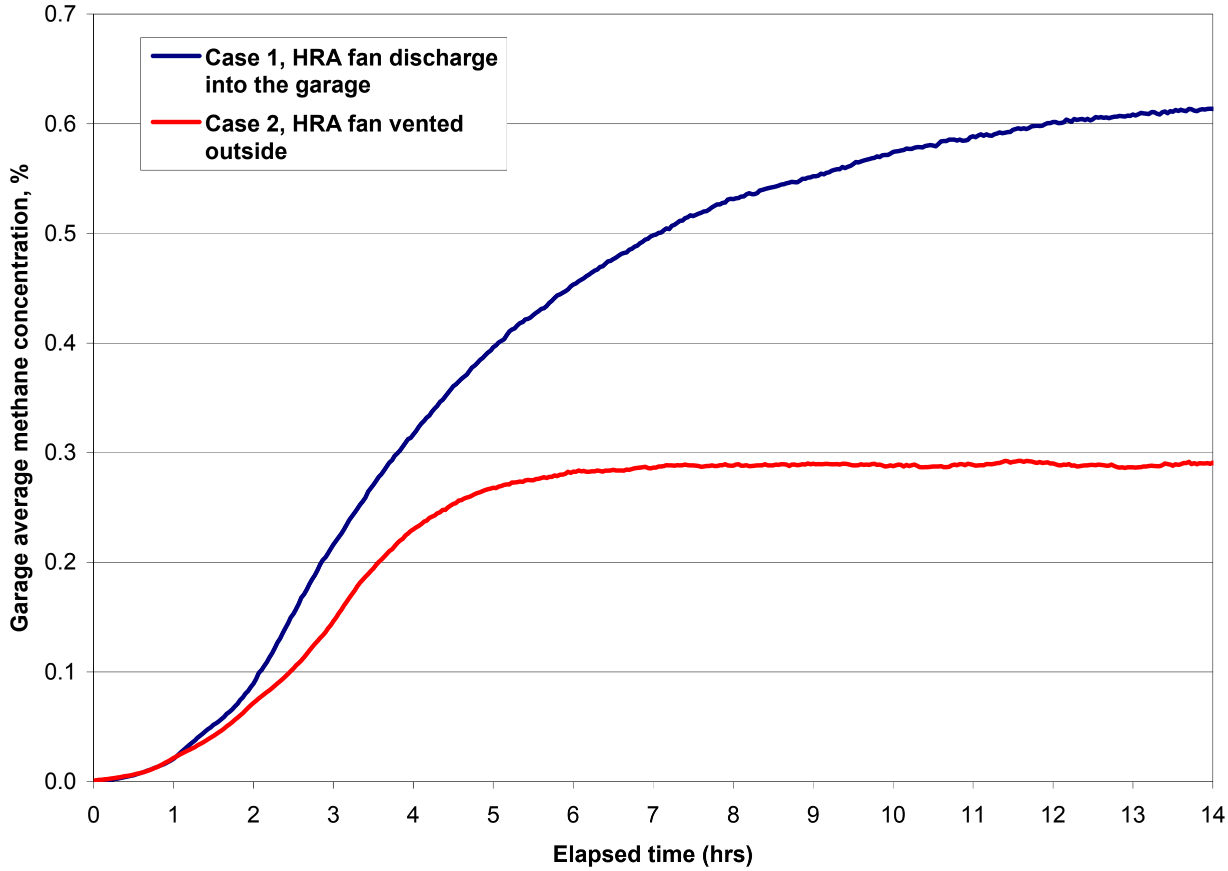

Figure 7-2. Garage volume average methane concentrations for Cases 1 and 2

7.2.1 Case 1 — Cooling Air Discharged into the Garage Interior

Figure 7-3 shows the isosurface of 5% methane concentration, the methane LFL, at steady state for the natural gas leak with the HRA cooling air discharge into the garage interior. This surface is the boundary of 5% methane concentration. Methane concentrations within the surface (closer to the leak) are greater than 5%, concentrations external to the surface are less than 5%. The surface is colored by the gas (methane plus air) velocity. What Figure 7-3 shows is that flammable methane concentrations exist only near the gas leak. Figure 7-4 is a corresponding isosurface for 1% methane concentration at steady state, again colored by the gas velocity at the surface. The figure shows that the 1% surface extends further into the garage, but concentrations

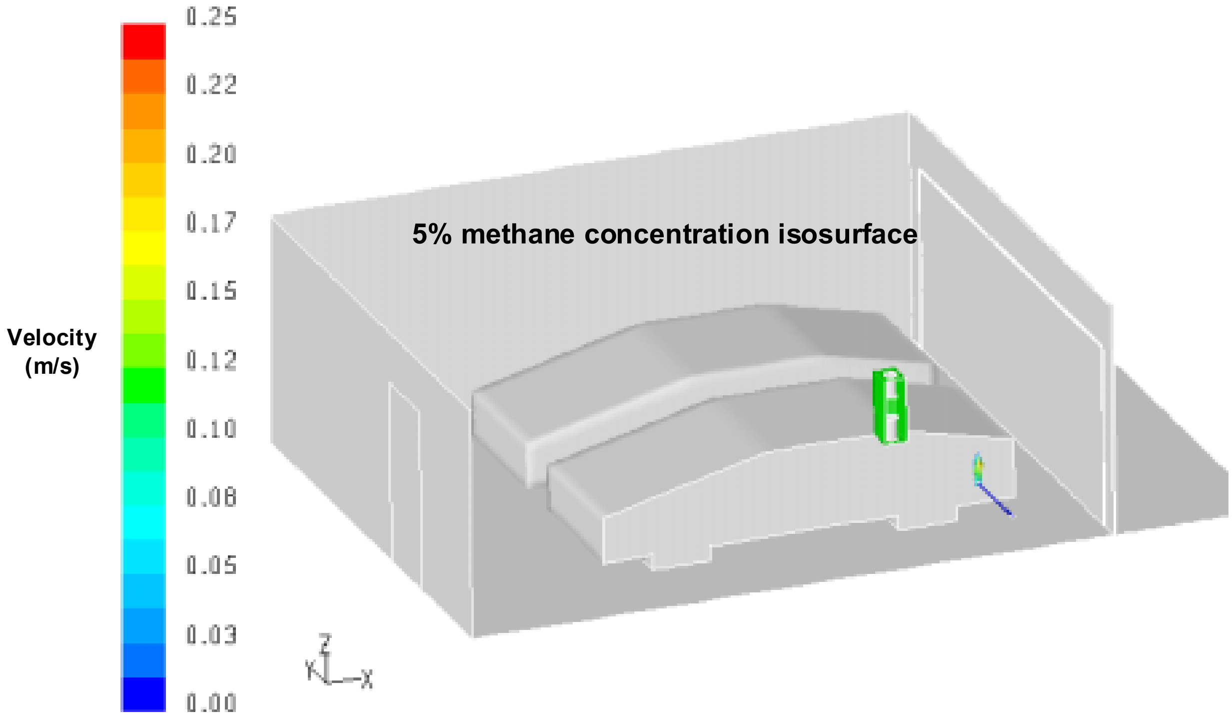

Figure 7-3. The 5% methane concentration isosurface for Case 1 at steady state

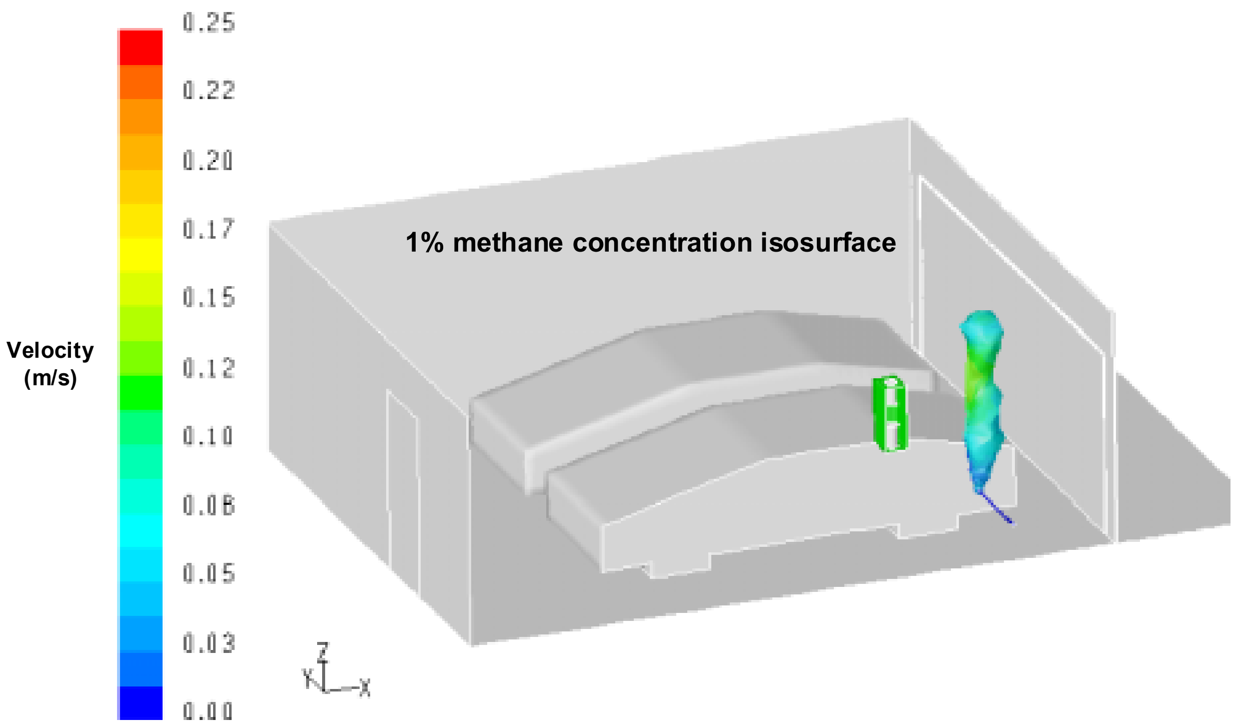

Figure 7-4. The 1% methane concentration isosurface for Case 1 at steady state

of 1% or greater still are confined to the volume directly above the leak. Figure 7-5 shows the 0.5% methane isosurface at steady state. The interpretation of this isosurface is slightly different than the 5% and 1% isosurfaces shown in Figures 7-3 and 7-4, however. For the 5% and 1% isosurfaces, methane concentrations within the plume are at or above the isosurface concentration. For the 0.5% isosurface, it is the volume above the surface (closer to the discharge) that are at or above 0.5% concentration. Methane concentrations below the surface (nearer the garage floor) are less than 0.5%. Figure 7-5 indicates that a significant fraction of the garage volume has 0.5% or higher methane concentration. But this concentration is a factor of 10 less than the methane LFL.

Figure 7-6 shows the pathlines emanating from the leak and the HRA fan discharge at the top of the appliance at steady state. These pathlines are the transit paths of gas "particles" leaving the leak and the HRA fan discharge. The pathlines are colored by methane concentration. The figure shows that high concentrations of methane, at 4 to 5%, exist only very close to the leak. Further from the leak, gas particle concentrations decline to 0.5% and below. The figure also shows that pathlines emanating from the HRA fan discharge into the garage are in the range of 0.5% at steady state.

Figure 7-7 shows the flow field in the plane of the leak, colored by gas velocity at steady state. The pattern of gas recirculation can be seen in this figure. Figure 7-8 shows the corresponding flow field in the plane of the HRA colored by temperature. As the figure shows, the HRA discharge temperature is 98°F (310 K). The relatively sparse set of velocity vectors over the vehicle itself reflects the less dense computational grid used in the space above the vehicle, as discussed in Appendix F.

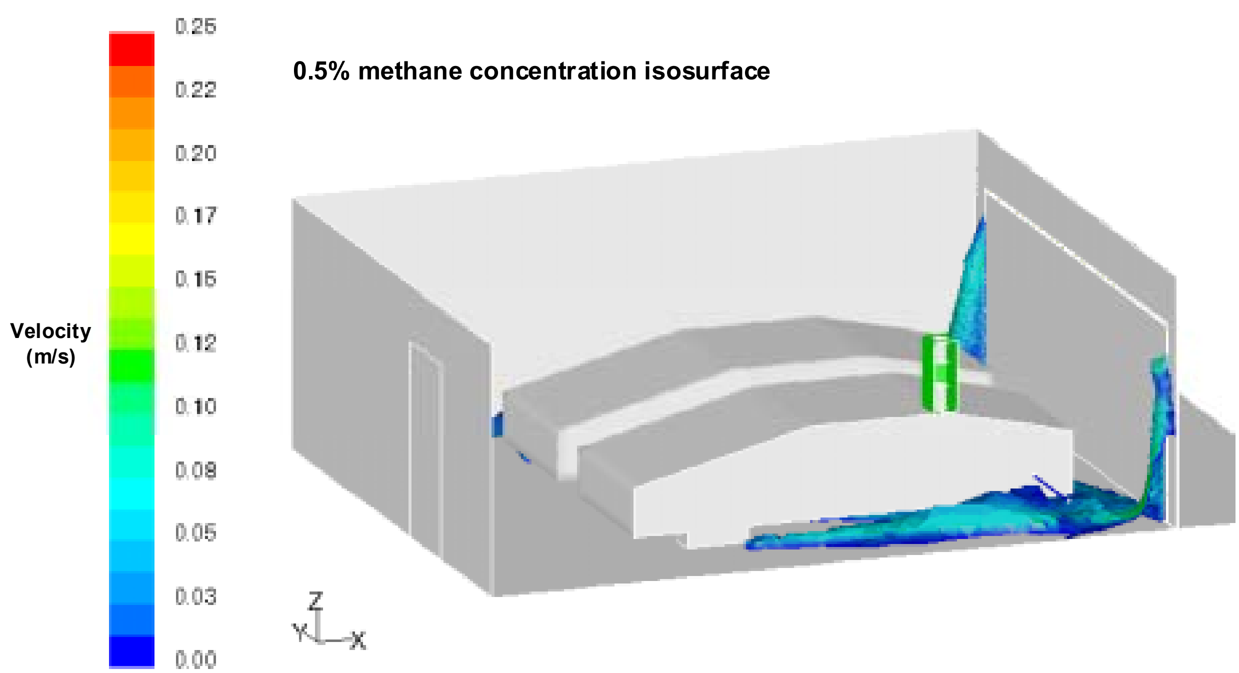

Figure 7-5. The 0.5% methane concentration isosurface for Case 1 at steady state

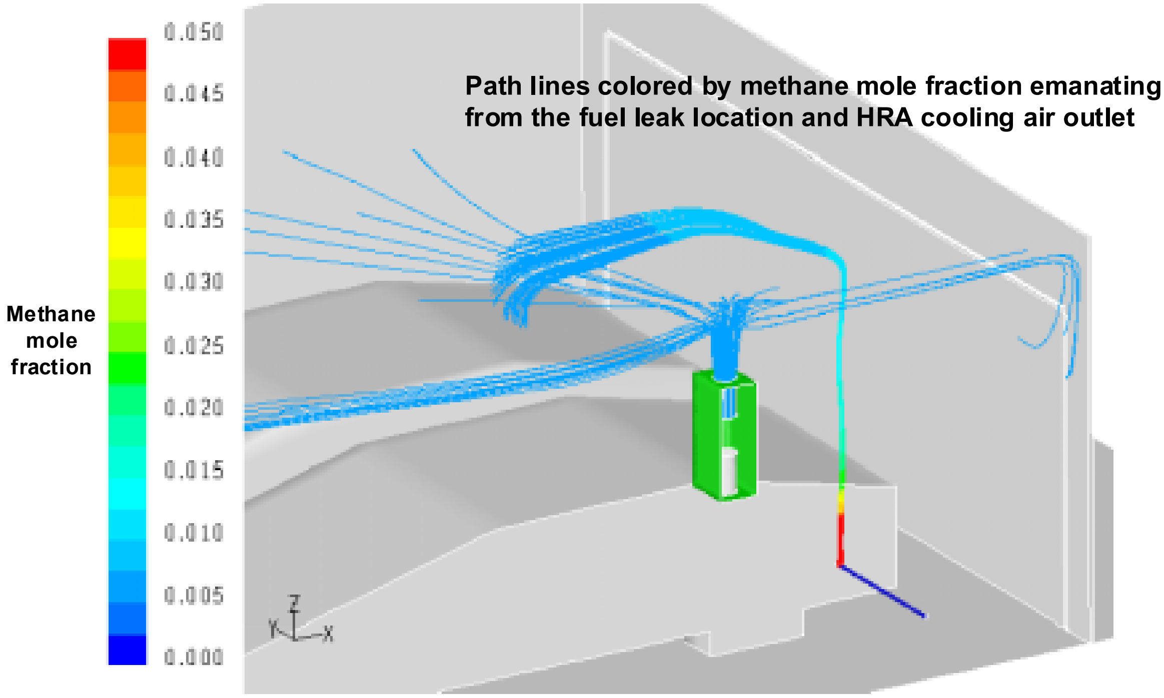

Figure 7-6. Gas particle pathlines from the gas leak for Case 1 at steady state

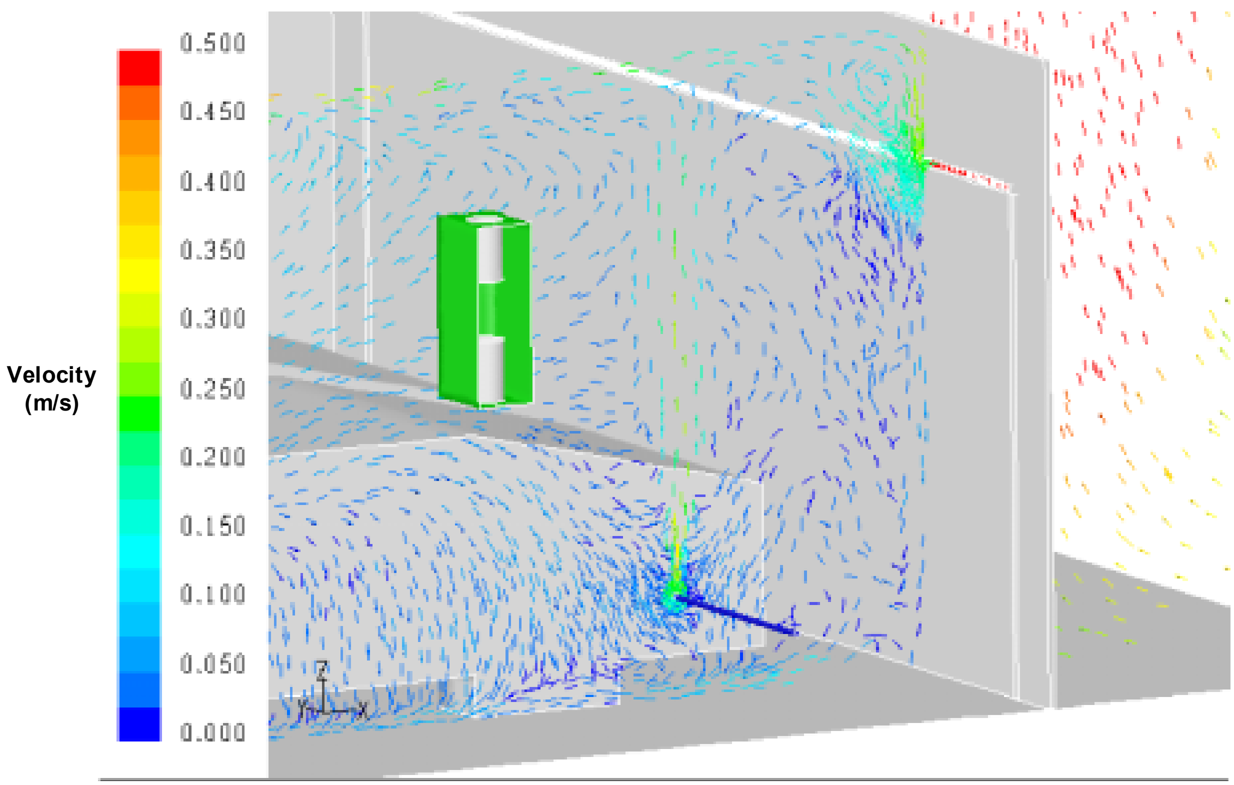

Figure 7-7. Flow field in the plane of the leak for Case 1 at steady state

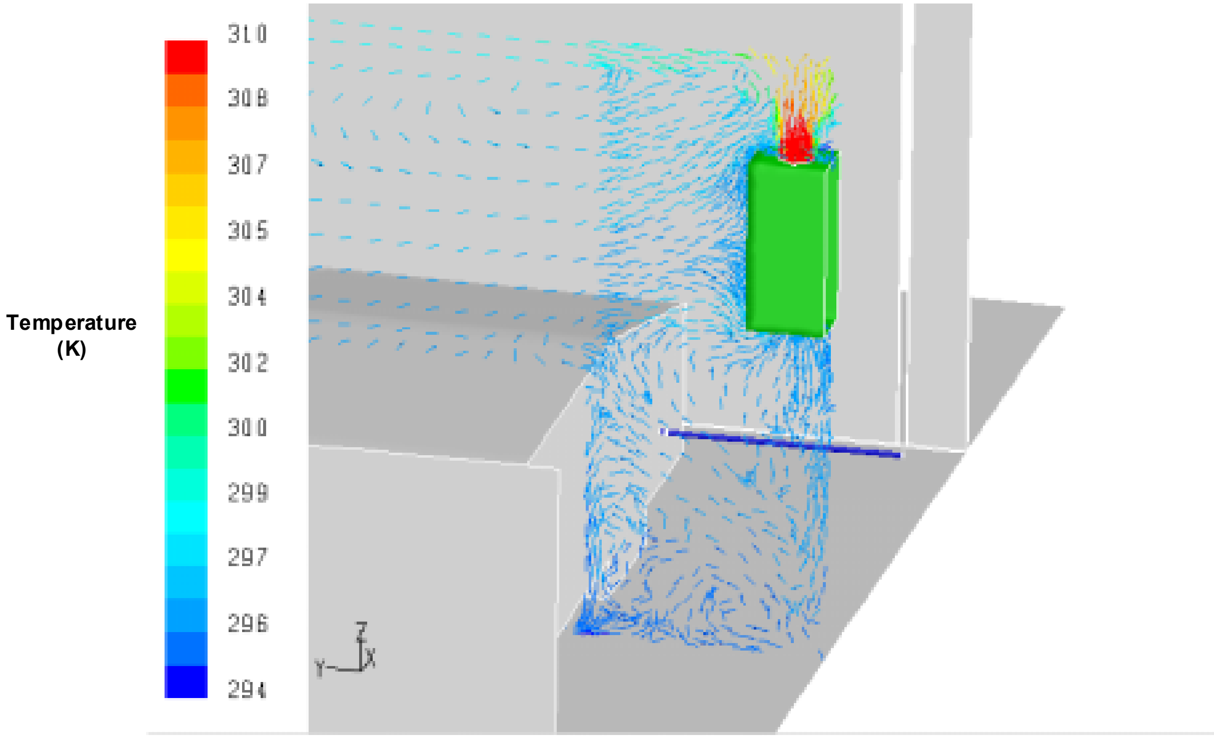

Figure 7-8. Flow field in the plane of the HRA centerline for Case 1 at steady state

Figures 7-9, 7-10, 7-11, and 7-12 show the transient buildup of the 1% methane isosurface at times of 2.6, 5.6, 8.6, and 11.6 hours, respectively. Comparing Figure 7-12 to Figure 7-4 shows that the steady state 1% concentration isosurface has been essentially established by the time 11.6 hours of continuous leak has elapsed. Isosurfaces of 5% methane concentration would be much closer to the leak itself at corresponding times. Even when steady state is reached, the region of flammable methane concentrations is quite small, as noted above with Figure 7-3.

Figure 7-13 shows the garage methane concentration distribution at 11.6 hours of elapsed time, which is near steady state, at the garage centerline. As indicated, the maximum centerline methane concentration is about 0.7%, which occurs at the garage ceiling near the plane of the leak.

Figure 7-14 shows the flow field at the plane of the leak colored by methane concentration at an elapsed time of 11.6 hours (near steady state), and can be compared to the analogous flow field at steady state colored by velocity shown in Figure 7-7. Figure 7-14 reemphasizes the point that flammable methane concentration exist only very near the leak. Figure 7-15 shows the flow field at the plane of the HRA, colored by methane concentration, at the same elapsed time. As noted above with Figure 7-6, methane concentrations in the HRA fan discharge are above 0.5%, and near the garage average steady state concentration of 0.61%.

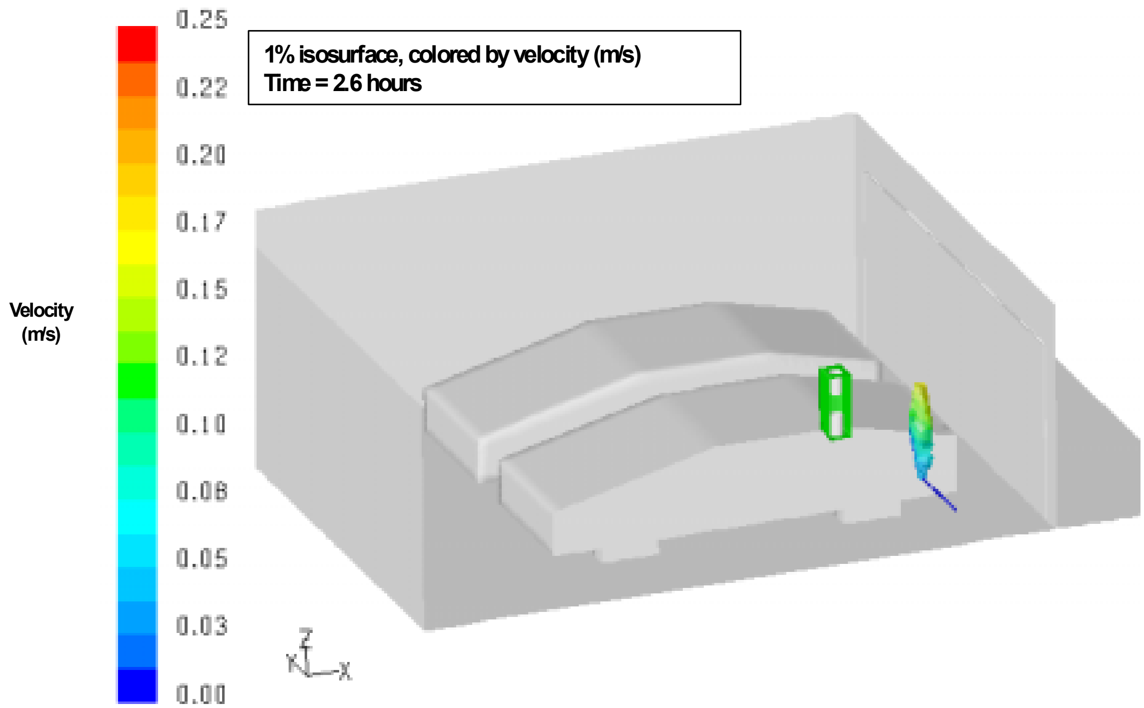

Figure 7-9. The 1% methane concentration isosurface for Case 1 at 2.6 hours of elapsed time

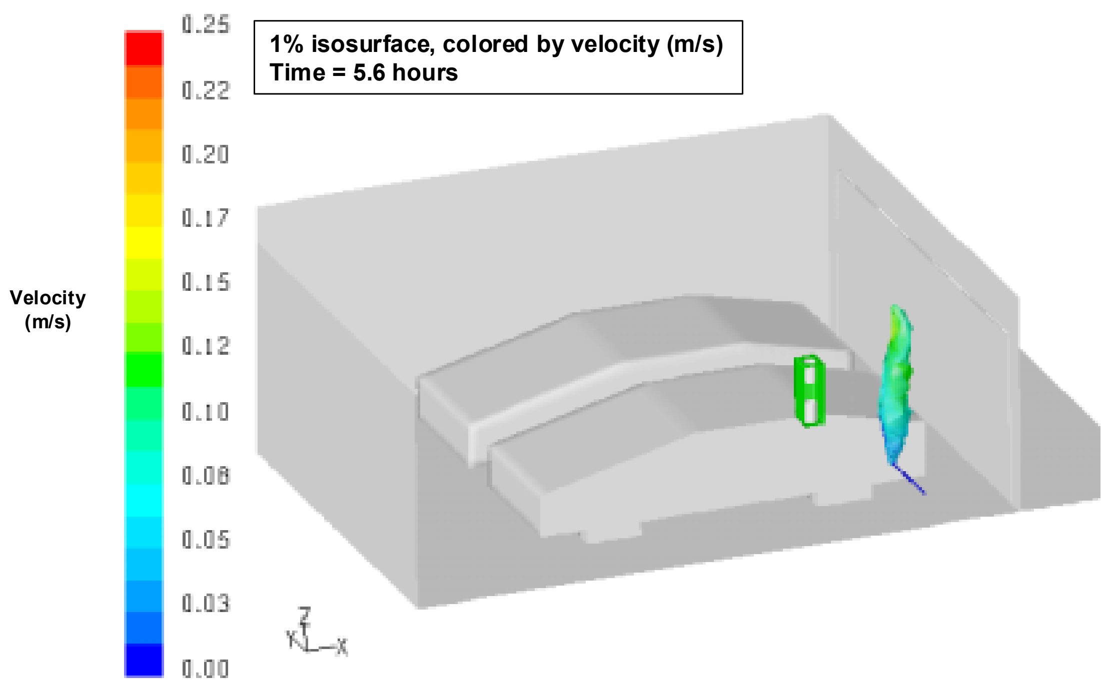

Figure 7-10. The 1% methane concentration isosurface for Case 1 at 5.6 hours of elapsed time

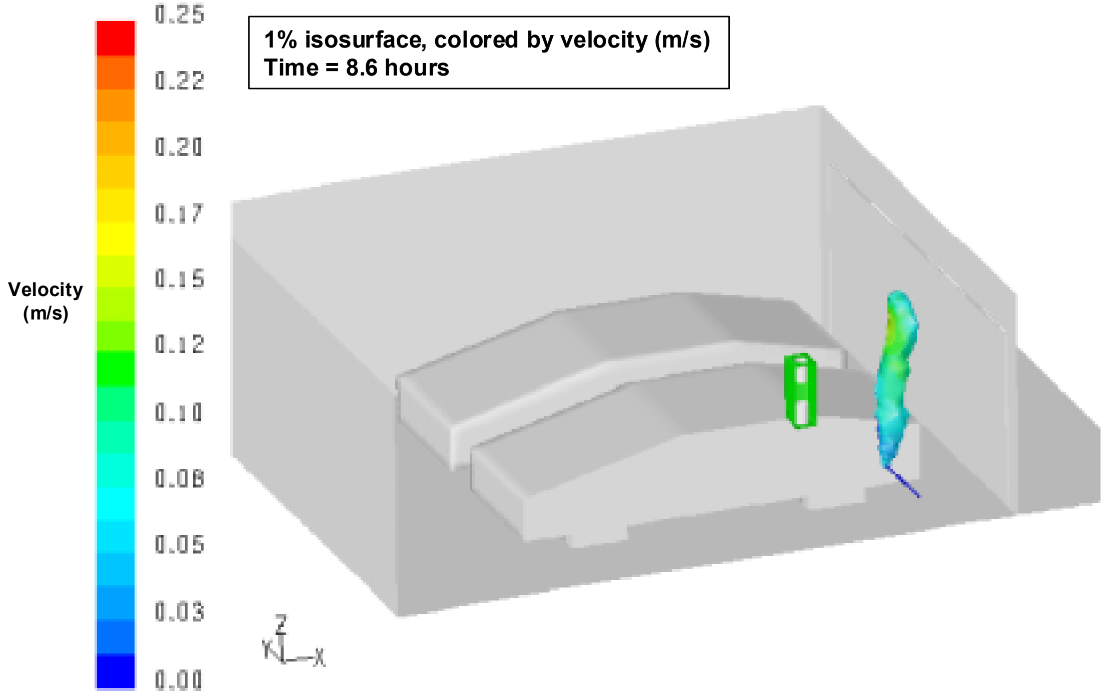

Figure 7-11. The 1% methane concentration isosurface for Case 1 at 8.6 hours of elapsed time

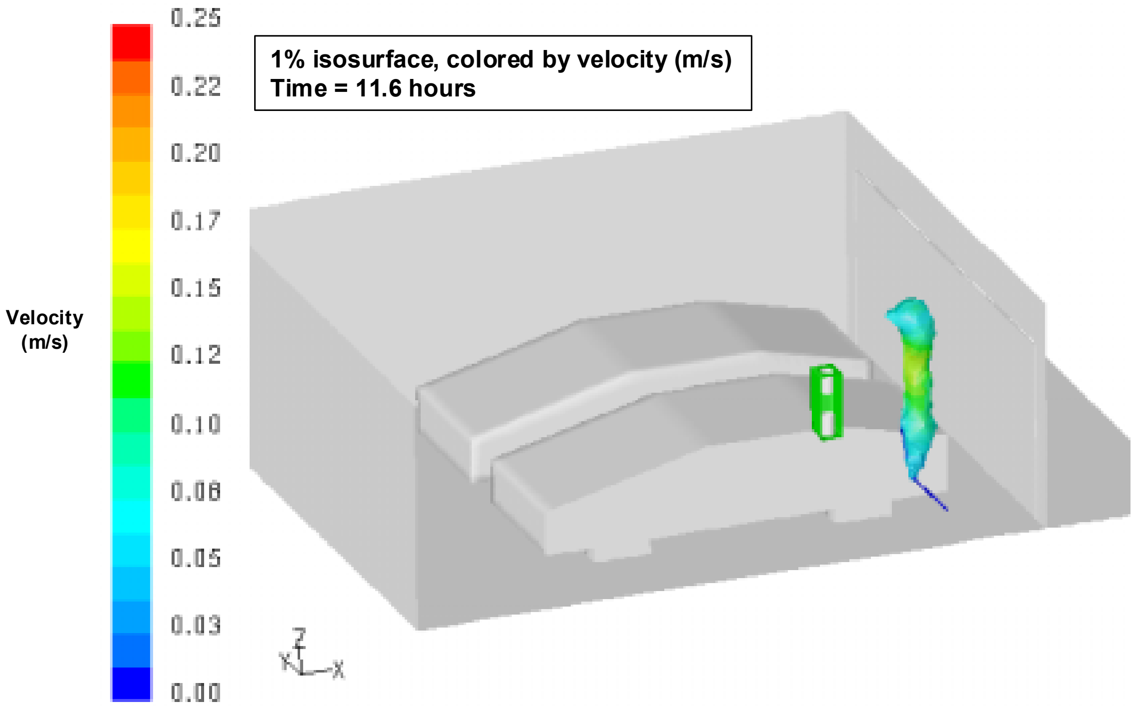

Figure 7-12. The 1% methane concentration isosurface for Case 1 at 11.6 hours of elapsed time

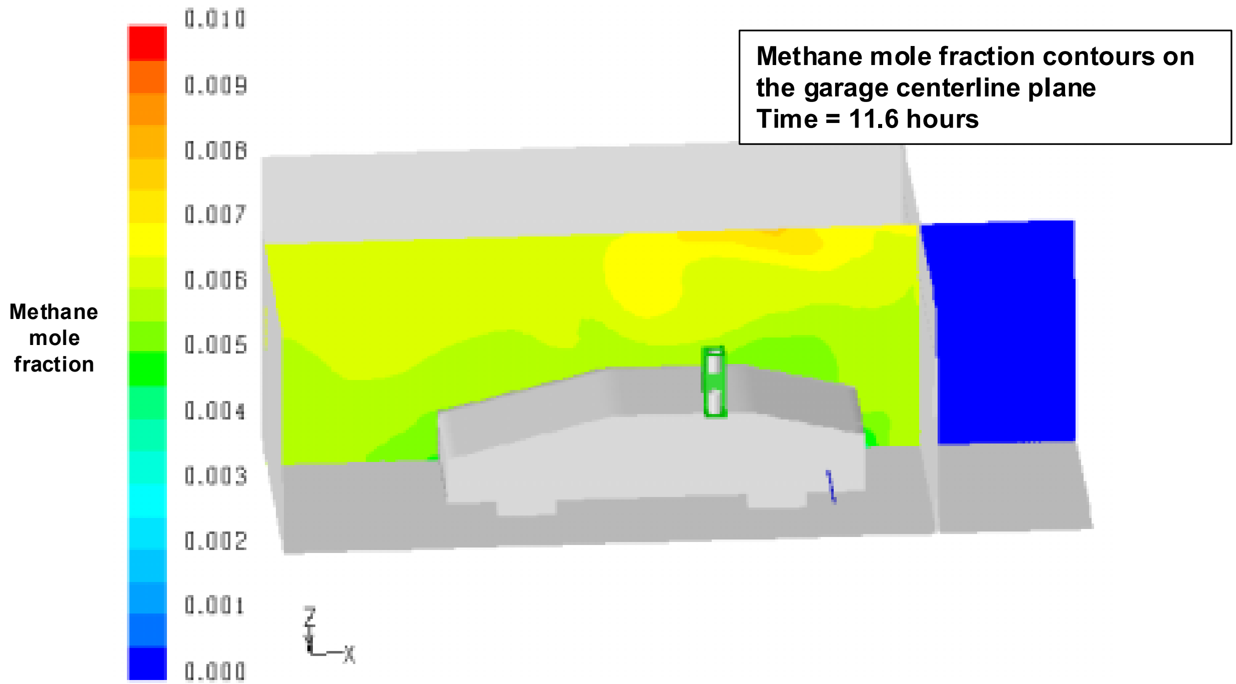

Figure 7-13. Methane concentration profile along the garage centerline for Case 1 at 11.6 hours of elapsed time

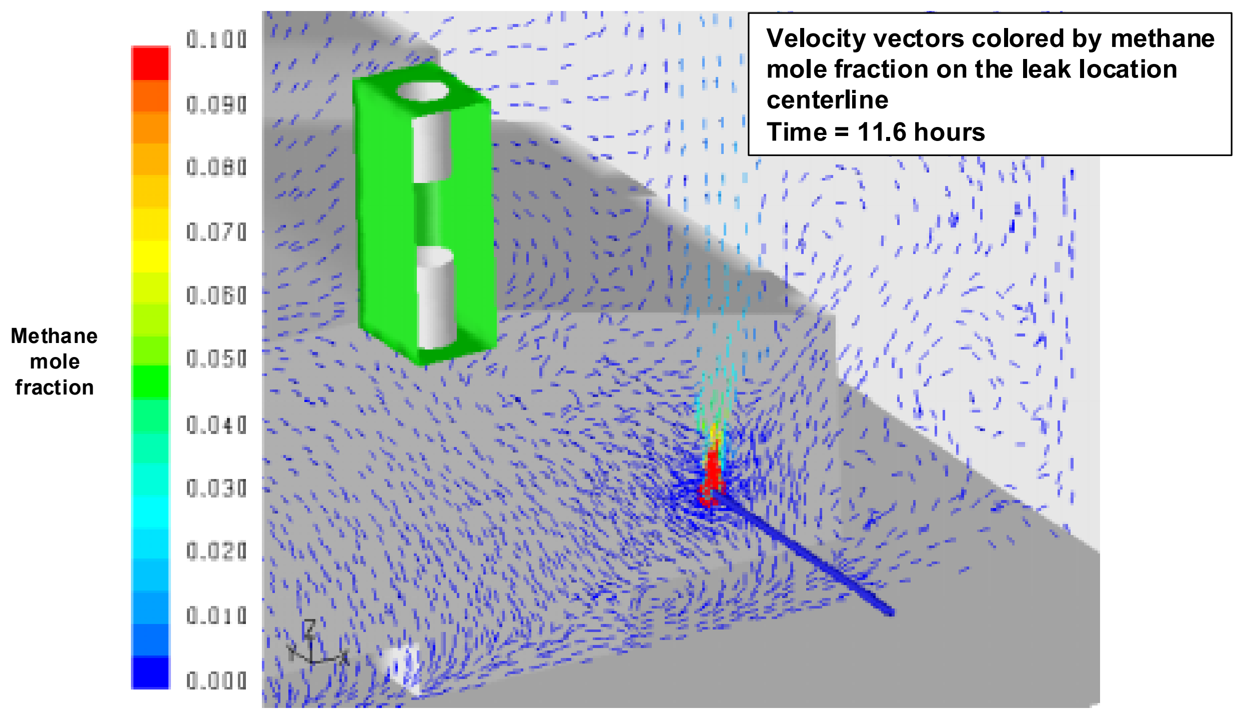

Figure 7-14. Flow field in the plane of the leak for Case 1 at 11.6 hours of elapsed time

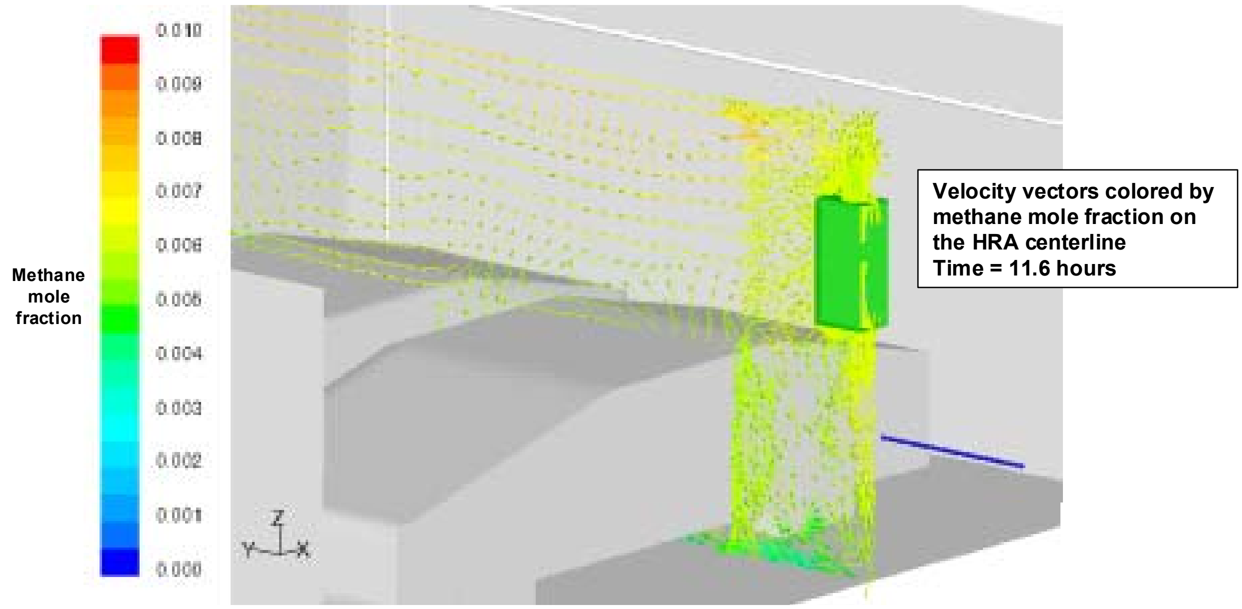

Figure 7-15. Flow field in the plane of the HRA centerline for Case 1 at 11.6 hours of elapsed time

The conclusion from the CFD analysis for Case 1, as illustrated by the figures discussed above, is that for a vehicle natural gas leak while connected to the HRA installed in an average (median or leakier) garage, flammable methane concentrations are unlikely to exist near possible ignition sources. This holds even with the HRA cooling air fan discharged into the garage interior. Flammable concentrations exist only above and very near the leak itself. Even methane concentrations at one-fifth of the methane LFL, or 1%, are confined to the region directly above the leak, and do not even reach the level of the 9-ft ceiling. Concentrations at the HRA cooling air discharge into the garage are about a factor of 10 below the methane LFL, and are near the more easily calculated steady state average concentration.

7.2.2 Case 2 — Cooling Air Discharged Outside the Garage

Figure 7-16 shows the isosurface of 5% methane concentration at 8.5 hours of elapsed time after the start of the gas leak with the HRA cooling air discharged to the garage exterior. Recall from above, an elapsed time of 8.5 hours is essentially a steady state situation for Case 2. Comparing this figure to the corresponding one for Case 1, Figure 7-3, shows that the methane LFL boundary is very similar in size, and also extends only a short distance from the leak. Figures 7-17, 7-18, and 7-19 show the transient buildup of the 1% methane isosurface at times of 3.1, 6.1, and 9.1 hours respectively. These figures can be compared to Figures 7-9, 7-10, 7-11, and 7-12 for the Case 1 1% isosurface transient buildup. This comparison shows that the 1% isosurface buildup is similar, and that the steady state volume of 1% or higher methane concentration is about the same regardless of whether the HRA cooling air is discharged into or out of the garage. The steady state isosurface buildup just occurs more quickly (steady state is reached sooner) when the cooling air is discharged outside the garage.

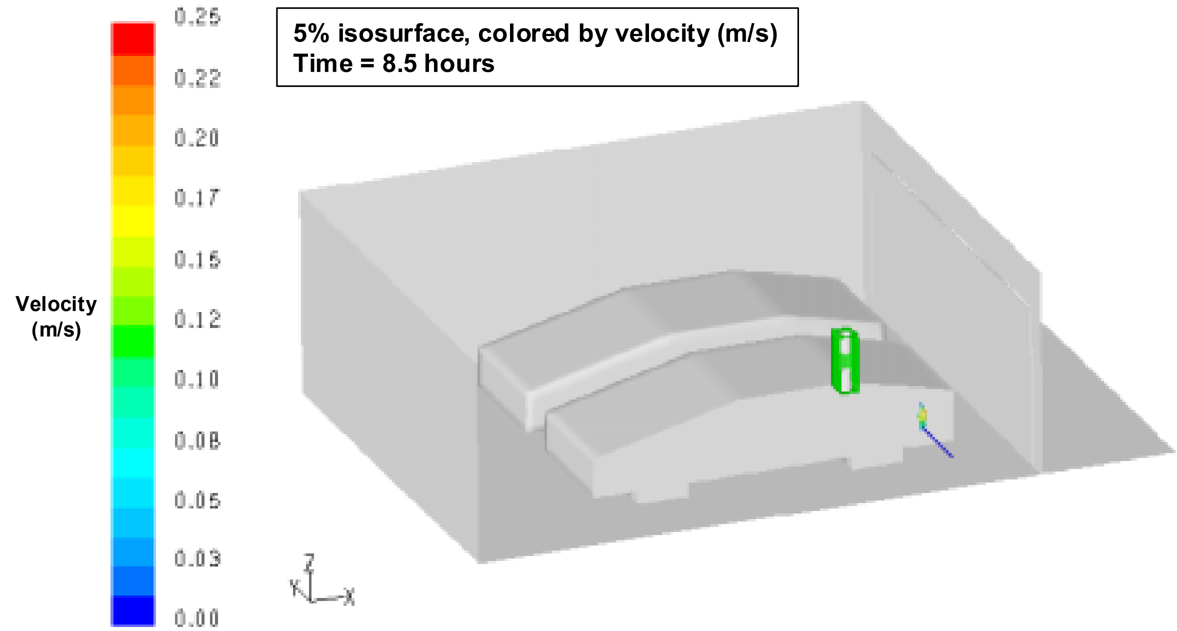

Figure 7-16. The 5% methane concentration isosurface for Case 2 at 8.5 hours of elapsed time

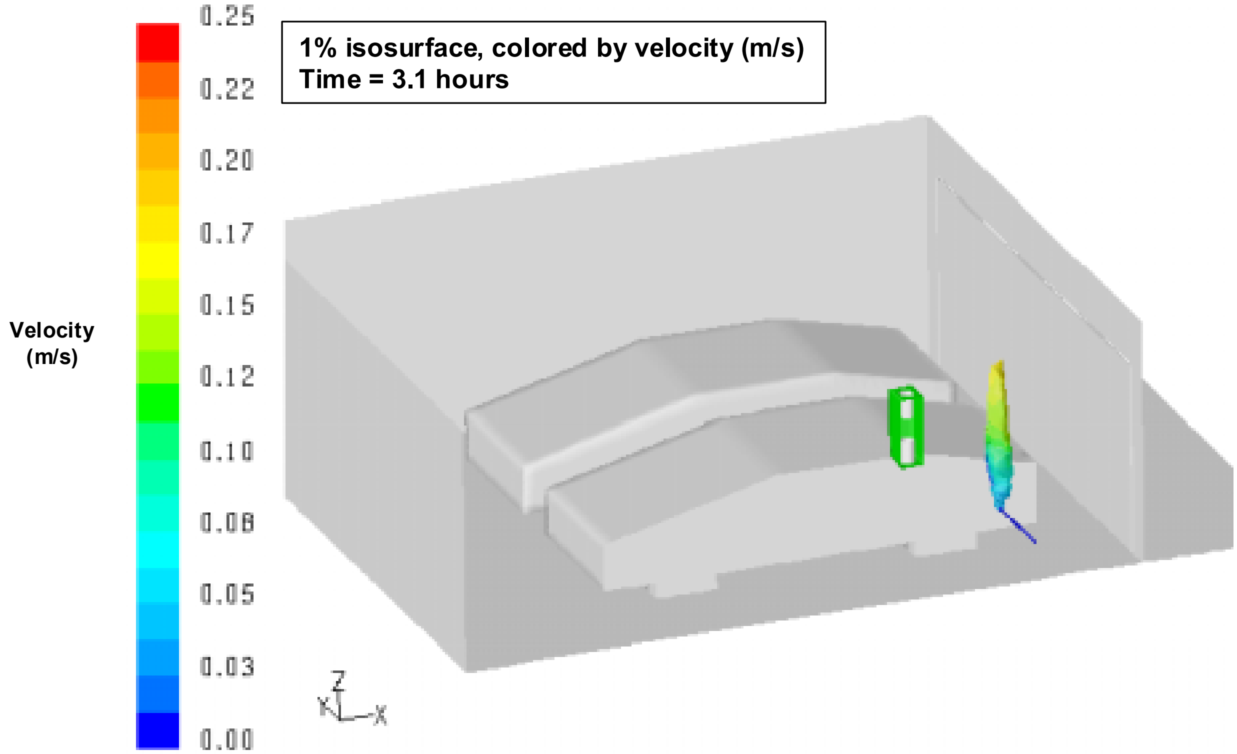

Figure 7-17. The 1% methane concentration isosurface for Case 2 at 3.1 hours of elapsed time

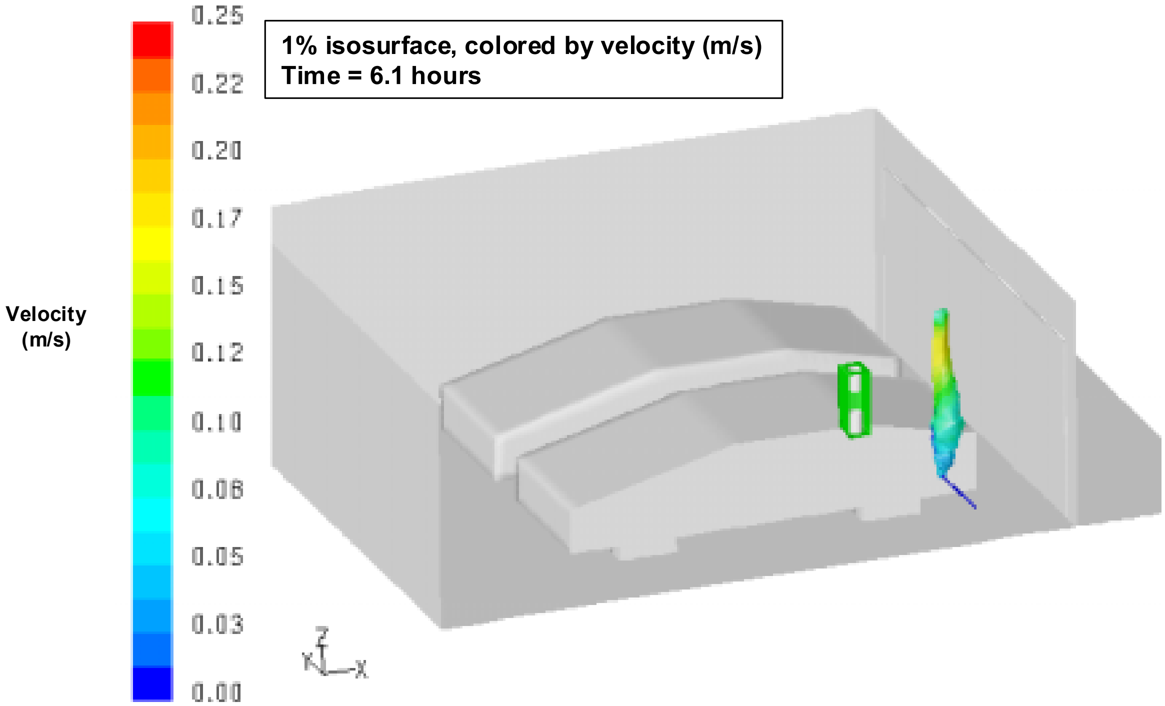

Figure 7-18. The 1% methane concentration isosurface for Case 2 at 6.1 hours of elapsed time

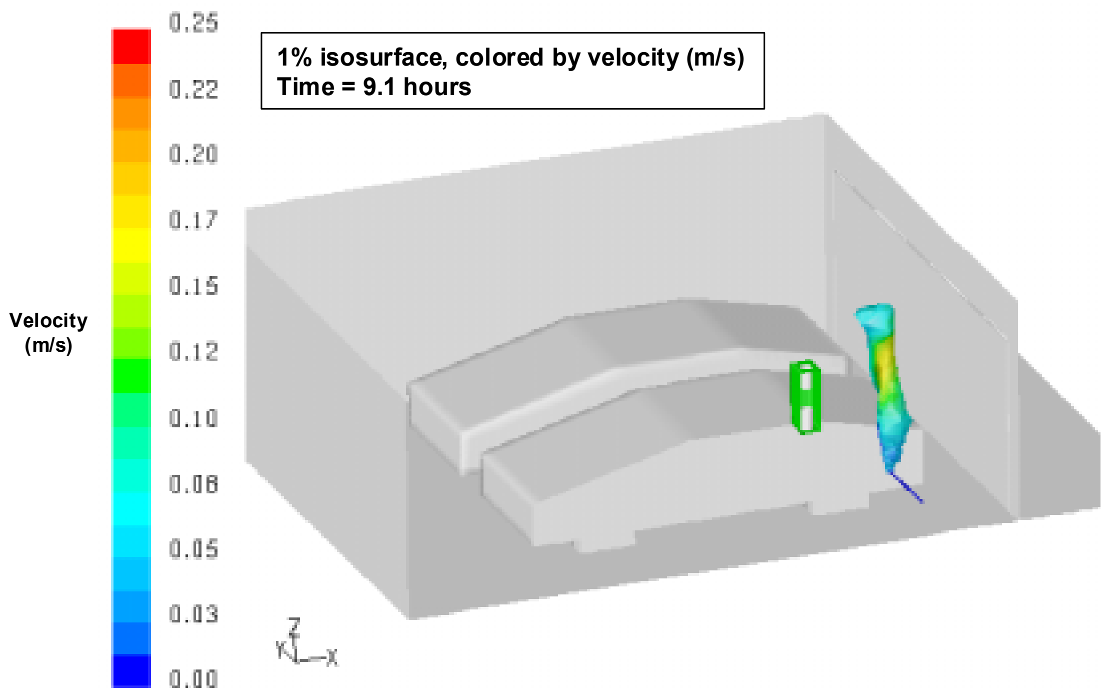

Figure 7-19. The 1% methane concentration isosurface for Case 2 at 9.1 hours of elapsed time

Figure 7-20 shows the garage methane concentration distribution at steady state (elapsed time of 11.5 hours, as indicated in the figure) at the garage centerline. Comparing this figure to the corresponding one for Case 1, Figure 7-13, shows that, while garage centerline concentrations were between about 0.5 and 0.7% with the cooling air discharged into the garage (Case 1, Figure 7-13), they were reduced, at between about 0.2 and 0.5% with the cooling air discharged to the outside. Evidently, venting the cooling air outside reduces already low methane concentrations with the cooling air discharged into the garage to even lower levels. This occurs despite leaving the pockets of relatively higher concentration, the 1% and 5% isosurfaces, essentially unchanged in size.

Figure 7-21 shows the flow field at the plane of the leak colored by methane concentration at an elapsed time of 9.1 hours, and can be compared to the analogous flow field for Case 1 shown in Figure 7-14. Figure 7-21 reemphasizes the point that flammable methane concentrations exist only very near the leak. Figure 7-22 shows the flow field at the plane of the HRA, colored by methane concentration, at the same elapsed time. The figure shows that methane concentrations above the HRA, extending along the garage ceiling toward the garage centerline, are about 0.5%, just above the garage average steady state concentration of 0.29%.

The conclusion from the CFD analysis for Case 2, as illustrated by the figures discussed above, are essentially the same as that from the analysis for Case 1. That is, that a vehicle natural gas leak while connected to the HRA installed in an average (median or leakier) garage is unlikely to produce flammable methane concentrations near possible ignition sources. Flammable concentrations exist only above and very near the leak itself. Even methane concentrations at one-fifth of the methane LFL, or 1%, are confined to the region directly above the leak, and do not even reach the level of the 9-ft ceiling. Discharging the HRA cooling air outside of the garage reduces the average garage concentration at any given time compared to discharging the

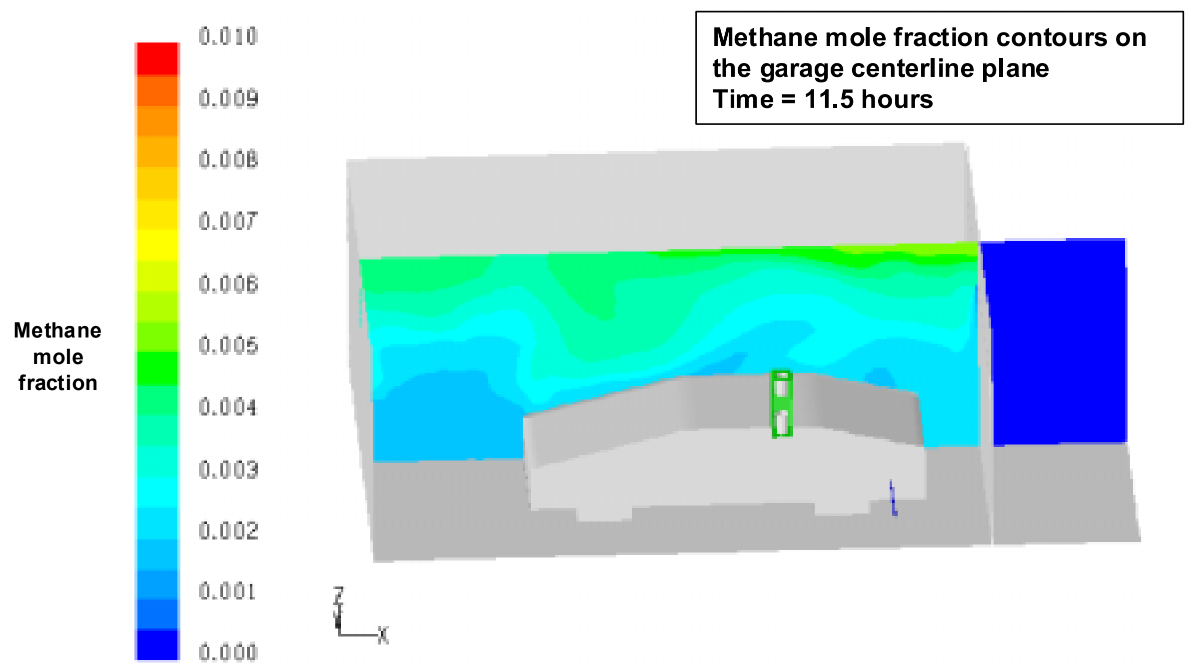

Figure 7-20. Methane concentration profile along the garage centerline for Case 2 at 11.5 hours of elapsed time

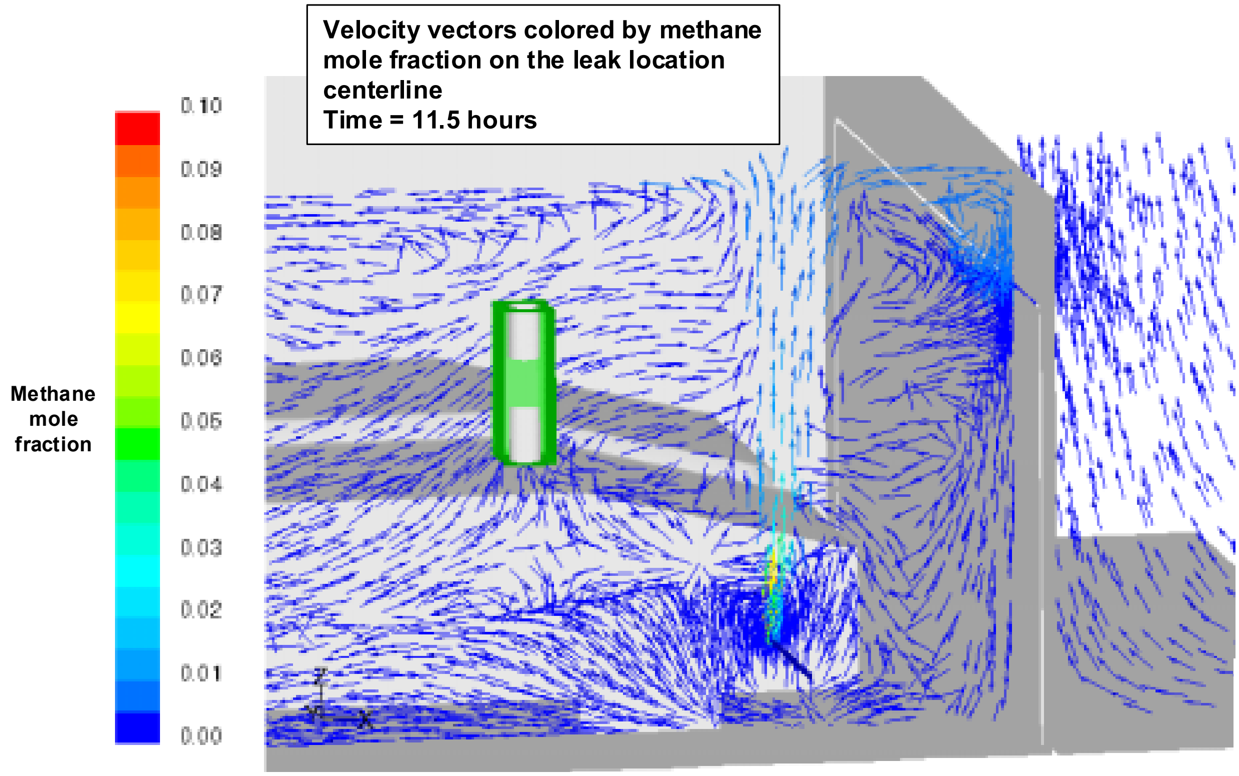

Figure 7-21. Flow field in the plane of the leak for Case 2 at 11.5 hours of elapsed time

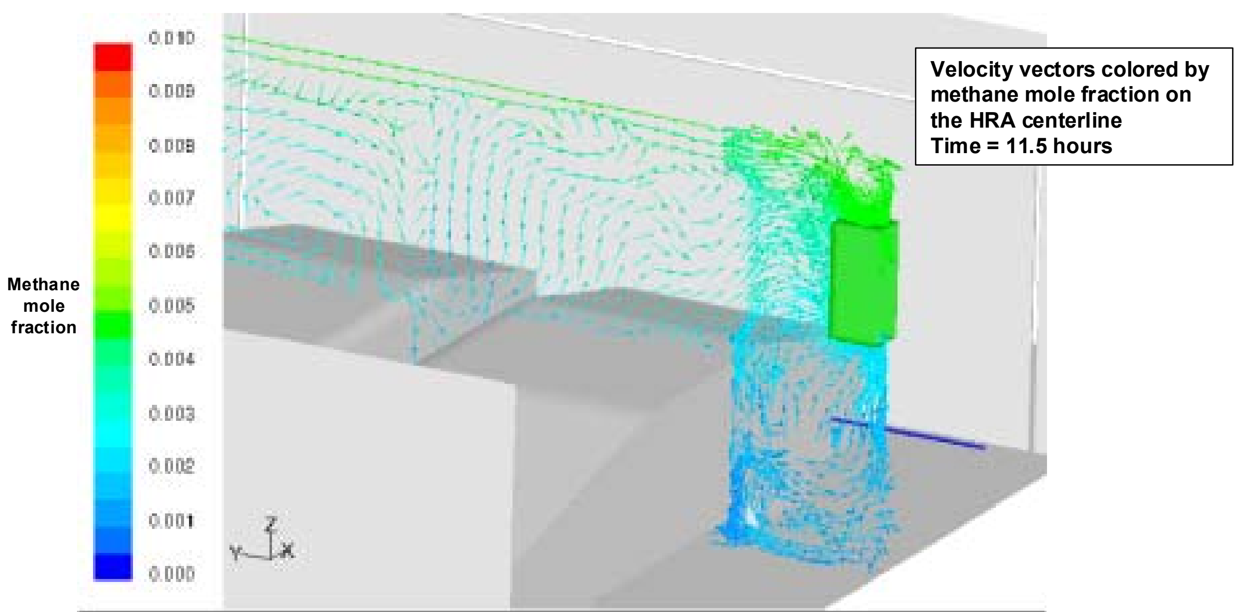

Figure 7-22. Flow field in the plane of the HRA centerline for Case 2 at 11.5 hours of elapsed time

cooling air into the garage, and methane concentrations distant from the leak are lower when the cooling air is discharged outside. However, the locus of methane concentrations of 1% or greater is not changed significantly by venting the cooling air outside. In addition, the buildup of the 1% methane isosurface to its steady state size occurs more quickly when the cooling air is vented outside the garage.

7.3 Garage Concentrations Resulting from a Gas Discharge

As noted above, the gas discharge failure scenarios had a gas discharge of 0.67 scfm from the HRA breakaway valve attendant to a refueling situation. The discharge was into a garage with low infiltration characteristics (ACH) associated with the most sealed (less "leaky) 30% of garages arising out of the garage survey discussed in Section 5.

Figure 7-23 shows the predicted average garage methane concentrations over time for the three gas discharge cases evaluated. The steady state garage average concentration for a 0.67 scfm discharge into the garage with the HRA fan not running (the specification for Case 5) is 4.8%, the target average concentration for the steady state calculation performed to establish the garage door gap width and airflow restriction for Cases 3, 4, and 5. Figure 7-21 shows that this steady state concentration had not been reached after 14 hours of continuous discharge. This steady state average concentration is also not reached after 14 hours for Case 3, with the HRA cooling fan discharging into the garage interior. The steady state garage average concentration for Case 4, with the HRA cooling fan discharged outside of the garage is a reduced 0.87%. This average concentration is essentially reached after about 6 hours. The decreased steady state concentration for Case 4 is, again, due to the increased infiltration caused by venting the 80 cfm

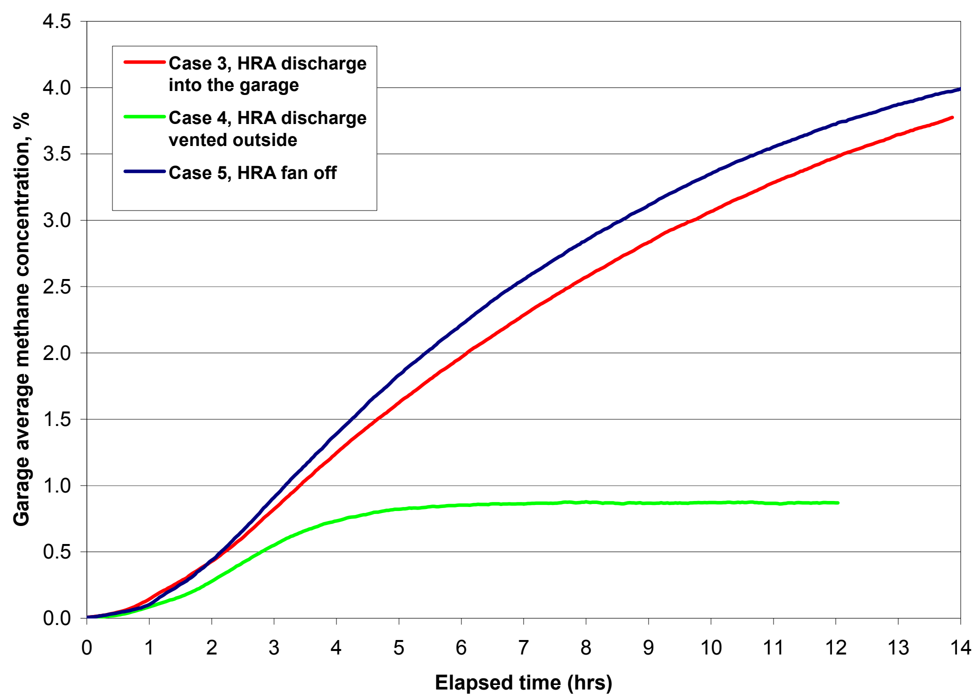

Figure 7-23. Garage volume average methane concentrations for Cases 3, 4, and 5

of HRA cooling air outside. By so doing, the garage ACH is increased to 1.0/hr, the same as for the “leakier” garage assumed in Case 2. Figure 7-23 indicates that the Case 4 calculation was carried out for an elapsed time of 12 hours, instead of the 14 hours for the other cases. There was no need to extend the calculations to longer times for this case as steady state had been reached.

7.3.1 Case 3 — Cooling Air Discharged into the Garage Interior

Figure 7-24 shows the isosurface of 5% methane concentration, the methane LFL, after 14 hours for the natural gas discharge, colored by the gas (methane plus air) velocity. The figure shows that flammable methane concentrations for the Case 3 scenario extend some distance from the gas discharge and reach about halfway toward the garage ceiling above the discharge. However, the volume of gas at or above the methane LFL has not spread beyond the “plume” to regions along the garage ceiling. A likely ignition source within the garage would be an electrically operated garage door opener. These, however, are typically located along a garage ceiling centerline. The 5% “plume” has not spread along the ceiling to such a likely location, even after 14 hours of continuous gas discharge.

Figure 7-25 shows the corresponding isosurface of 4% methane concentration after 14 hours. The 4% plume has indeed spread along the garage ceiling, and has reached the garage centerline to a location where a garage door opener may be located. The 4% concentration is less than the methane LFL however. Figure 7-26 shows the 3% methane isosurface after 14 hours. The interpretation of this isosurface is slightly different than the 5% and 4% isosurfaces shown in Figures 7-24 and 7-25, however, and is analogous to the interpretation of Figure 7-5 for the 0.5% concentration isosurface for Case 1. Thus, for the 5% and 4% isosurfaces, methane concentrations within the plume are at or above the isosurface concentration. For the 3% isosurface, it is the volume above the surface (closer to the discharge and further from the garage door side gaps) that are at or above 3% concentration. Figure 7-26 indicates that a significant fraction of the garage volume has 3% or higher methane concentration. This point is also illustrated by Figure 7-27, which shows the methane concentration profile along the garage centerline after 14 hours. This figure shows that all of the garage volume along the centerline has methane concentration of 3% or higher, with a centerline maximum concentration 4% in a pocket along the ceiling. It bears repeating, however, that, even though most of the garage volume has methane concentrations of 3% or greater, the only locations at or above the methane LFL are directly above the discharge.

Figures 7-28, 7-29, 7-30, and 7-31 show the transient buildup of the 5% methane isosurface at times of 2.8, 5.8, 8.8, and 11.8 hours, respectively. Figure 7-32 shows the pathlines emanating from the gas discharge, the HRA fan discharge at the top of the appliance, and the garage door gap at 14 hours of elapsed time, colored by methane concentration. The figure shows that methane concentrations are above 4% along the garage ceiling above the discharge, extending toward the center of the garage. The figure also shows that pathlines emanating from the HRA fan discharge have methane concentrations of just over 3.5%.

Figure 7-33 shows the flow field in the plane of the discharge, colored by gas velocity, at 14 hours of elapsed time. The pattern of gas recirculation can be seen in this figure. Figure 7-34 shows the corresponding flow field colored by methane concentration, and shows a substantial

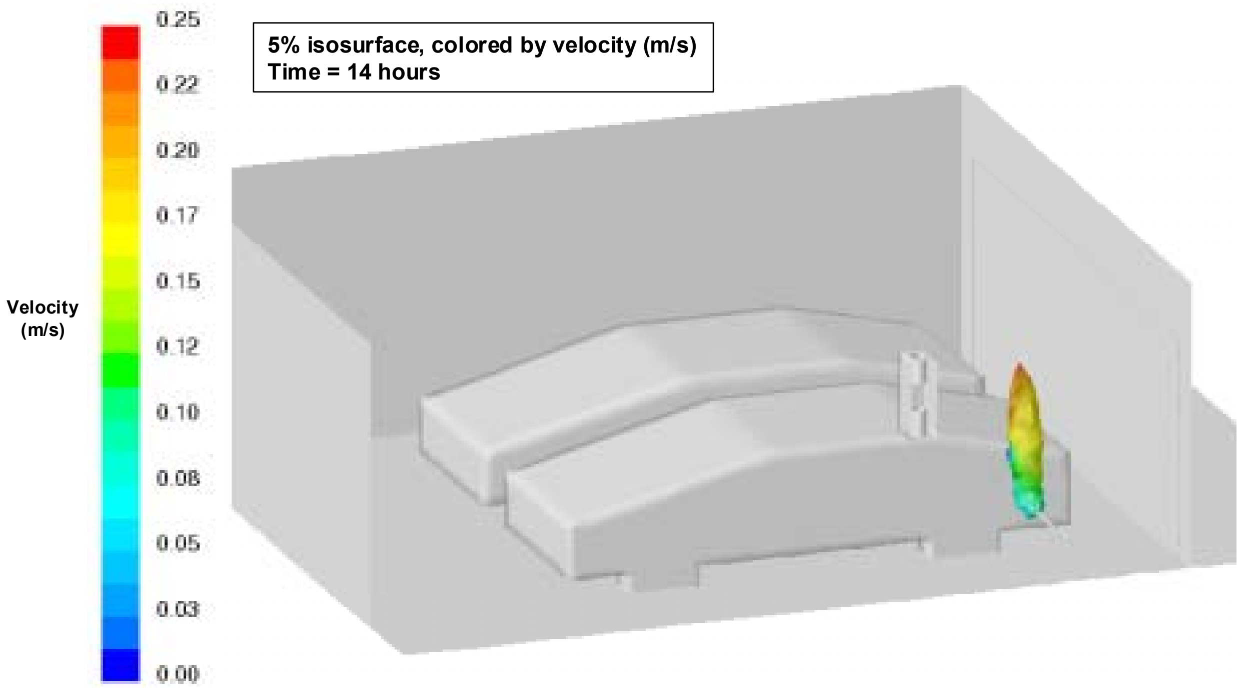

Figure 7-24. The 5% methane concentration isosurface for Case 3 at 14 hours of elapsed time

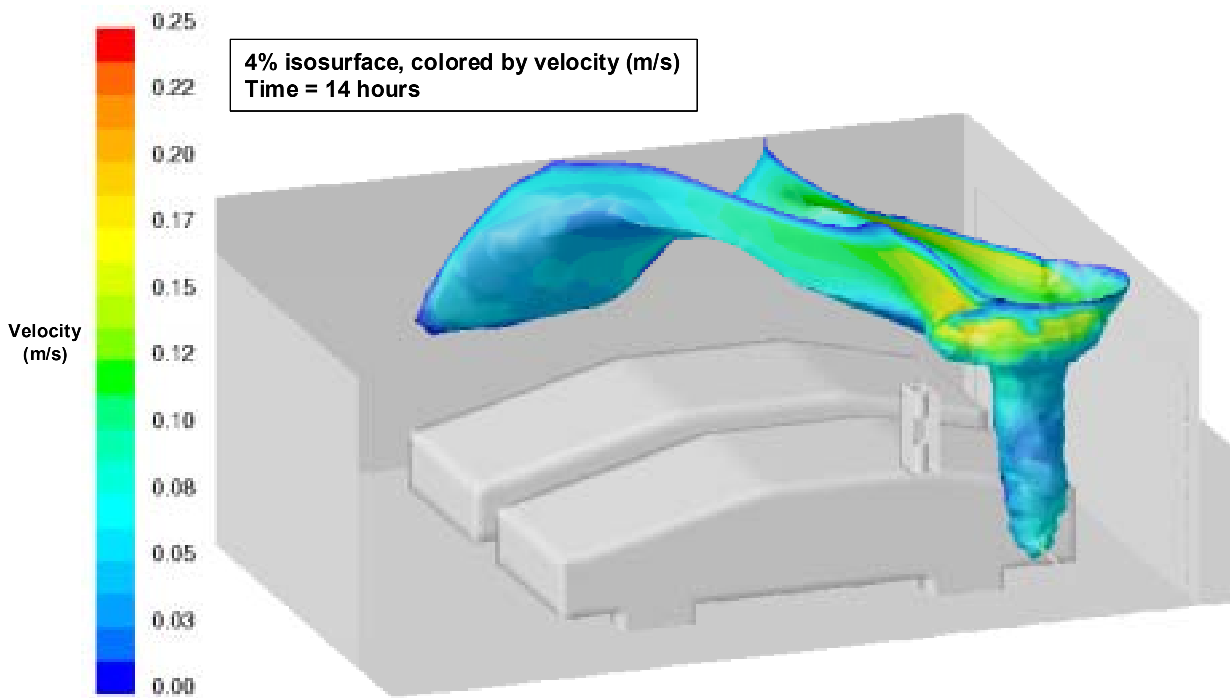

Figure 7-25. The 4% methane concentration isosurface for Case 3 at 14 hours of elapsed time

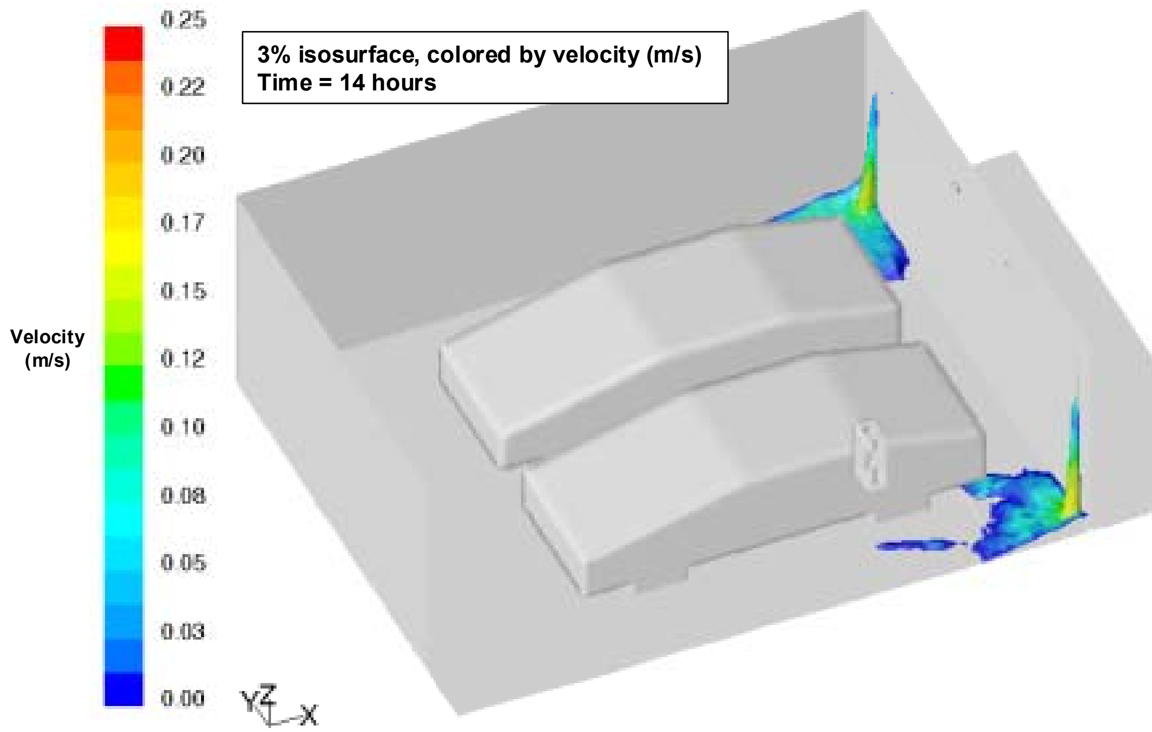

Figure 7-26. The 3% methane concentration isosurface for Case 3 at 14 hours of elapsed time

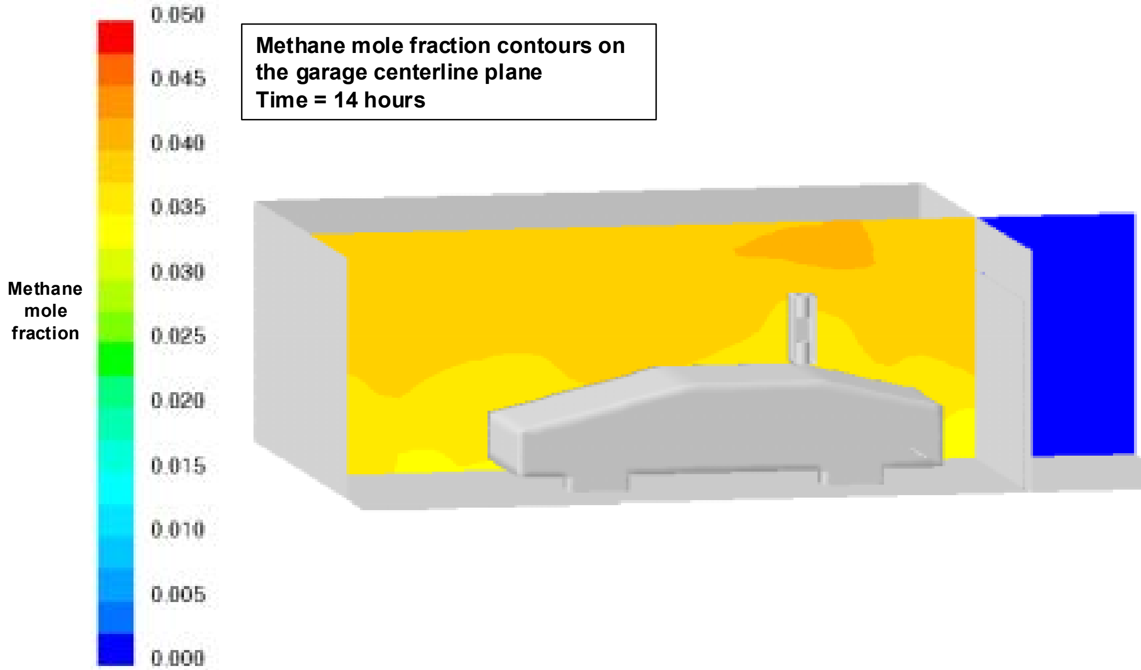

Figure 7-27. Methane concentration profile along the garage centerline for Case 3 at 14 hours of elapsed time

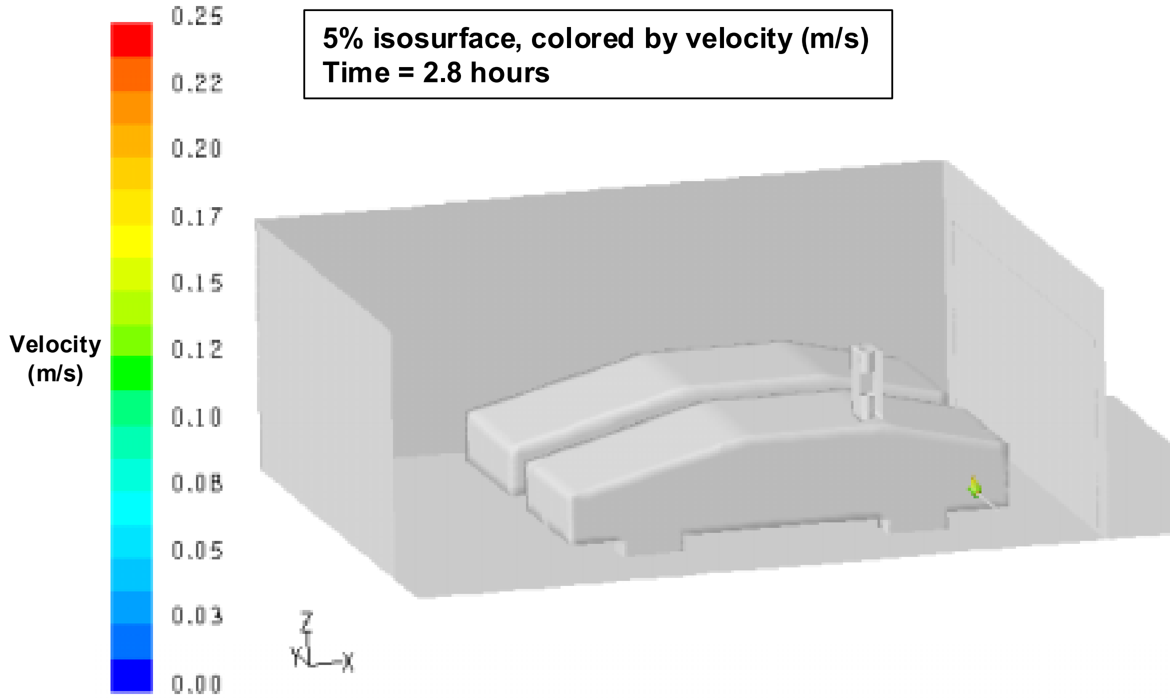

Figure 7-28. The 5% methane concentration isosurface for Case 3 at 2.8 hours of elapsed time

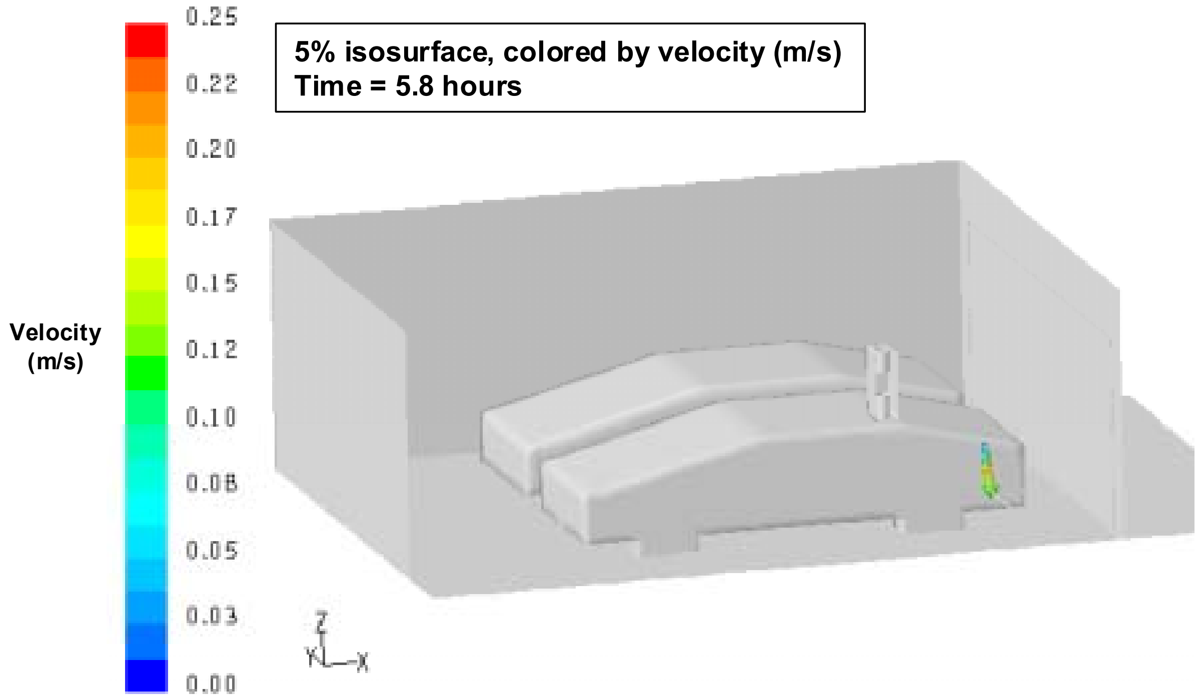

Figure 7-29. The 5% methane concentration isosurface for Case 3 at 5.8 hours of elapsed time

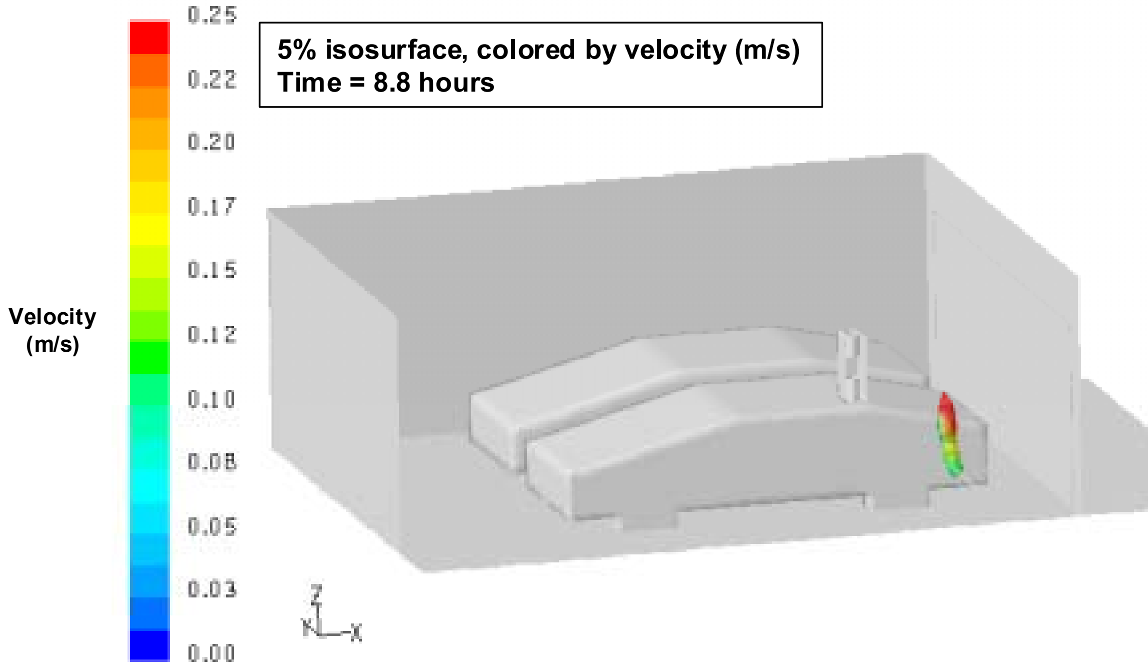

Figure 7-30. The 5% methane concentration isosurface for Case 3 at 8.8 hours of elapsed time

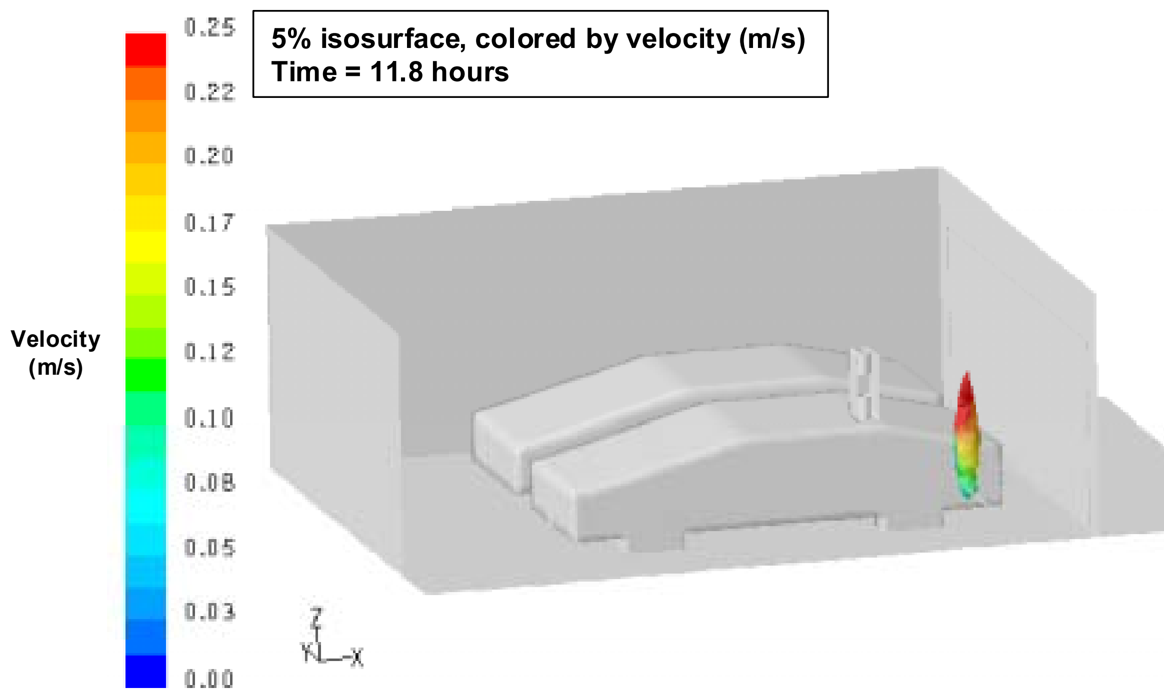

Figure 7-31. The 5% methane concentration isosurface for Case 3 at 11.8 hours of elapsed time

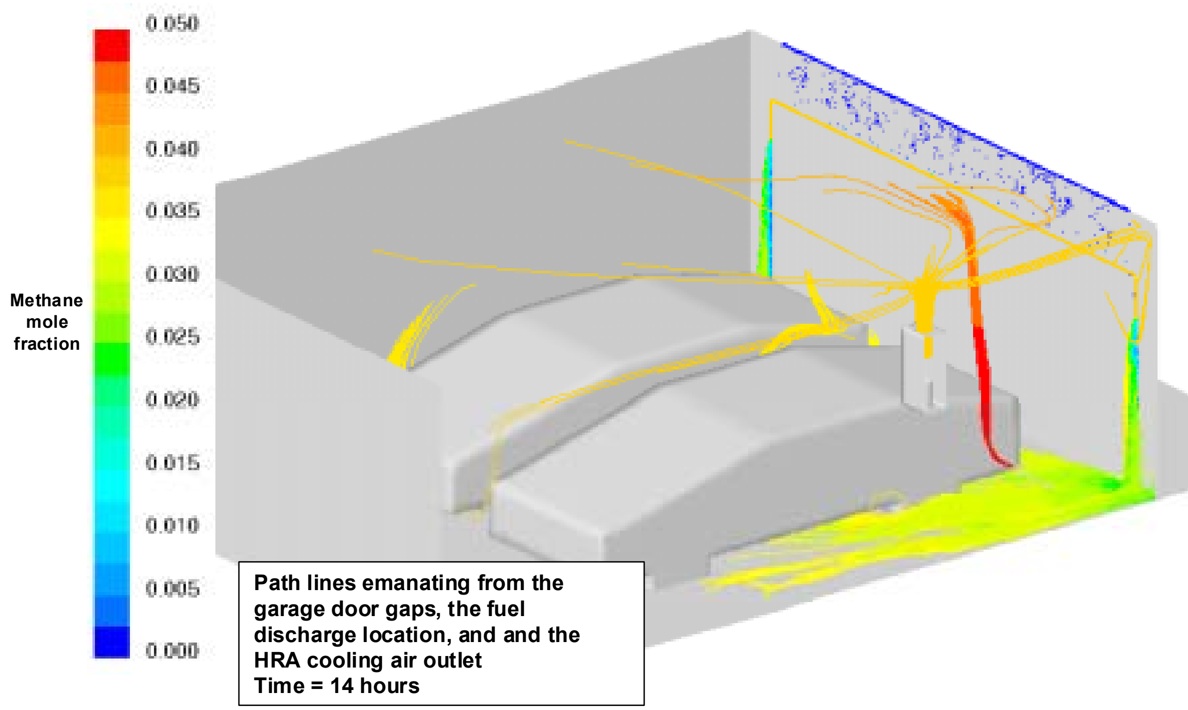

Figure 7-32. Gas particle pathlines from the gas discharge for Case 3 at steady state

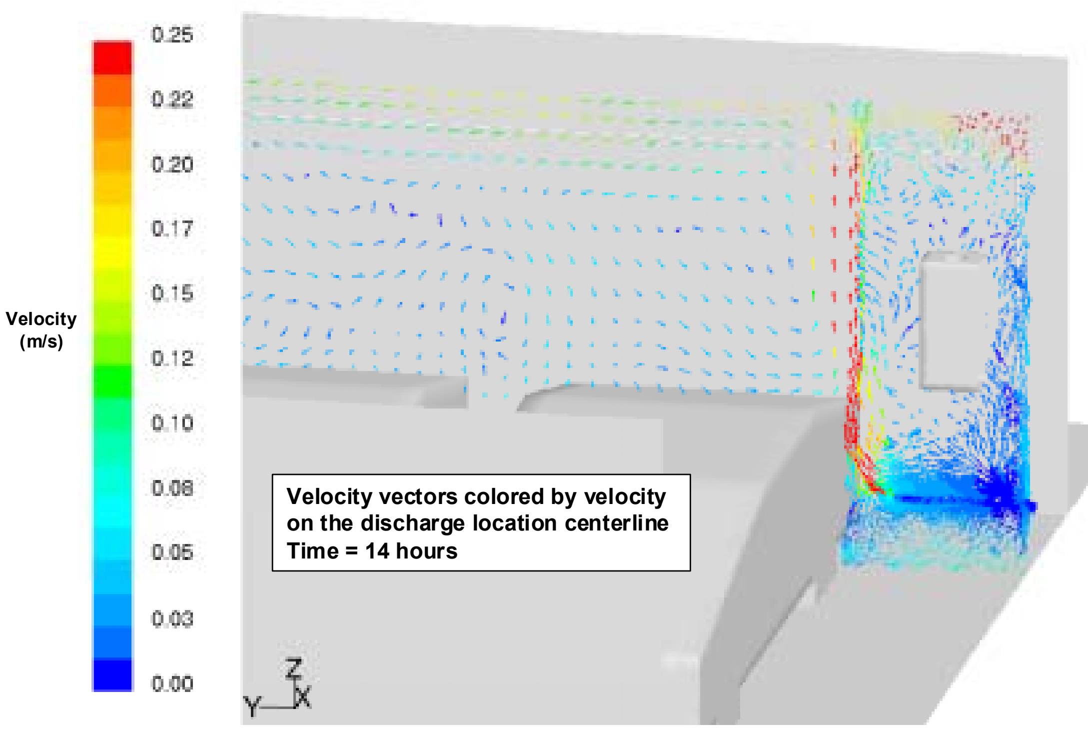

Figure 7-33. Flow field in the plane of the discharge for Case 3 at 14 hours of elapsed time

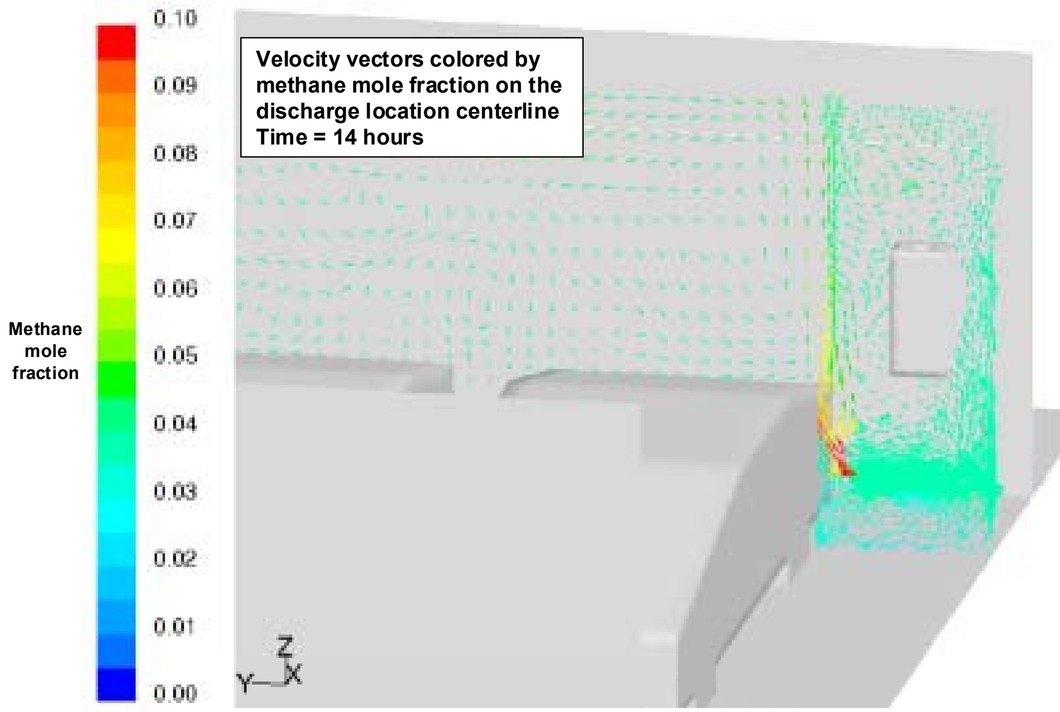

Figure 7-34. Flow field in the plane of the discharge for Case 3 at 14 hours of elapsed time

fraction of the plane has methane concentrations at or over 4%. Figure 7-35 shows the flow field in the plane of the of the HRA colored by temperature at an elapsed time of 14 hours. The figure shows that the HRA cooling air discharge from the top of the appliance is 93°F (307 K). As noted in Section 7.1, the relatively sparse set of velocity vectors over the vehicle itself reflects the less dense computational grid used in the space above the vehicle. Figure 7-36 shows the corresponding flow field in the plane of the HRA colored by methane concentration.

The conclusion from the CFD analysis for Case 3, as illustrated by the figures discussed above, is that a natural gas discharge from the HRA in which the HRA continues to pump gas at its refueling rate into a relatively well-sealed garage can result in flammable methane concentrations that extend a significant distance into the garage above the discharge. However, this locus of flammable methane concentration becomes significant only after relatively long periods of time, 12 to 14 hours. Further this locus of flammable methane concentration is confined to a region immediately above the gas discharge and does not extend to locations that can be considered to contain likely ignition sources.

Near flammable methane concentrations of 4% do extend along the garage ceiling to a location where an electric garage door opener might be located. But, again, this concentration buildup requires a long period of time, 12 hours or more. Methane concentrations of 3% or greater exist in most of the garage volume after this period of time, and the average garage concentration is 3.8% after 14 hours of continuous discharge. The methane concentration in the HRA cooling air discharge into the garage is nominally 3.5% after 14 hours, near the garage average concentration.

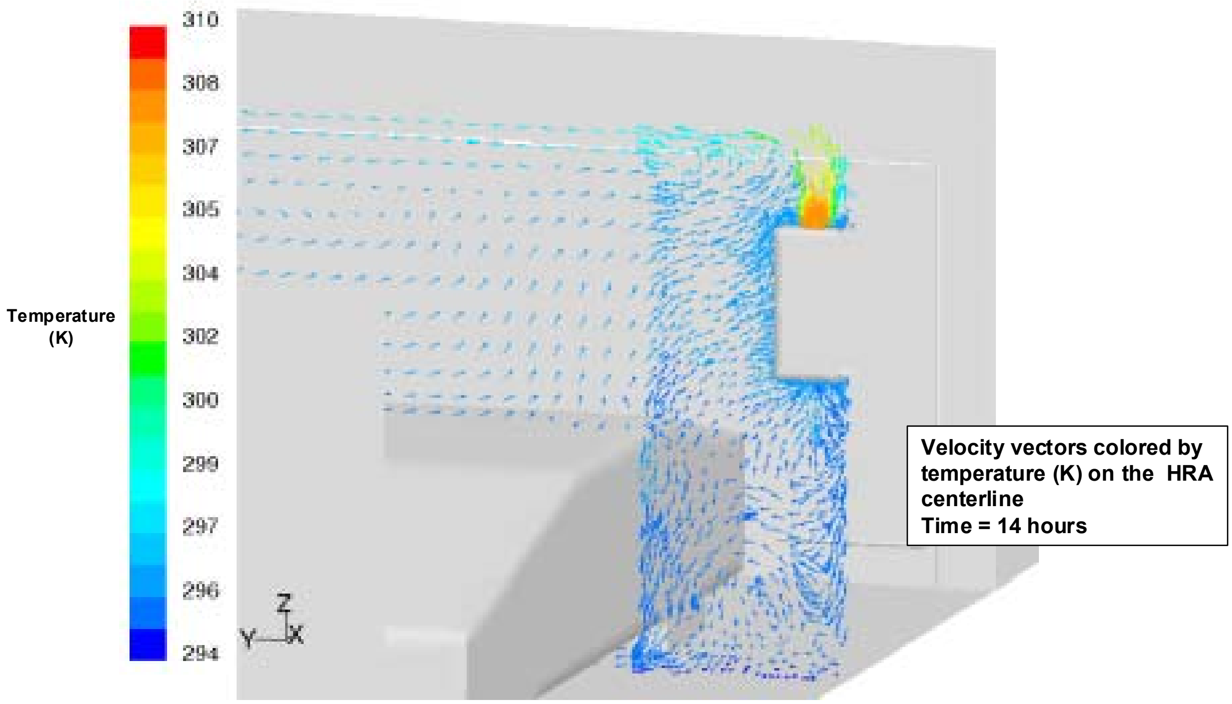

Figure 7-35. Flow field in the plane of the HRA centerline for Case 3 at 14 hours of elapsed time

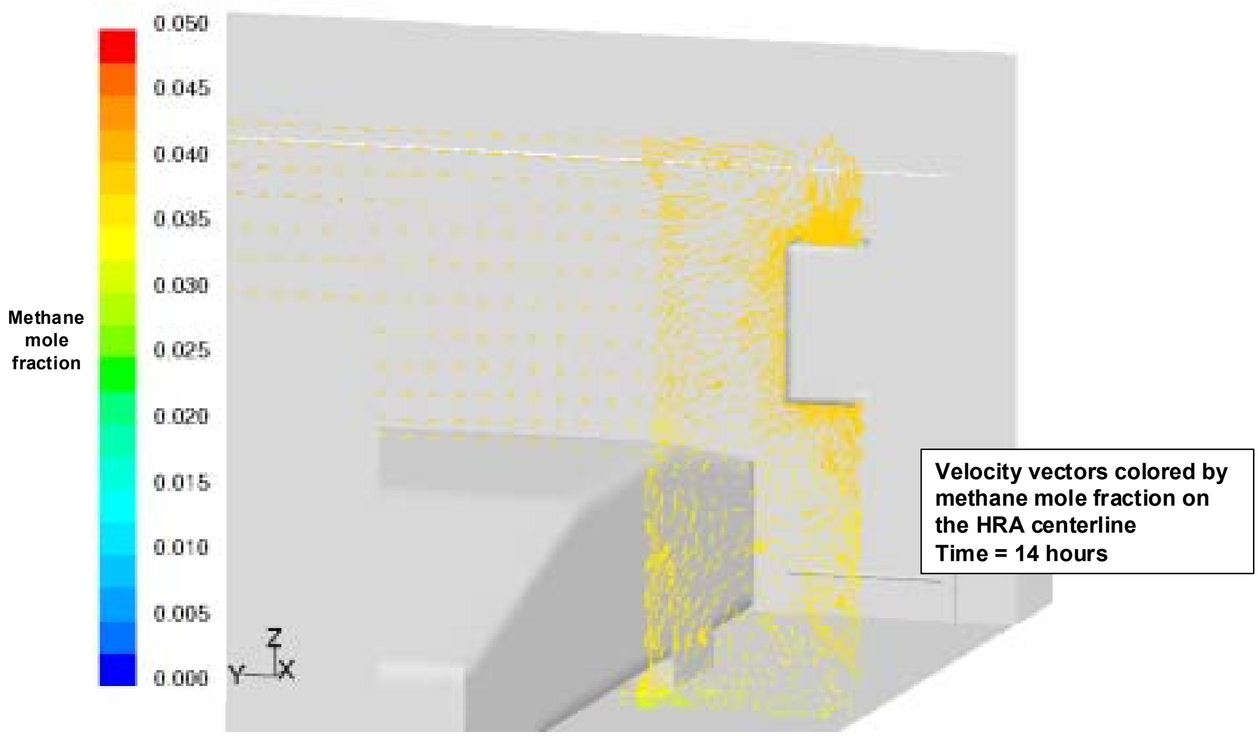

Figure 7-36. Flow field in the plane of the HRA centerline for Case 3 at 14 hours of elapsed time

7.3.2 Case 4 — Cooling Air Discharged Outside the Garage

Figure 7-37 shows the isosurface of 5% methane concentration at 9 hours of elapsed time after the start of the undetected gas discharge with the HRA cooling air vented to the garage exterior. Recall from above, an elapsed time of 9 hours is essentially a steady state situation. This figure shows that the methane LFL boundary for this case is very similar in size to that shown in Figure 7-16 for the gas leak into a typical garage with the HRA cooling air vented outside (Case 2), and also extends only a short distance from the leak. Evidently, an increase in the gas release rate from the 0.22 scfm leak to the 0.67 scfm discharge and a decrease in the base (before HRA installation) garage ACH has little effect on the size of the garage volume having flammable methane concentrations when 80 cfm of cooling air is being drawn into the garage to be vented outside.

Figures 7-38, 7-39, and 7-40 show the transient buildup of the 1% methane isosurface at times of 2.5, 5.5, and 8.5 hours, respectively. These figures can be compared to Figures 7-17, 7-18, and 7-19 for the Case 2 1% isosurface transient buildup. This comparison shows that the 1% isosurface buildup for the gas discharge occurs much more rapidly and extends to a much larger fraction of the garage volume compared to the gas leak case. The other major difference between the gas leak Case 2 and the gas discharge Case 4 is that the higher rate of gas release for the discharge leads to a higher steady state average methane concentration, 0.87% for the discharge compared to 0.29% for the leak.

Figure 7-41 shows the garage methane concentration distribution at steady state (elapsed time of 8.5 hours, as indicated in the figure) at the garage centerline. Comparing this figure to the corresponding one for Case 2, Figure 7-20, shows that garage centerline concentrations are between about 0.6 and 1.3% for the gas discharge into a well-sealed garage (Case 4) compared to between about 0.2 and 0.5% for the gas leak into a typical garage (Case 2).

Figure 7-42 shows the flow field at the plane of the discharge colored by methane concentration at steady state (elapsed time of 12 hours), and can be compared to the analogous flow field for Case 2 shown in Figure 7-21. Both figures emphasizes the point that flammable methane concentrations exist only very near the leak or discharge when the HRA cooling air discharge is vented outside the garage. Figure 7-43 shows the flow field at the plane of the HRA, colored by methane concentration, at the same elapsed time. The figure shows that methane concentrations in the vicinity of HRA fan discharge are about 1.2%, just over the garage average steady state concentration of 0.87%.

The conclusion from the CFD analysis for Case 4, as illustrated by the figures discussed above, are essentially the same as that from the analysis for Case 2. That is, that an undetected natural gas discharge from the HRA, even installed in a well-sealed garage is unlikely to produce flammable methane concentrations near possible ignition sources if the HRA cooling air is vented to the outside. Flammable concentrations exist only above and very near the leak itself. However, methane concentrations at one-fifth of the methane LFL, or 1%, do exist over a significant fraction of the garage volume.

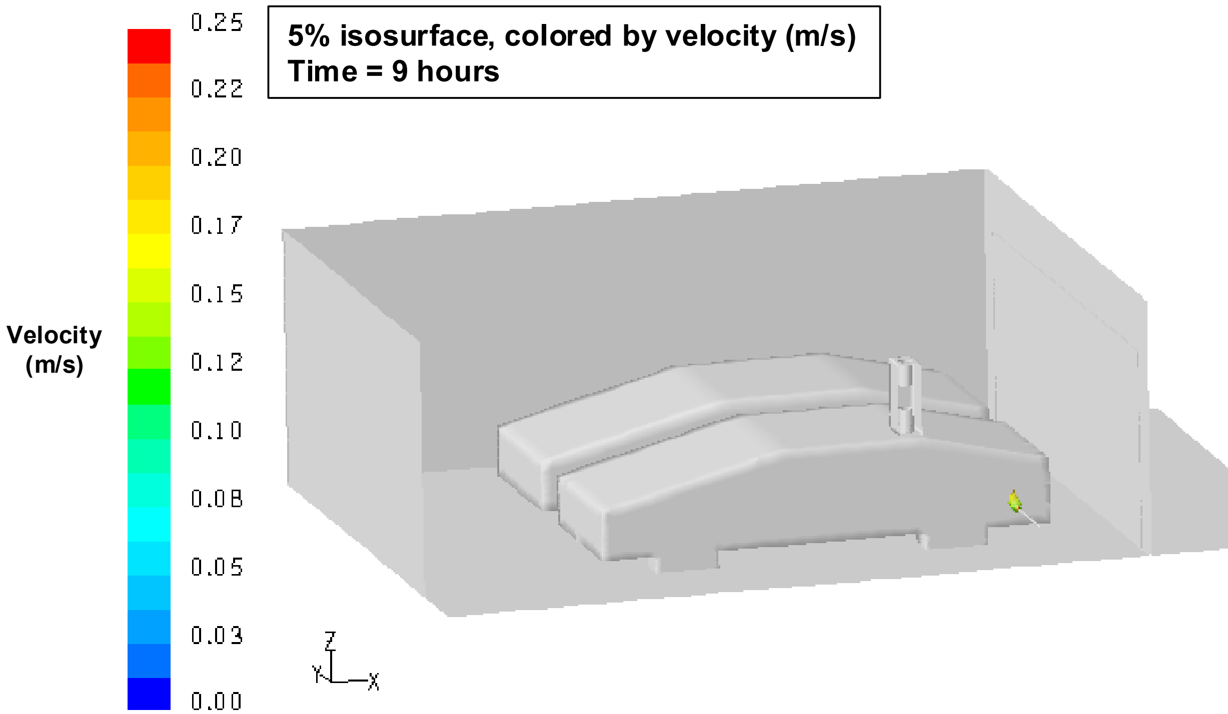

Figure 7-37. The 5% methane concentration isosurface for Case 4 at 9 hours of elapsed time

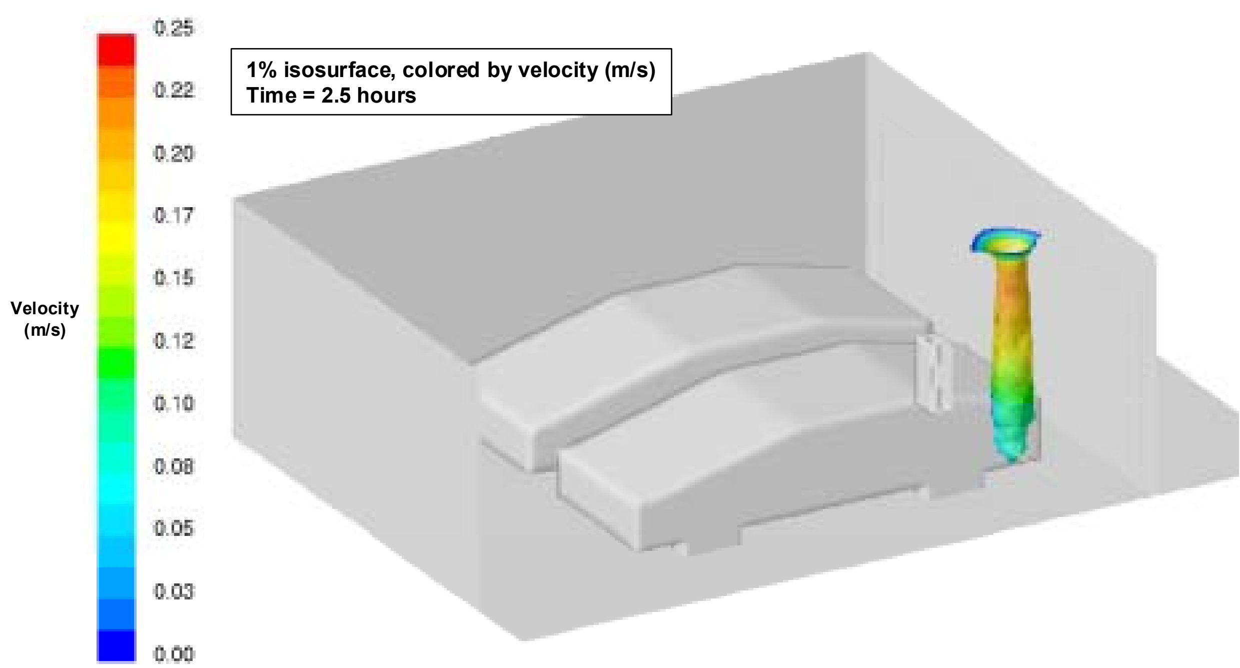

Figure 7-38. The 1% methane concentration isosurface for Case 4 at 2.5 hours of elapsed time

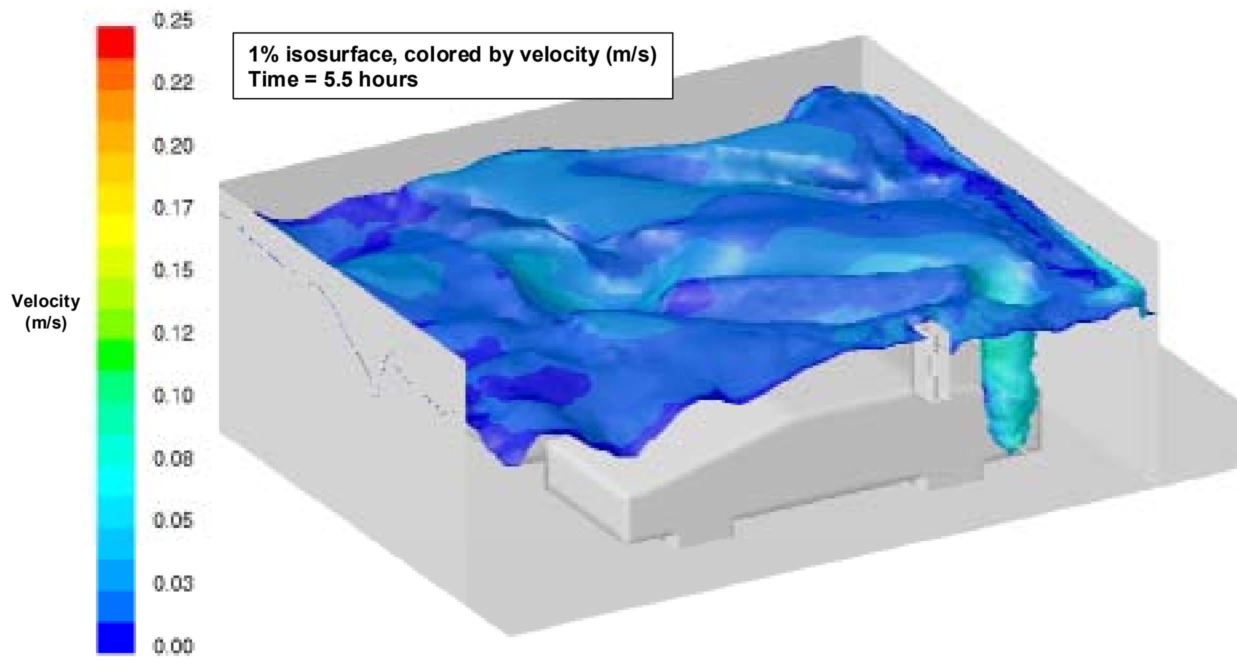

Figure 7-39. The 1% methane concentration isosurface for Case 4 at 5.5 hours of elapsed time

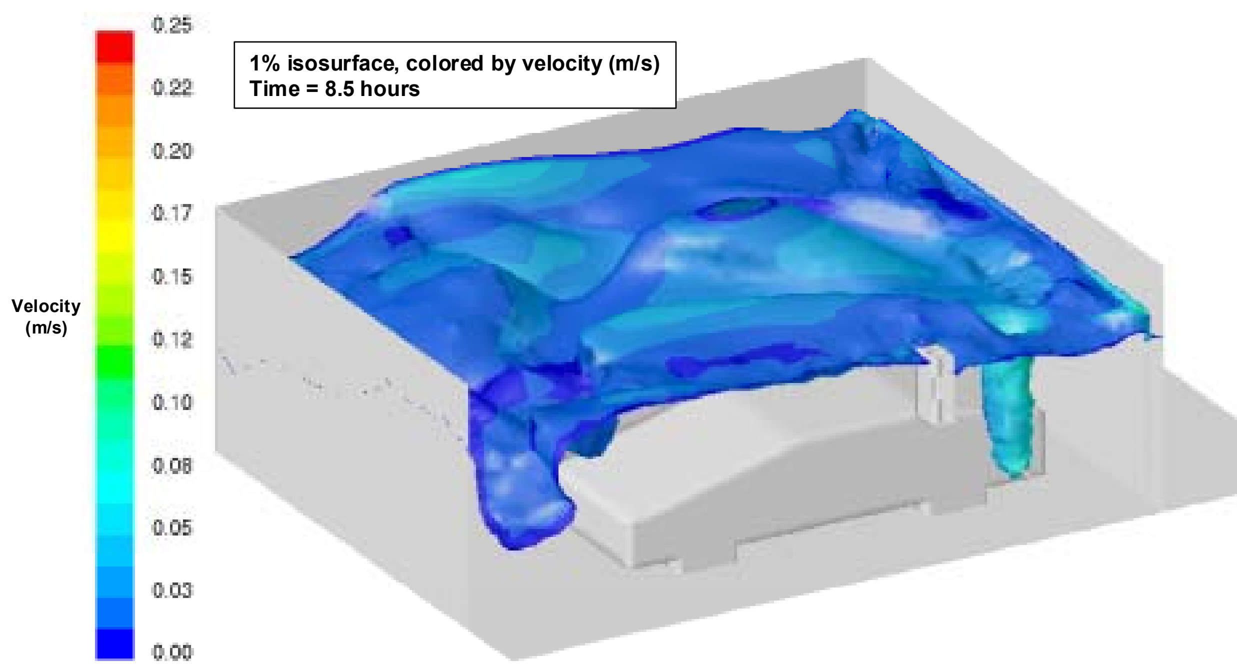

Figure 7-40. The 1% methane concentration isosurface for Case 4 at 8.5 hours of elapsed time

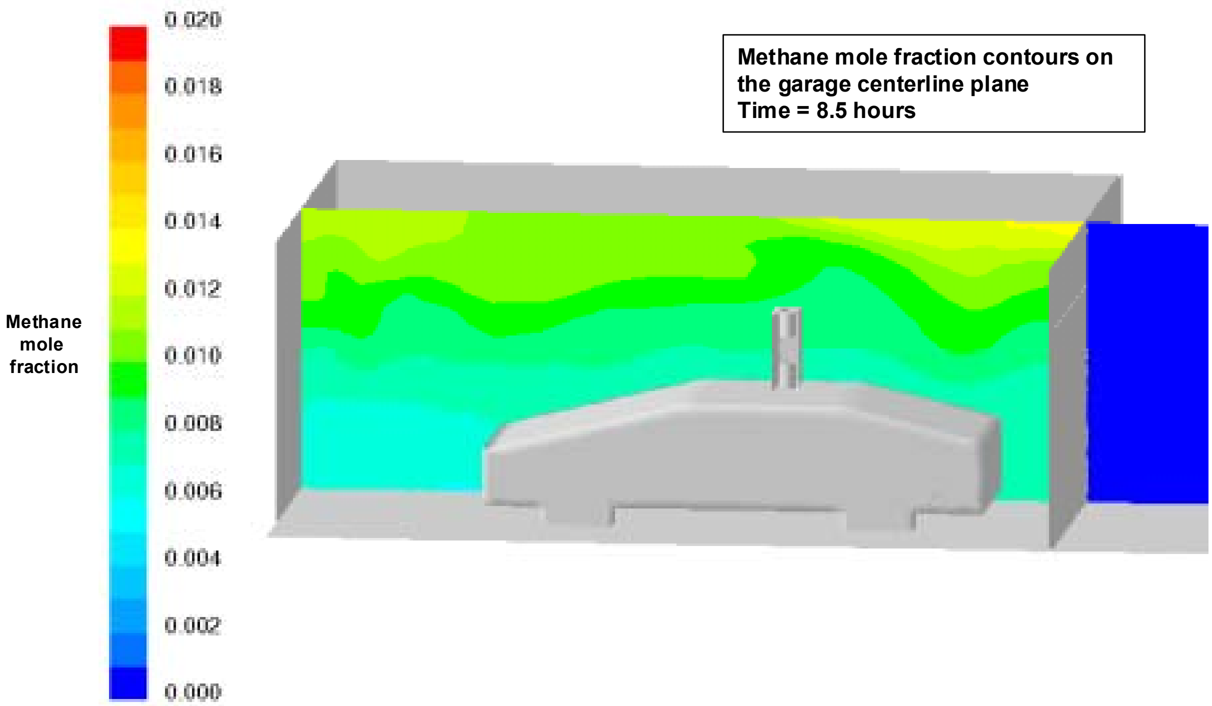

Figure 7-41. Methane concentration profile along the garage centerline for Case 4 at 8.5 hours of elapsed time

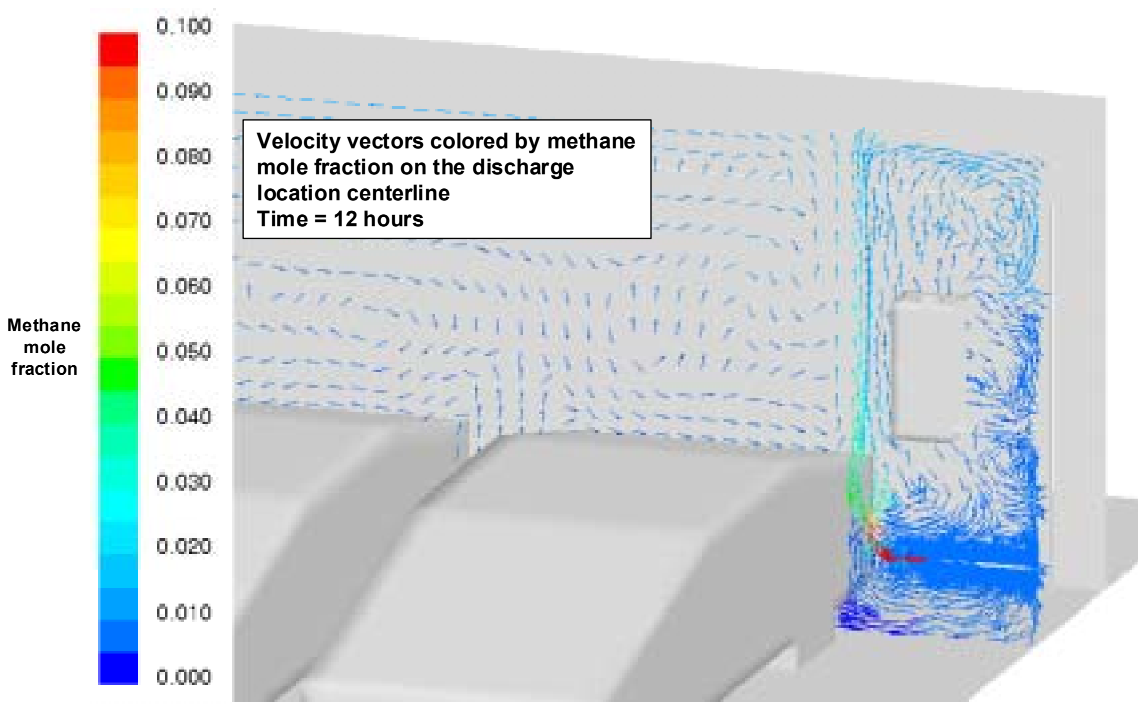

Figure 7-42. Flow field in the plane of the discharge for Case 4 at 12 hours of elapsed time

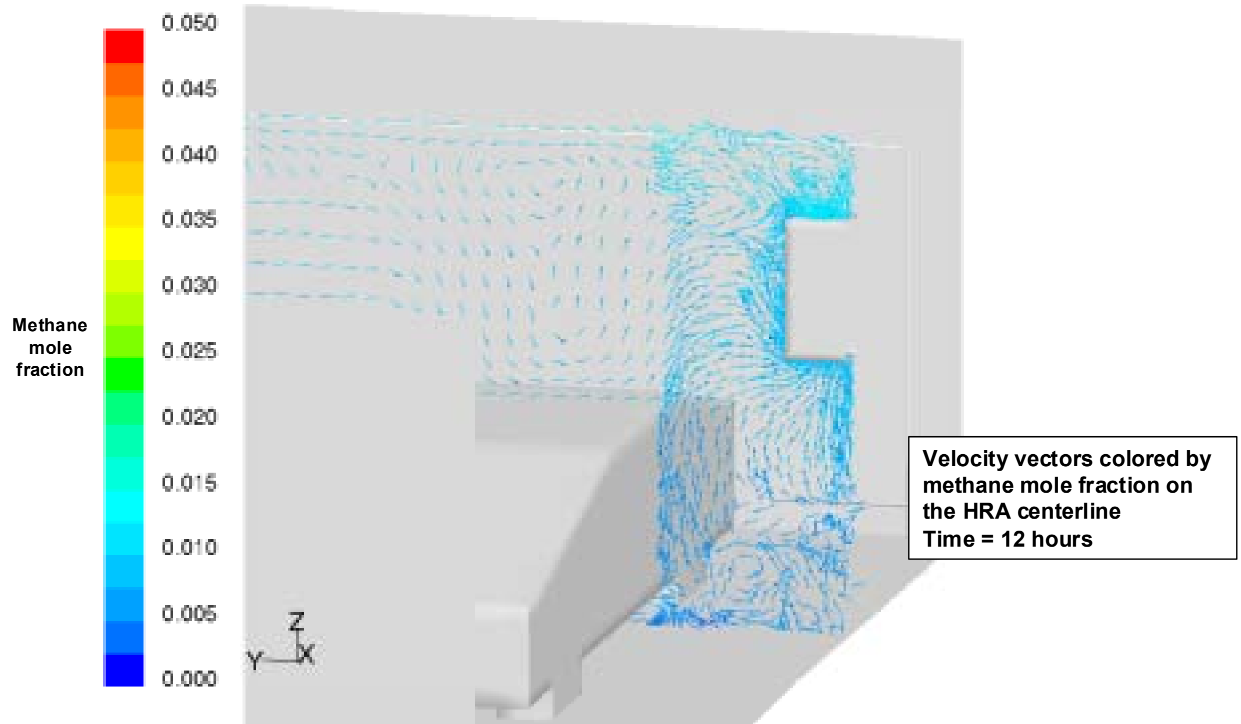

Figure 7-43. Flow field in the plane of the HRA centerline for Case 4 at 12 hours of elapsed time

7.3.3 Case 5 — Cooling Air Off Having Failed

Figure 7-44 shows the isosurface of 5% methane concentration, colored by the gas (methane plus air) velocity, after 14 hours for the gas discharge case with the HRA cooling fan off, having presumably had an undetected failure. This calculational case would also apply to a situation with the HRA cooling air fan in operation, but with the outside discharge vent completely blocked. Recall from the introductory discussion in Section 7.1, this scenario represents a near worst case situation. The figure shows that flammable methane concentrations for the Case 5 scenario extend some distance from the gas discharge and begin to approach the garage ceiling above the discharge. Comparing Figure 7-44 to the analogous figure for Case 3 (cooling air discharged into the garage interior, Figure 7-24) shows that the 14-hour 5% isosurface with the cooling air fan off extends further from the discharge location, and approaches the garage ceiling, as just noted. However, even after this length of time (14 hours) the 5% plume has not yet begun to spread along the garage ceiling, certainly not to along the ceiling centerline, the most likely location of an electrically operated garage door opener ignition source. Figure 7-45 shows the isosurface of 4% methane concentration after 14 hours. The interpretation of this figure is the same as for Figures 7-5 and 7-26. That is, the surface shown is the 4% concentration boundary. Methane concentrations above the surface are greater than 4%. The figure shows that much of the garage volume has greater than 4% methane concentration. This volume has certainly enveloped the location where a garage door opener would likely be located.

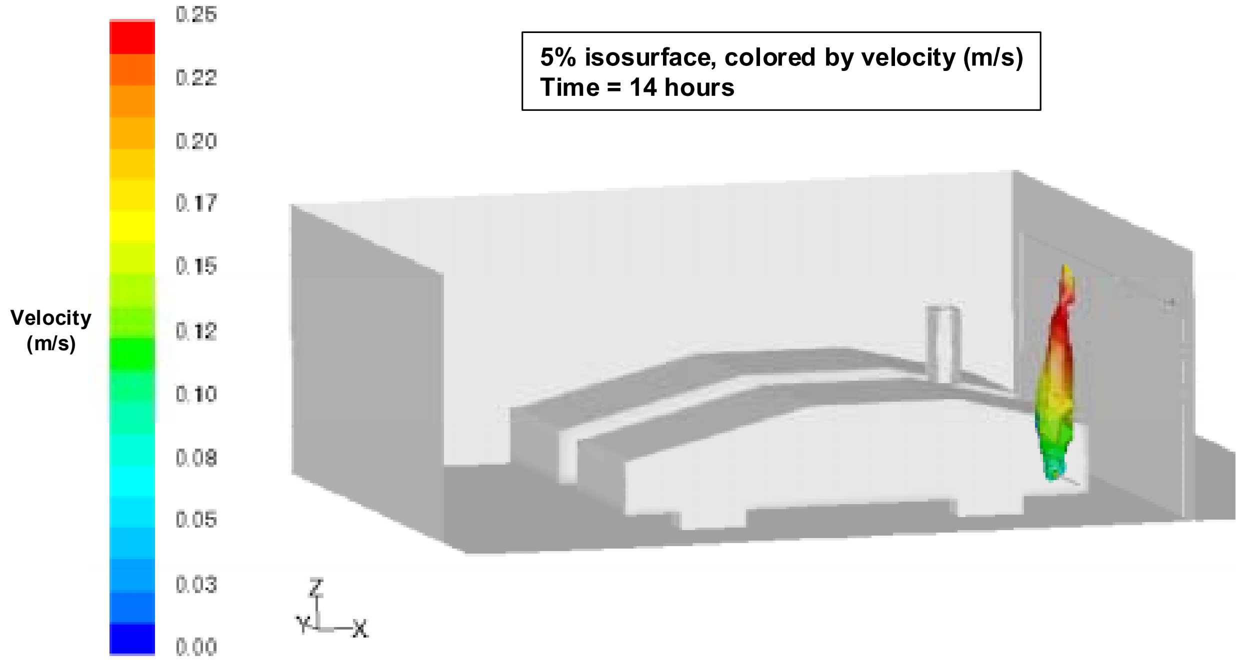

Figure 7-44. The 5% methane concentration isosurface for Case 5 at 14 hours of elapsed time

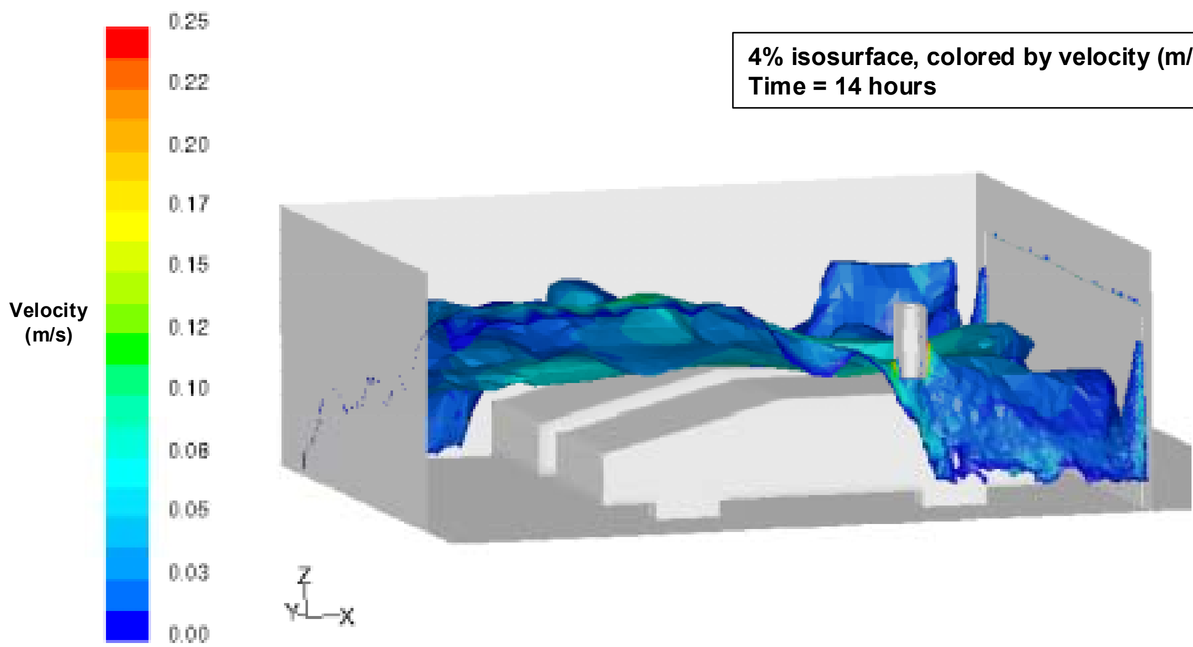

Figure 7-45. The 4% methane concentration isosurface for Case 5 at 14 hours of elapsed time

Figure 7-46 shows the methane concentration profile along the garage centerline after 14 hours. The figure shows that essentially all of the garage volume along the centerline has methane concentration of 3.5% or higher, with a centerline maximum concentration of 4.2% in a pocket along the ceiling. This is essentially the same result noted for Case 3 (HRA fan on, discharging into the garage) in Figure 7-27, although all centerline concentrations are slightly higher for Case 5.

Figures 7-47, 7-48, 7-49, and 7-50 show the transient buildup of the 5% methane isosurface at times of 3, 6, 9, and 12 hours, respectively. Comparing these figures to the ones at roughly the same elapsed times for Case 3, shows that at each time the 5% isosurface extends a little further from the discharge location for the Case 5 situation with the HRA cooling fan off or its outside discharge vent blocked.

Figure 7-51 shows the isosurface of 5% methane concentration when steady state has been reached. This isosurface envelops much of the garage volume above the vehicles. Figure 7-52 is the corresponding isosurface of 4% methane concentration. The interpretation of Figure 7-52 is analogous to the interpretation of Figure 7-45. That is, methane concentrations of less than 4% are beneath the surface shown in the figure. Methane concentrations in the garage volume above the 4% isosurface are greater than 4%. Figure 7-52 suggests that most of the garage volume contains methane concentrations above 4% when steady state is reached. However, it bears emphasizing that, for the Case 5 scenario, reaching steady state will take significantly longer than 14 hours. Recall from the introductory paragraphs of Section 7.2, the steady state volume average methane concentration for the Case 5 scenario is 4.8%. At an elapsed time of 14 hours, the average garage methane concentration had only reached 4.0%, as shown in Figure 7-23, and its rate of increase is steadily decreasing.

Figure 7-53 shows the flow field in the plane of the discharge, colored by methane concentration, at 14 hours of elapsed time. The figure shows that methane concentrations are high in the immediate vicinity of the discharge, but they decline to below 5% along the garage ceiling above the vehicles. Figure 7-54 shows the flow field at the plane of the HRA, colored by methane concentration, at the same elapsed time. This figure shows most of the plane has methane concentrations above 4%.

The conclusions from the CFD analysis for Case 5, as illustrated by the figures discussed above, are very similar to the conclusions for Case 3 discussed in Section 7.2.1. Specifically, a natural gas discharge from the HRA in which the HRA continues to pump gas at its refueling rate into a relatively well-sealed garage can result in flammable methane concentrations that extend a significant distance into the garage above the discharge. This locus of flammable methane concentrations extends a little further into the garage when the HRA cooling air fan is off or its discharge vent is blocked (Case 5) than when it is on and discharging into the garage interior (Case 3). In fact, flammable methane concentrations nearly reach the ceiling above the vehicle having the failed refueling event with the HRA fan off. However, the locus of flammable methane concentration becomes significant only after relatively long periods of time, 12 to 14 hours.

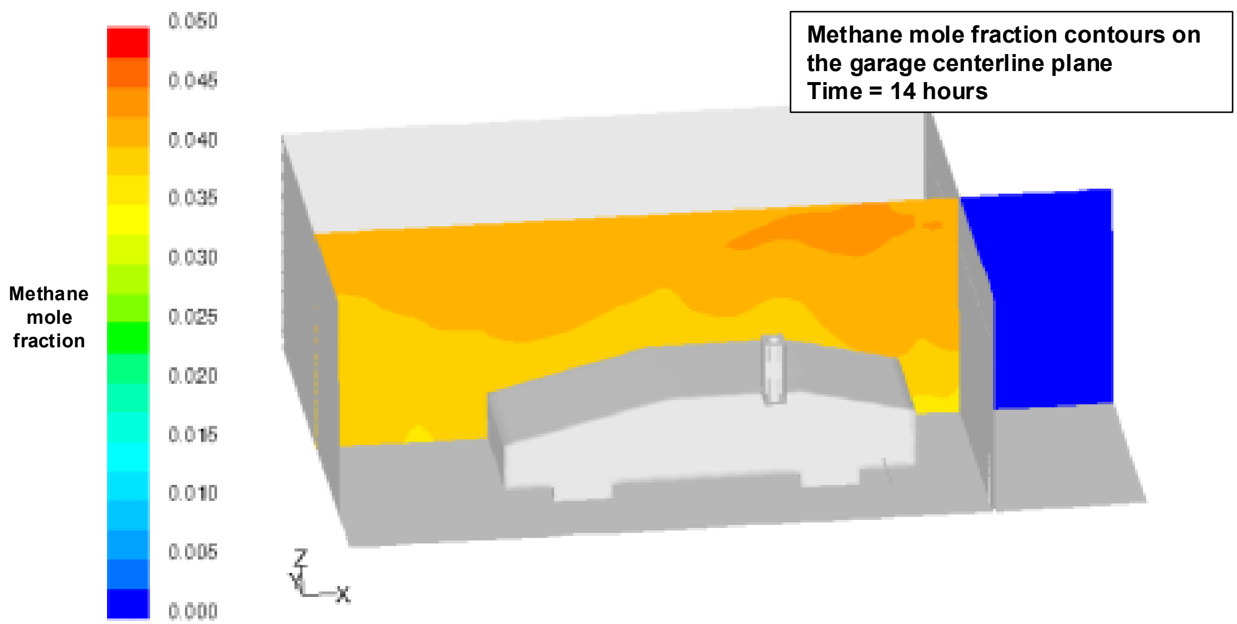

Figure 7-46. **Methane concentration profile along the garage centerline for Case 4 at 14 hours of elapsed time**

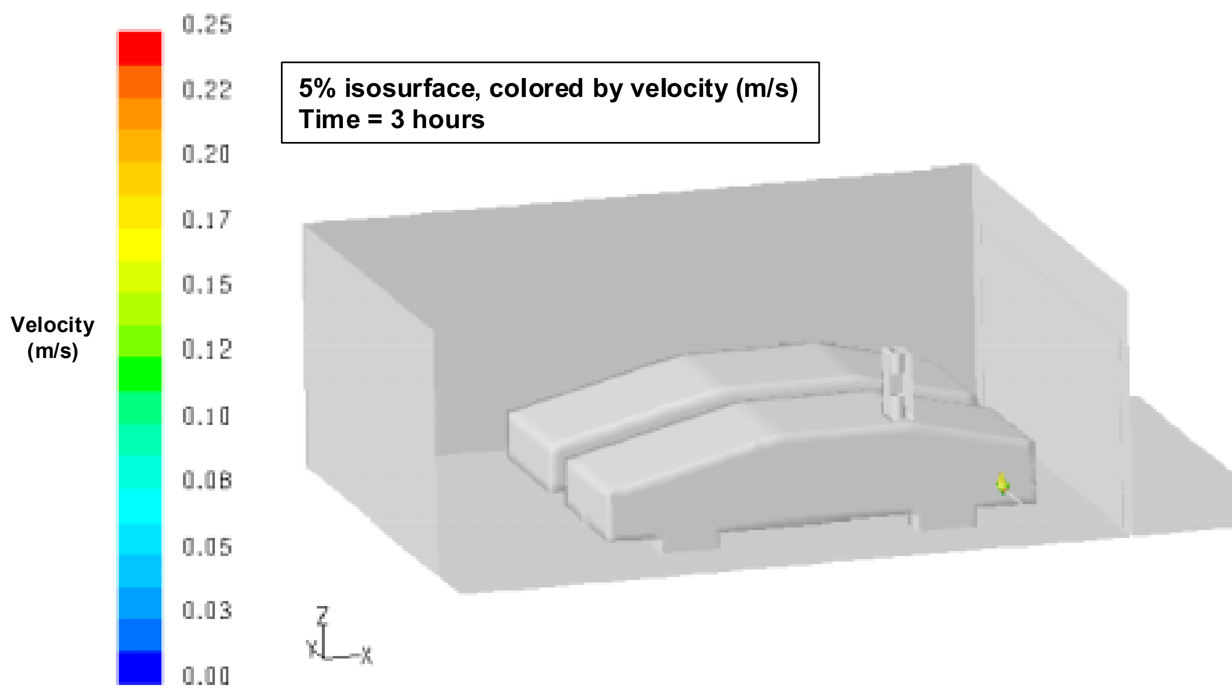

Figure 7-47. **The 5% methane concentration isosurface for Case 5 at 3 hours of elapsed time**

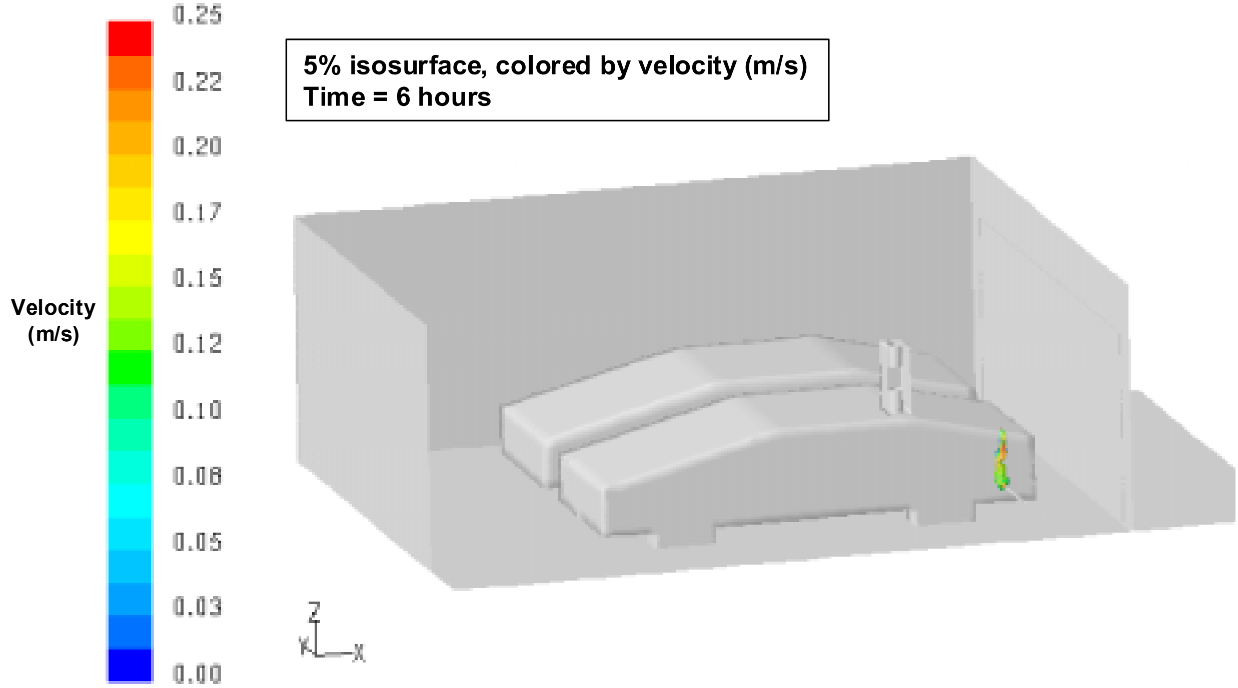

Figure 7-48. The 5% methane concentration isosurface for Case 5 at 6 hours of elapsed time

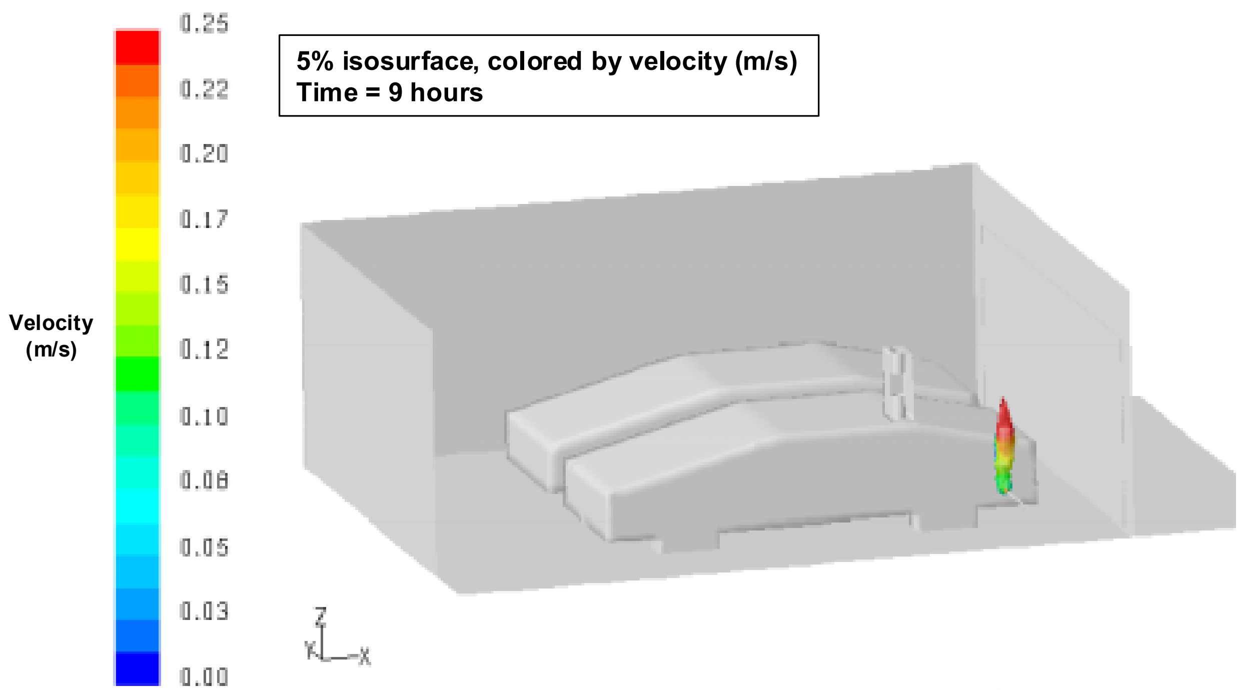

Figure 7-49. The 5% methane concentration isosurface for Case 5 at 9 hours of elapsed time

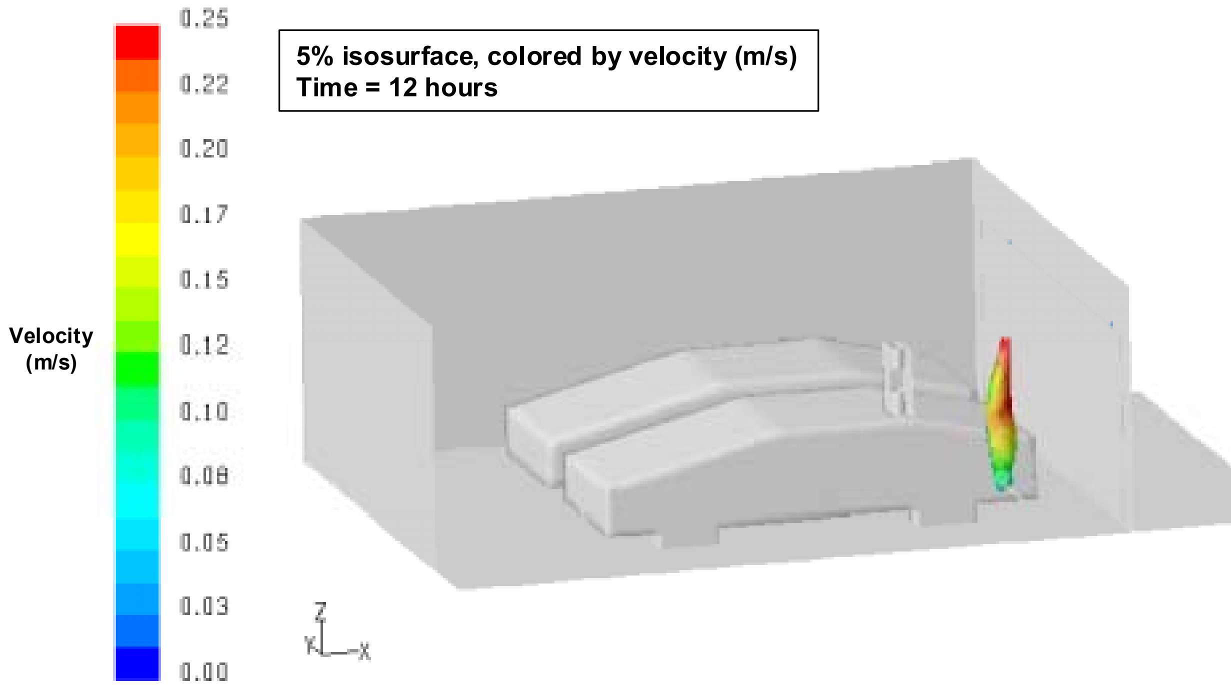

Figure 7-50. The 5% methane concentration isosurface for Case 5 at 12 hours of elapsed time

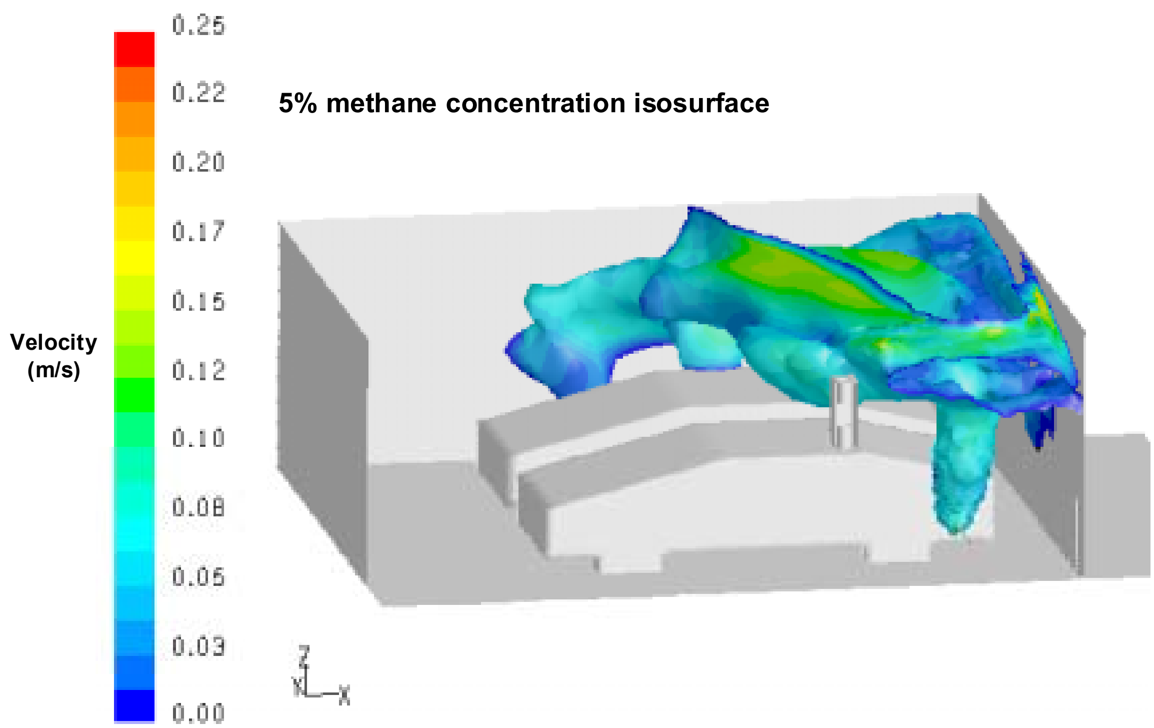

Figure 7-51. The 5% methane concentration isosurface for Case 5 at steady state

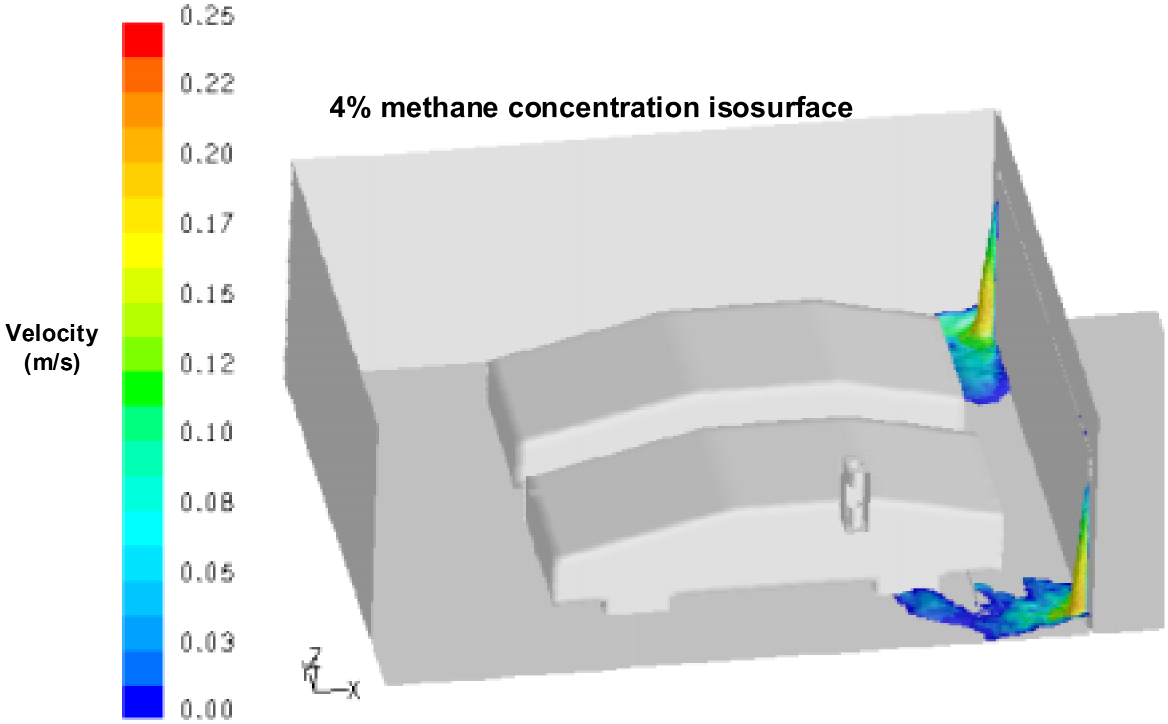

Figure 7-52. The 4% methane concentration isosurface for Case 5 at steady state

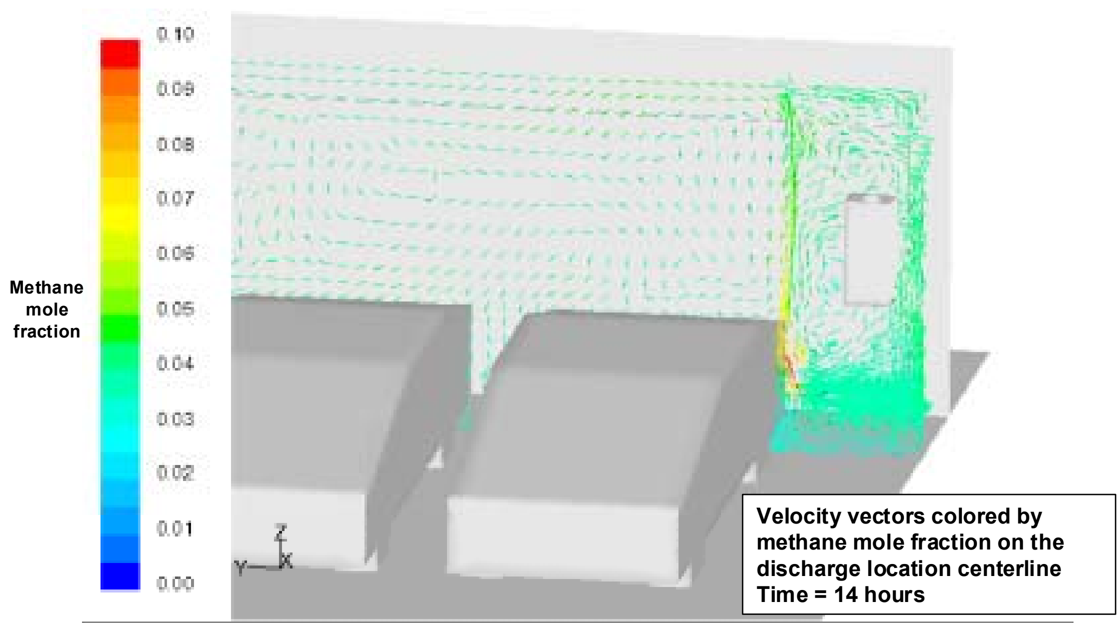

Figure 7-53. Flow field in the plane of the discharge for Case 5 at 14 hours of elapsed time

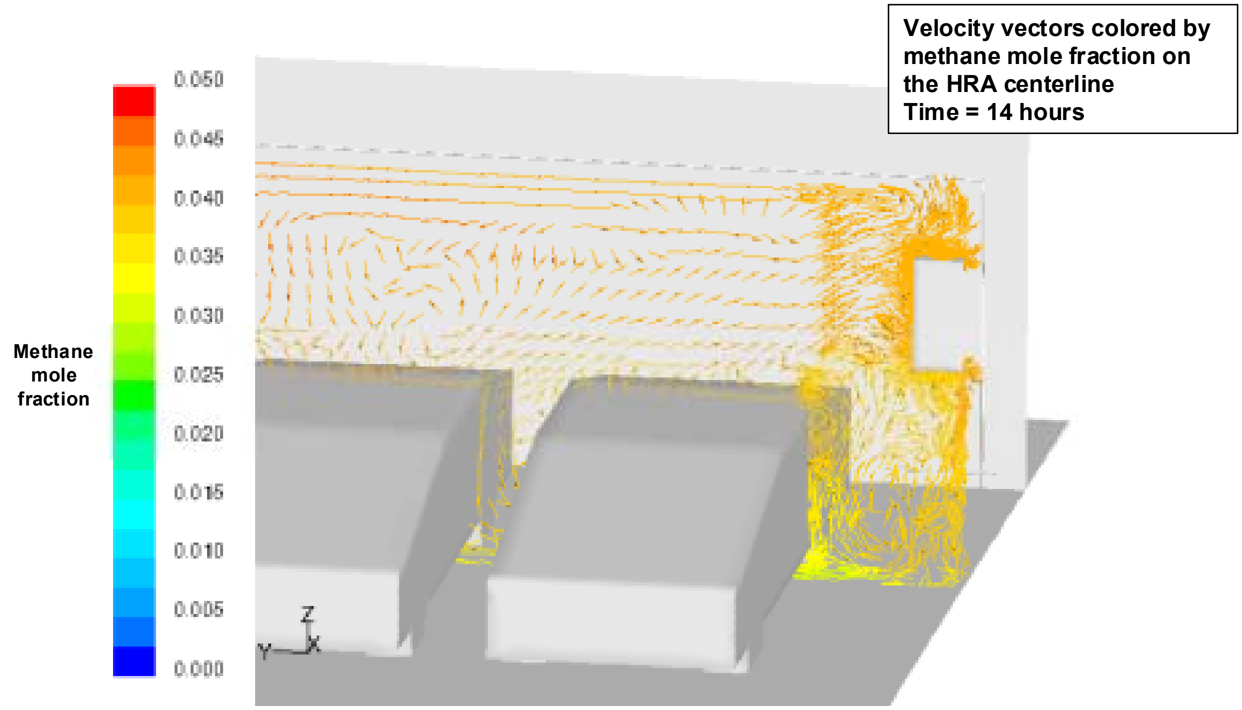

Figure 7-54. Flow field in the plane of the HRA centerline for Case 5 at 14 hours of elapsed time

Near flammable methane concentrations of 4% and slightly higher do extend along the garage ceiling, well into locations where an electric garage door opener might be located. But, again, this concentration buildup requires a long period of time, 12 hours or more. Methane concentrations of 3.5% or greater exist in most of the garage volume after this period of time, and the average garage concentration is 4% after 14 hours of continuous discharge.

If the gas discharge goes undetected for a sufficient period of time that steady state is reached, flammable methane concentrations will exist in much of the garage volume above the vehicles in the garage. Most of the garage volume will have methane concentrations above 4%, and the volume average concentration will reach 4.8%. However, the time to reach steady state is significantly greater than 14 hours, which is most likely the longest period of time a vehicle set up to refuel would remain unattended.

8. Conclusions and Recommendations

8.1 Summary of Results and Conclusions

The safety evaluation of the FuelMaker home refueling appliance (HRA) performed in this study concludes that the appliance has a process control approach that incorporates a number of safety features designed to prevent accidental gas releases such that the probability of a gas release is relatively low. Moreover, during the course of this study, FuelMaker incorporated a few refined process control system design and appliance installation specifications that further reduce the predicted frequency of gas releases and the consequences (e.g. fire or deflagration) of a gas release.

The fault tree analysis (FTA) performed as part of the evaluation concluded that, of the non-misuse failures evaluated, the frequency of an HRA leak at less than full flow while the HRA cooling air fan was operating normally was the predicted most frequent failure. The frequency of this failure event was estimated to be 2.6×10^{-6}/unit-year. The predicted frequencies of all nine other non-misuse failure events evaluated were at least an order of magnitude lower. At this frequency, one leak event with HRA cooling air discharged outside (as required in the FuelMaker installation specifications) would be expected per year after a total of 39,000 appliance units had been installed. The most frequent misuse failure events were the rupture of a LPG bottle or toy being inflated with an HRA with cooling air discharging to the outside (once for every 250,000 HRA units installed in the prior year) and a gas release from a buffer tank added to the HRA with cooling air discharging to the outside (once for every 860,000 HRA units installed in the prior year). The predicted frequencies of the other six misuse failures were more than an order of magnitude lower.

The most serious consequences from the HRA failures evaluated were structure fires or deflagrations. A structure fire might occur if the gas release encounters an ignition source, ignites to form a flame, and in turn ignites combustible material near the gas release. A deflagration would occur if the release resulted in a buildup of methane concentrations to its lower flammability limit (LFL) over a substantial volume, and this volume of high concentration encountered an ignition source.

The event tree analysis (ETA), supported by computational fluid dynamics (CFD) modeling and a residential garage infiltration survey, concluded that the non-misuse failure leading to the highest probability of both structure fire and deflagration was the gas piping failure resulting from a vehicle strike on an HRA. Other significant contributors to the predicted frequency of both structure fires and deflagrations are a continuous gas leak and a full flow gas discharge, both with the HRA cooling air fan operating normally. A vehicle tank blowdown into the garage with the cooling air fan in operation provides a significant contribution to the predicted frequency of deflagrations; an HRA deflagration due to air ingress into the appliance provides some contribution to the predicted frequency of structure fires. A deflagration associated with HRA use is predicted to be roughly twice as frequent as a structure fire. The total predicted frequency of a deflagration from all non-misuse causes considered in the analysis corresponds to one predicted deflagration per year after a total of about 7,000,000 HRAs have been installed.

The corresponding result for structure fires is that one fire per year would be predicted after a total of 14,600,000 HRAs have been installed.

The two misuse failures giving rise to the highest incidence of structure fires and deflagrations were attempting to fill a LPG bottle or inflatable item and installing a buffer tank to allow fast fill operation. A deflagration associated with HRA misuse was predicted to be over seven times more frequent than a structure fire. The total predicted frequency of a deflagration from all misuse causes considered in the analysis corresponds to one predicted deflagration per year if about 1,400,000 HRAs were installed in the previous year. The corresponding result for structure fires is that one fire per year would be predicted if about 10,700,000 HRAs were installed in the previous year.

With regard to less than full-flow gas leaks into a garage with median infiltration characteristics, the CFD analyses showed that methane concentrations that exceed the methane LFL are confined to regions above and very close to the leak itself such that the flammable region would be unlikely to encounter a fixed ignition source such as a water heater pilot or a garage door opener. This holds for an HRA operating scenario in which the HRA cooling air is discharged into the garage interior, as well as for the scenario in which the cooling air is vented outside.

For a full-flow gas discharge into a garage with poor ventilation characteristics (infiltration at the thirtieth percentile in the garage survey completed), the CFD analyses showed that regions of flammable methane concentrations extend further into the garage volume, but still are confined to the region above the discharge itself, and do not extend to the garage ceiling even after 14 hours of continuous discharge, when the cooling air is discharged into the garage interior. Methane concentrations of 4%, which is 80% of the LFL concentration of 5%, do extend to a location where a garage door opener ignition source might be located, though it takes a long period of continuous discharge (12 hours or more) for this situation to develop. Venting the cooling air discharge outside the garage substantially reduces the volume of the region of flammable methane concentrations and confines them to very near the discharge.

8.2 Recommendations

As noted above, this safety evaluation concluded that the HRA has a process control system that incorporates a number of safety features designed to prevent accidental gas releases, especially with modifications to the control system and appliance installation specifications FuelMaker instituted over the course of this study. The safety evaluation arrived at no recommendation regarding how the design’s inherent safety could be further improved.

The vehicle refueling appliance and CNG vehicle user survey noted that gas leaks have been more commonly experienced with aftermarket vehicle fuel system conversions. Aftermarket conversions often incorporate a single fuel tank reverse flow check valve. Confining HRA use to OEM vehicles with two reverse-flow check valves (or equivalent components) is recommended.

As also noted above, the CFD analyses showed that discharging the HRA cooling air outside the garage substantially reduces the volume of the already small region of flammable methane concentrations resulting from a full flow gas discharge. This is an installation specification that FuelMaker currently requires. The CFD analyses suggest that it would be best to place the gas sensor (alarms if gas is detected, and included in the HRA design) along the garage ceiling above where the vehicle fuel tank fill receptacle would be during a typical refueling. However, mounting the detector inside the appliance in the path of the cooling air flow likely provides comparable protection. The CFD analyses showed that methane concentrations in the vicinity of the HRA, placed in accordance with FuelMaker specifications, are near the garage volume average concentrations for the leak and discharge cases evaluated. If the HRA cooling air is vented outside as specified, gas concentrations in the vicinity of the HRA were not substantially lower than those near the garage ceiling.

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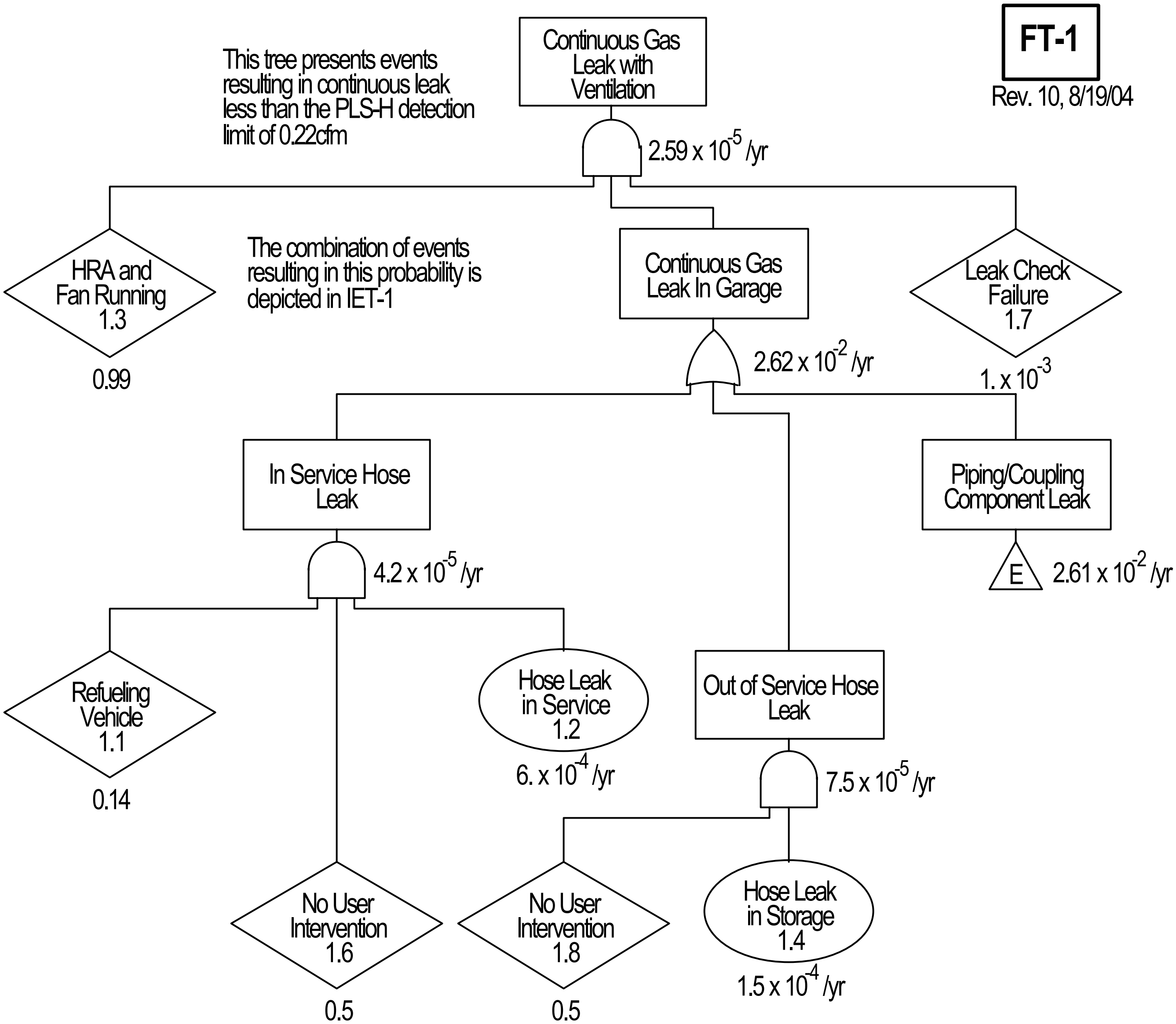
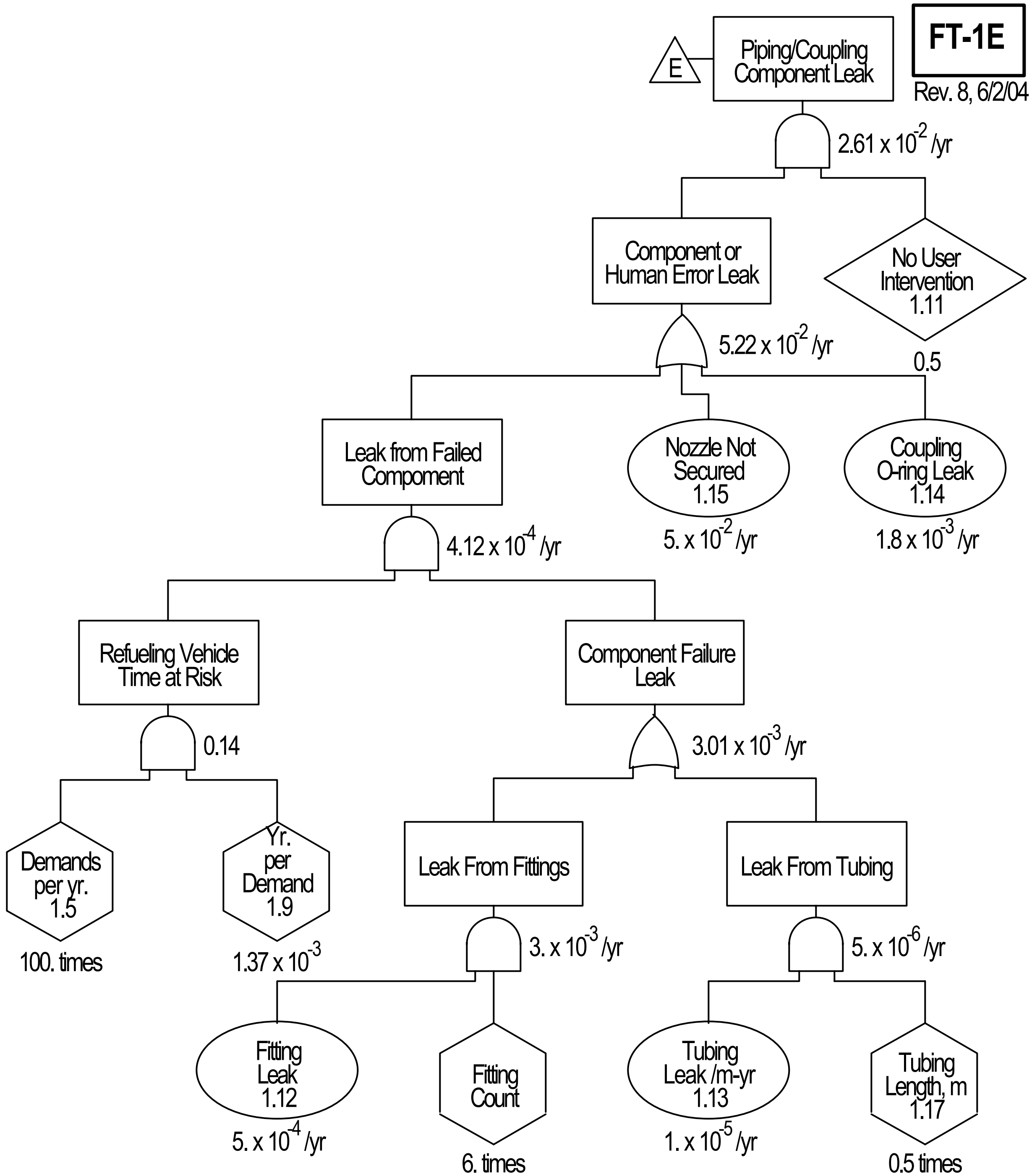
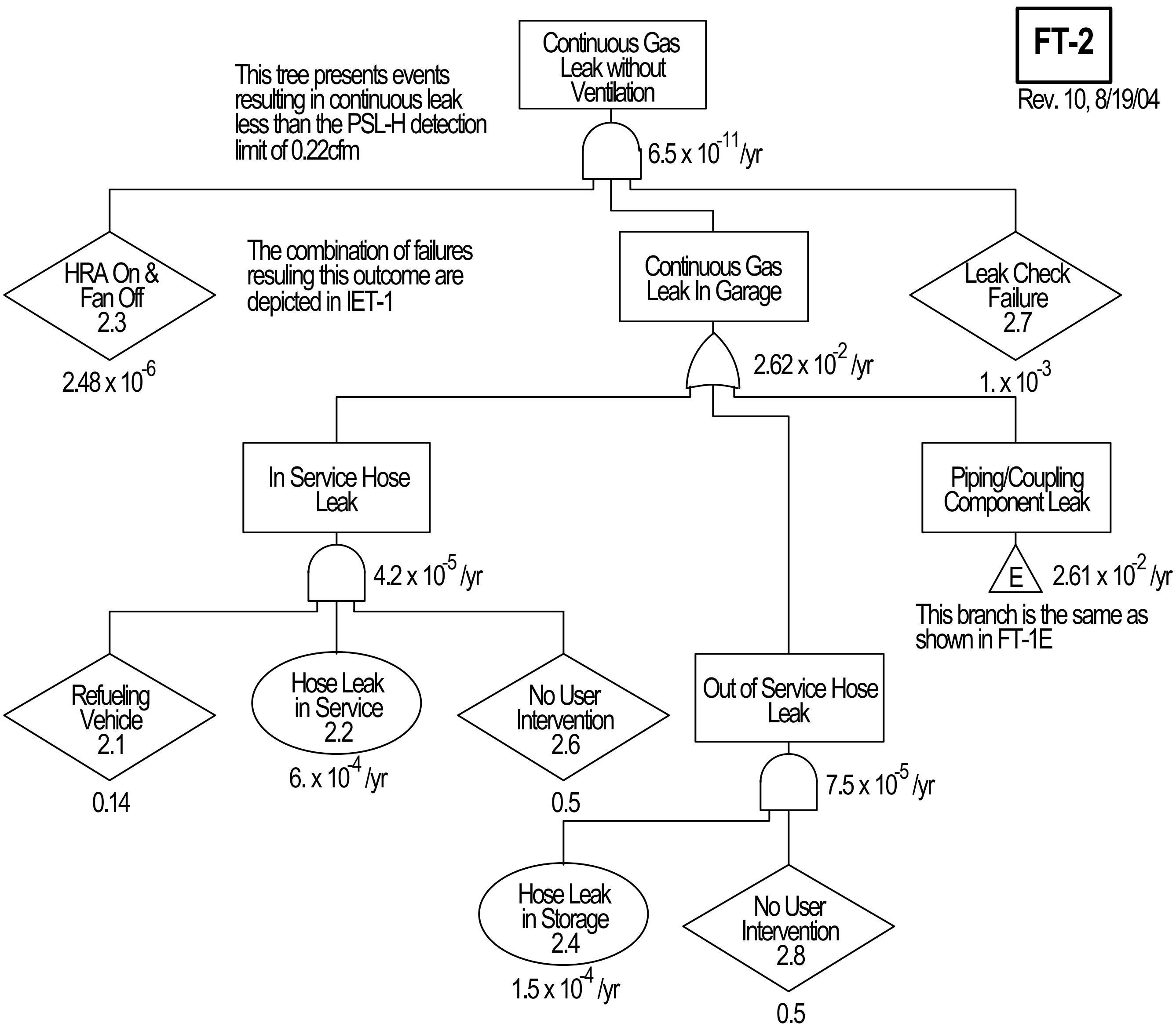
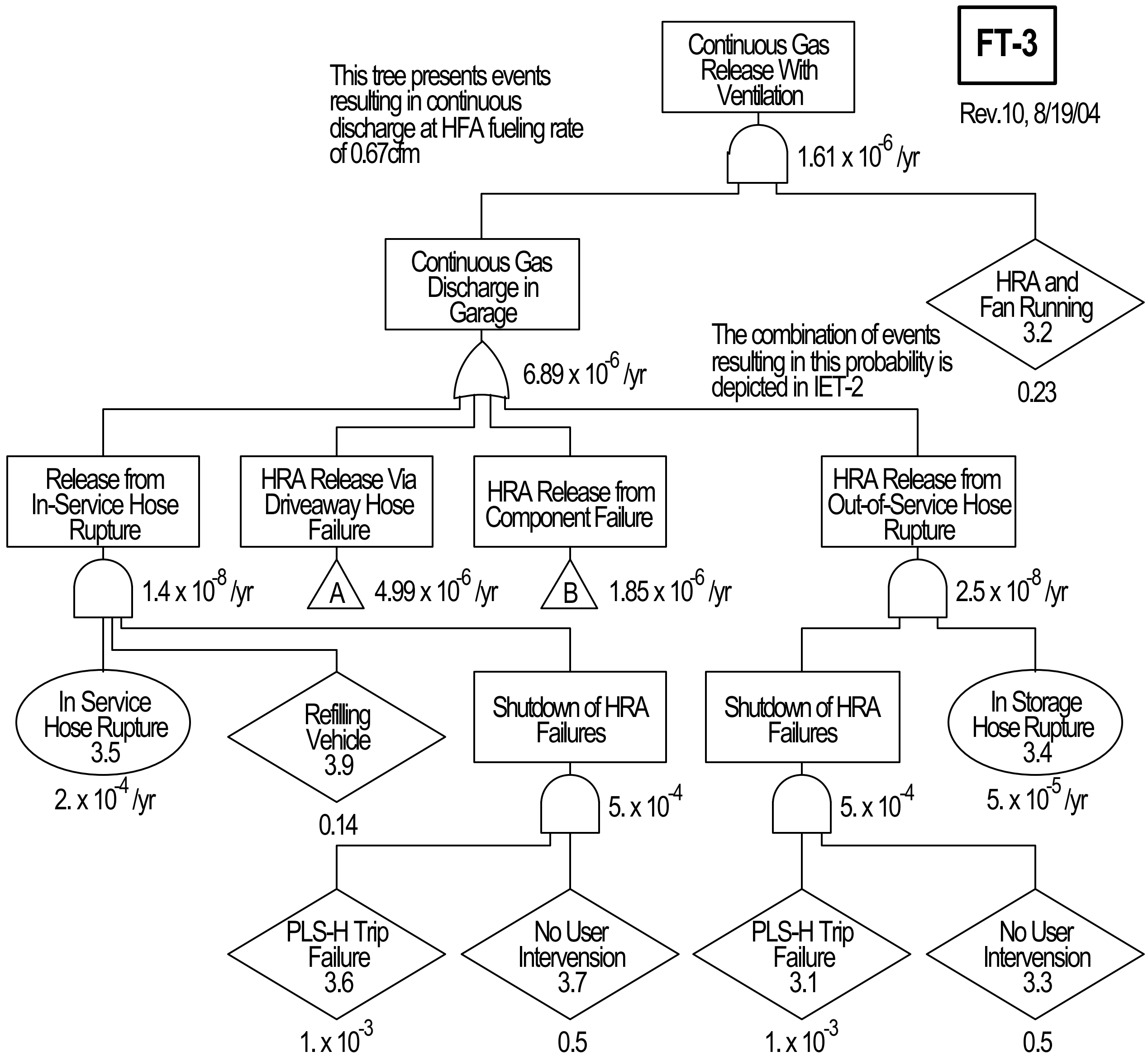
Appendix A. Fault Trees, Intermediate Event Trees, and Summary Statistics Table

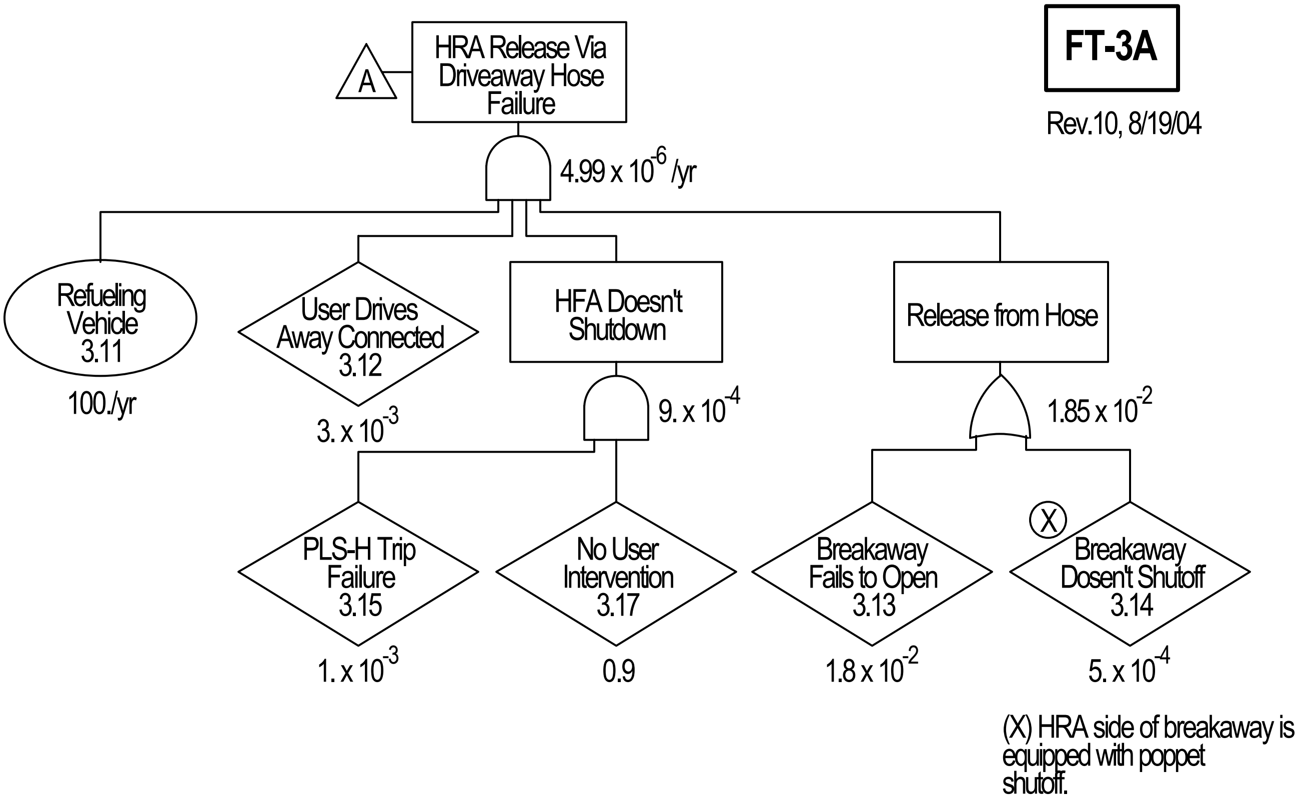
The 18 fault trees developed are given in the following. Immediately following FT-18 are the three intermediate event trees developed to supply the probabilities needed that the HRA cooling fan was on and operating or off needed for the three gas release volume discharge flowrates considered. Immediately following IET-3 is the summary statistics table (Table A-1) that summarizes the sources and rationale for the frequencies of the numbered initiating events and probabilities of the numbered contributing events contained in the fault trees, as well as the probabilities of the branches of the IETs.

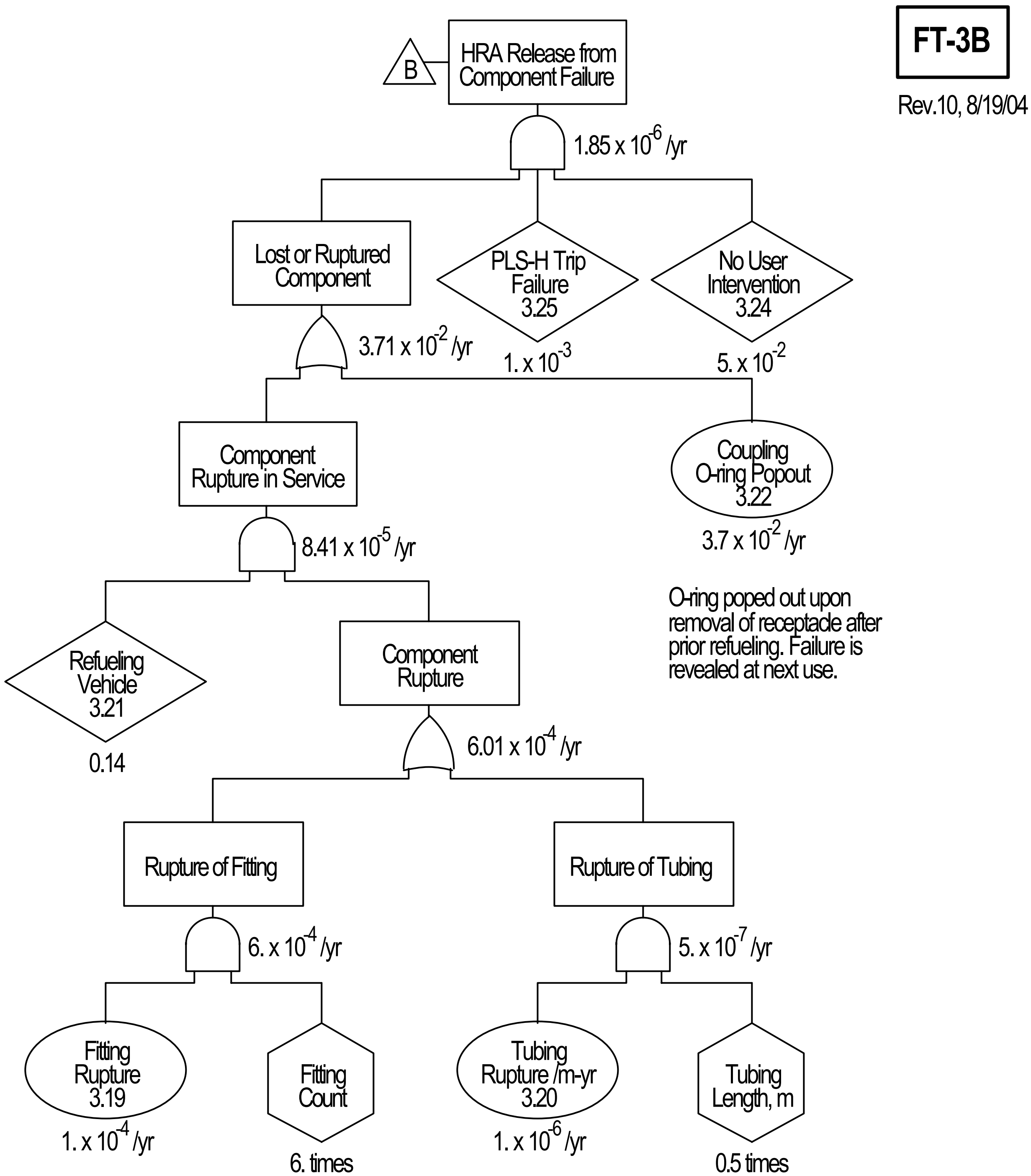

FT-1
Rev. 10, 8/19/04
This tree presents events resulting in continuous leak less than the PLS-H detection limit of 0.22cfm
Continuous Gas Leak with Ventilation
2.59 x 10-5 /yr
HRA and Fan Running 1.3
0.99
The combination of events resulting in this probability is depicted in IET-1
Continuous Gas Leak In Garage
2.62 x 10-2 /yr
Leak Check Failure 1.7
1. x 10-3
In Service Hose Leak
4.2 x 10-5 /yr
Piping/Coupling Component Leak
E
2.61 x 10-2 /yr
Refueling Vehicle 1.1
0.14
Hose Leak in Service 1.2
6. x 10-4 /yr
Out of Service Hose Leak
7.5 x 10-5 /yr
No User Intervention 1.6
0.5
No User Intervention 1.8
0.5
Hose Leak in Storage 1.4
1.5 x 10-4 /yr

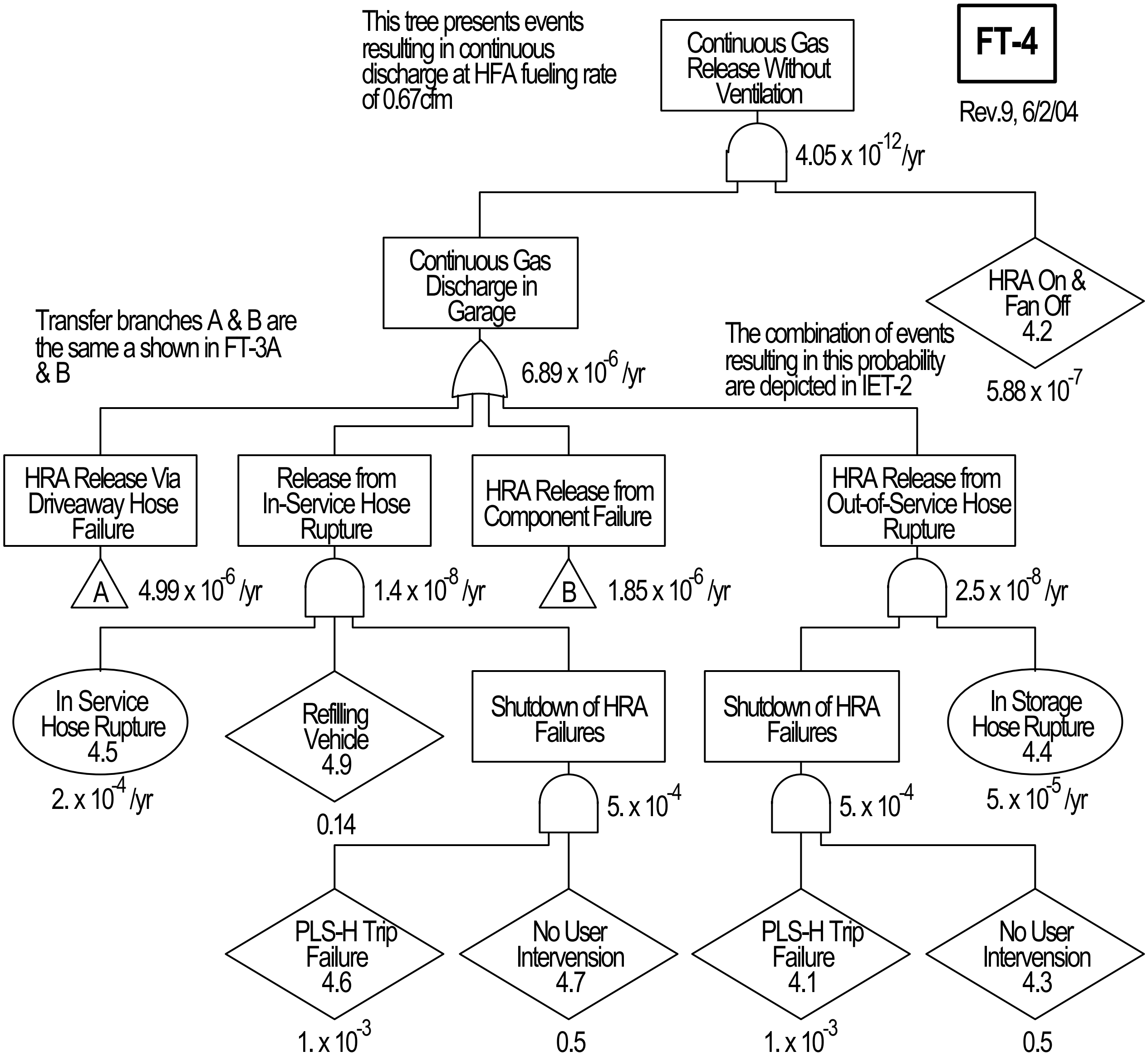

FT-1E
Rev. 8, 6/2/04
E
Piping/Coupling Component Leak
2.61 x 10-2 /yr
Component or Human Error Leak
No User Intervention 1.11
0.5
5.22 x 10-2 /yr
Leak from Failed Compoment
Nozzle Not Secured 1.15
5. x 10-2 /yr
Coupling O-ring Leak 1.14
1.8 x 10-3 /yr
4.12 x 10-4 /yr
Refueling Vehicle Time at Risk
Component Failure Leak
0.14
3.01 x 10-3 /yr
Demands per yr. 1.5
100. times
Yr. per Demand 1.9
1.37 x 10-3
Leak From Fittings
Leak From Tubing
3. x 10-3 /yr
5. x 10-6 /yr
Fitting Leak 1.12
5. x 10-4 /yr
Fitting Count
6. times
Tubing Leak /m-yr 1.13
1. x 10-5 /yr
Tubing Length, m 1.17
0.5 times

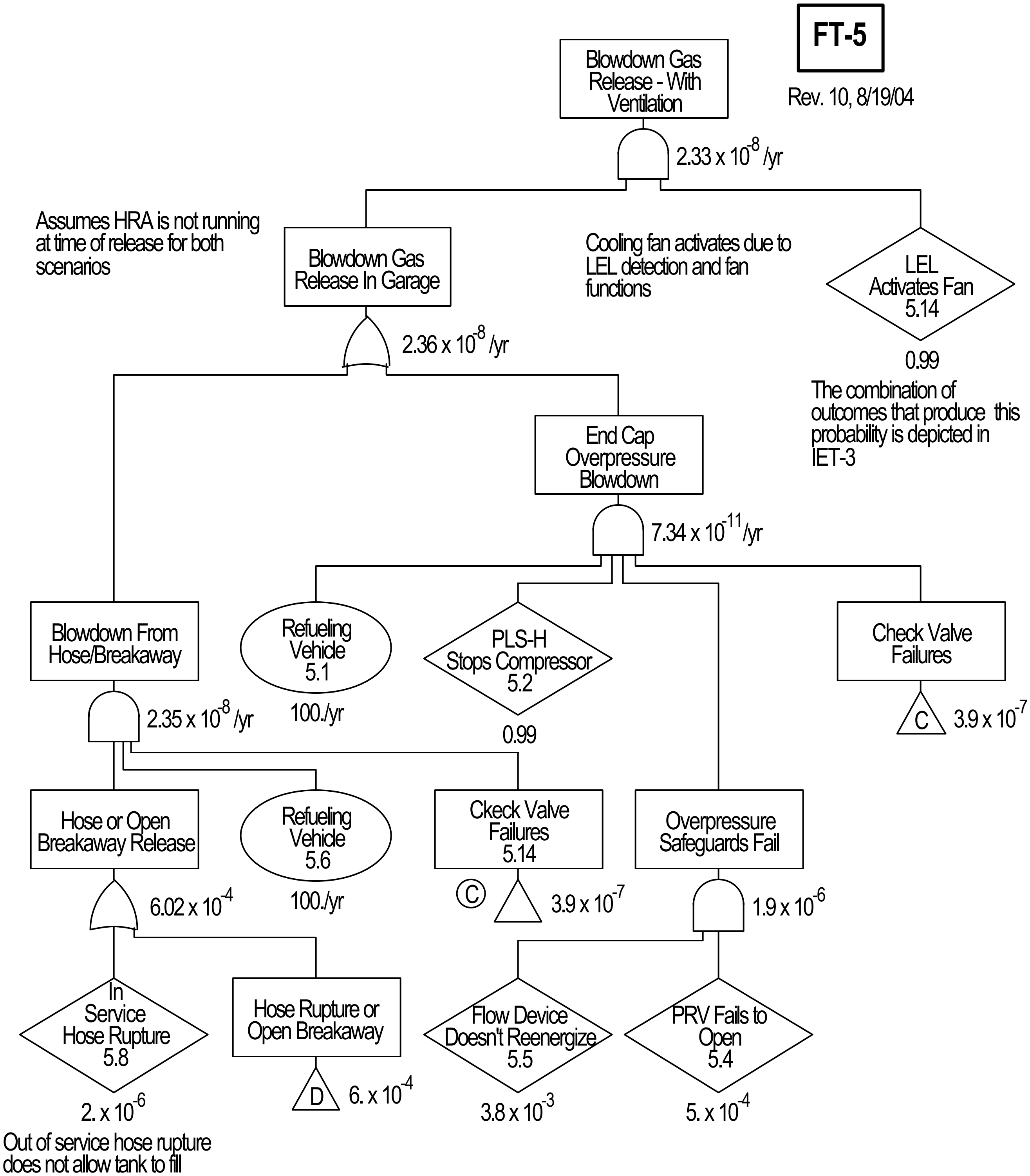

FT-2
Rev. 10, 8/19/04
Continuous Gas Leak without Ventilation
This tree presents events resulting in continuous leak less than the PSL-H detection limit of 0.22cfm
6.5 x 10-11/yr
HRA On & Fan Off 2.3
2.48 x 10-6
The combination of failures resuling this outcome are depicted in IET-1
Continuous Gas Leak In Garage
2.62 x 10-2 /yr
Leak Check Failure 2.7
1. x 10-3
In Service Hose Leak
4.2 x 10-5 /yr
Piping/Coupling Component Leak
E
2.61 x 10-2 /yr
This branch is the same as shown in FT-1E
Refueling Vehicle 2.1
0.14
Hose Leak in Service 2.2
6. x 10-4 /yr
No User Intervention 2.6
0.5
Out of Service Hose Leak
7.5 x 10-5 /yr
Hose Leak in Storage 2.4
1.5 x 10-4 /yr
No User Intervention 2.8
0.5


FT-3
Rev.10, 8/19/04
This tree presents events resulting in continuous discharge at HFA fueling rate of 0.67cfm
Continuous Gas Release With Ventilation
1.61 x 10-6 /yr
Continuous Gas Discharge in Garage
6.89 x 10-6 /yr
HRA and Fan Running 3.2
0.23
The combination of events resulting in this probability is depicted in IET-2
Release from In-Service Hose Rupture
1.4 x 10-8 /yr
HRA Release Via Driveaway Hose Failure
A
4.99 x 10-6 /yr
HRA Release from Component Failure
B
1.85 x 10-6 /yr
HRA Release from Out-of-Service Hose Rupture
2.5 x 10-8 /yr
In Service Hose Rupture 3.5
2. x 10-4 /yr
Refilling Vehicle 3.9
0.14
Shutdown of HRA Failures
5. x 10-4
Shutdown of HRA Failures
5. x 10-4
In Storage Hose Rupture 3.4
5. x 10-5 /yr
PLS-H Trip Failure 3.6
1. x 10-3
No User Intervension 3.7
0.5
PLS-H Trip Failure 3.1
1. x 10-3
No User Intervension 3.3
0.5

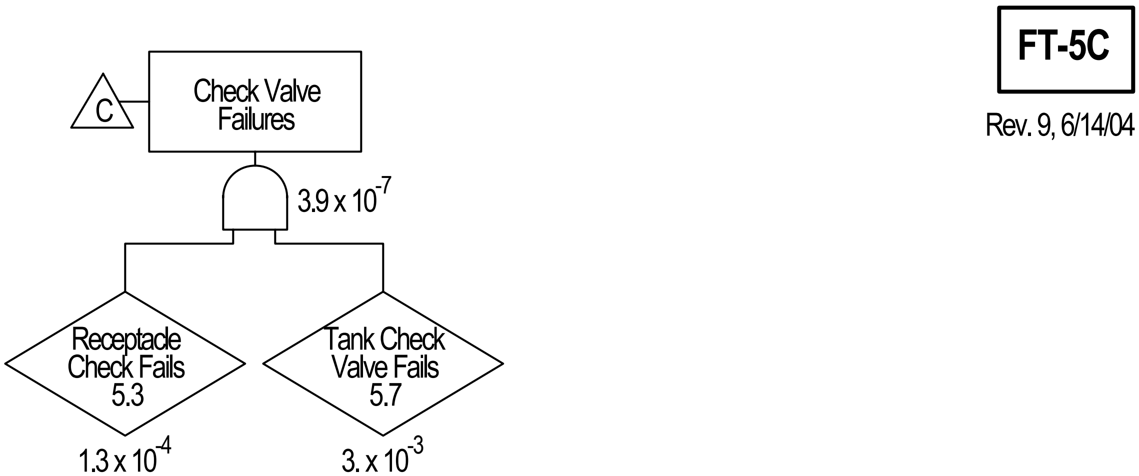

FT-3A
Rev.10, 8/19/04
A
HRA Release Via Driveaway Hose Failure
4.99 x 10-6 /yr
Refueling Vehicle 3.11
100./yr
User Drives Away Connected 3.12
3. x 10-3
HFA Doesn't Shutdown
9. x 10-4
Release from Hose
1.85 x 10-2
PLS-H Trip Failure 3.15
1. x 10-3
No User Intervention 3.17
0.9
Breakaway Fails to Open 3.13
1.8 x 10-2
X
Breakaway Dosen't Shutoff 3.14
5. x 10-4
(X) HRA side of breakaway is equipped with poppet shutoff.


FT-3B
Rev.10, 8/19/04
B
HRA Release from Component Failure
1.85 x 10-6 /yr
Lost or Ruptured Component
PLS-H Trip Failure 3.25
No User Intervention 3.24
3.71 x 10-2 /yr
1. x 10-3
5. x 10-2
Component Rupture in Service
Coupling O-ring Popout 3.22
8.41 x 10-5 /yr
3.7 x 10-2 /yr
O-ring poped out upon removal of receptacle after prior refueling. Failure is revealed at next use.
Refueling Vehicle 3.21
Component Rupture
0.14
6.01 x 10-4 /yr
Rupture of Fitting
Rupture of Tubing
6. x 10-4 /yr
5. x 10-7 /yr
Fitting Rupture 3.19
Fitting Count
Tubing Rupture /m-yr 3.20
Tubing Length, m
1. x 10-4 /yr
6. times
1. x 10-6 /yr
0.5 times

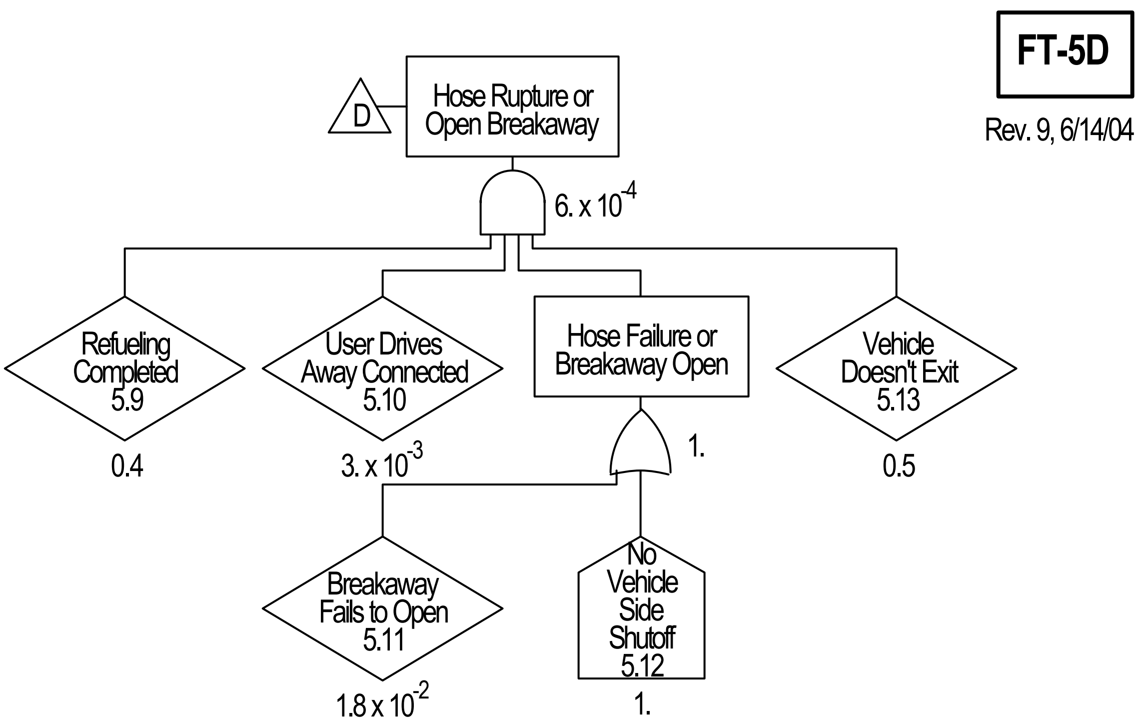

This tree presents events resulting in continuous discharge at HFA fueling rate of 0.67cfm
Continuous Gas Release Without Ventilation
FT-4
Rev.9, 6/2/04
4.05 x 10-12/yr
Continuous Gas Discharge in Garage
HRA On & Fan Off 4.2
5.88 x 10-7
Transfer branches A & B are the same a shown in FT-3A & B
6.89 x 10-6 /yr
The combination of events resulting in this probability are depicted in IET-2
HRA Release Via Driveaway Hose Failure
Release from In-Service Hose Rupture
HRA Release from Component Failure
HRA Release from Out-of-Service Hose Rupture
A
4.99 x 10-6 /yr
1.4 x 10-8 /yr
B
1.85 x 10-6 /yr
2.5 x 10-8 /yr
In Service Hose Rupture 4.5
2. x 10-4 /yr
Refilling Vehicle 4.9
0.14
Shutdown of HRA Failures
5. x 10-4
Shutdown of HRA Failures
5. x 10-4
In Storage Hose Rupture 4.4
5. x 10-5 /yr
PLS-H Trip Failure 4.6
1. x 10-3
No User Intervention 4.7
0.5
PLS-H Trip Failure 4.1
1. x 10-3
No User Intervention 4.3
0.5



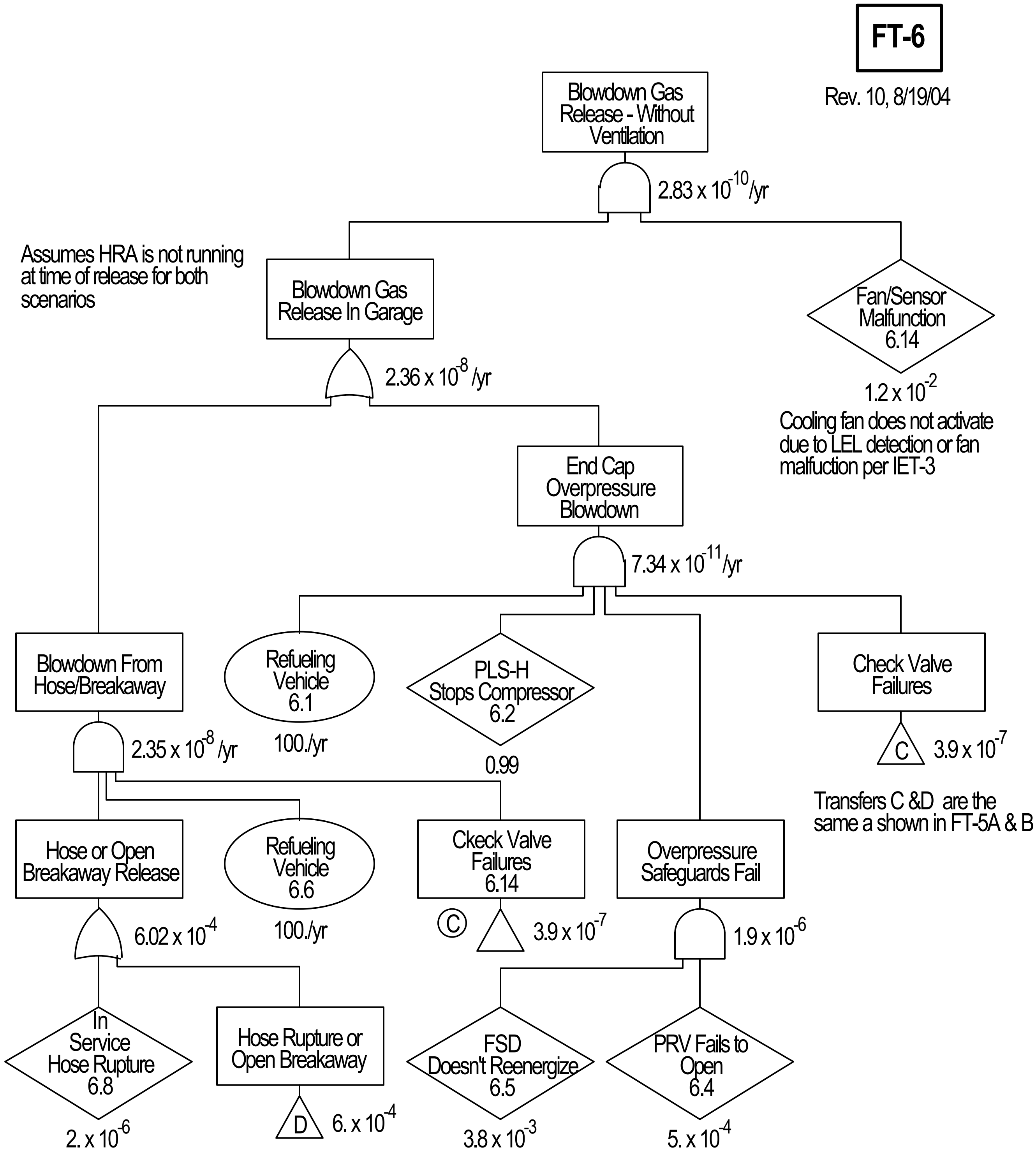
FT-5
Rev. 10, 8/19/04
Blowdown Gas Release - With Ventilation
2.33 x 10-8 /yr
Assumes HRA is not running at time of release for both scenarios
Blowdown Gas Release In Garage
Cooling fan activates due to LEL detection and fan functions
LEL Activates Fan 5.14
0.99
The combination of outcomes that produce this probability is depicted in IET-3
2.36 x 10-8 /yr
End Cap Overpressure Blowdown
7.34 x 10-11 /yr
Blowdown From Hose/Breakaway
Refueling Vehicle 5.1
100./yr
PLS-H Stops Compressor 5.2
0.99
Check Valve Failures
C
3.9 x 10-7
2.35 x 10-8 /yr
Hose or Open Breakaway Release
Refueling Vehicle 5.6
100./yr
Ckeck Valve Failures 5.14
C
3.9 x 10-7
Overpressure Safeguards Fail
6.02 x 10-4
1.9 x 10-6
In Service Hose Rupture 5.8
2. x 10-6
Out of service hose rupture does not allow tank to fill
Hose Rupture or Open Breakaway
D
6. x 10-4
Flow Device Doesn't Reenergize 5.5
3.8 x 10-3
PRV Fails to Open 5.4
5. x 10-4

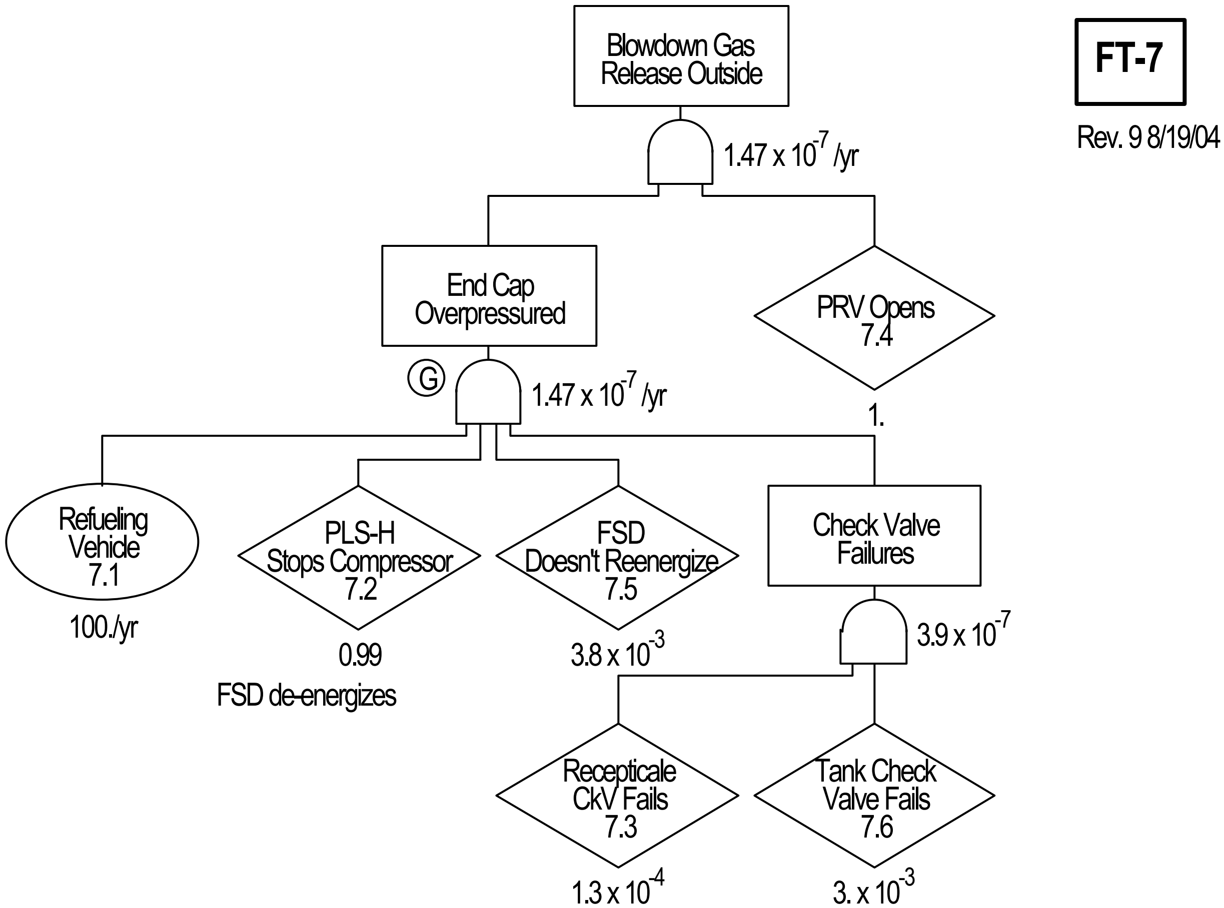


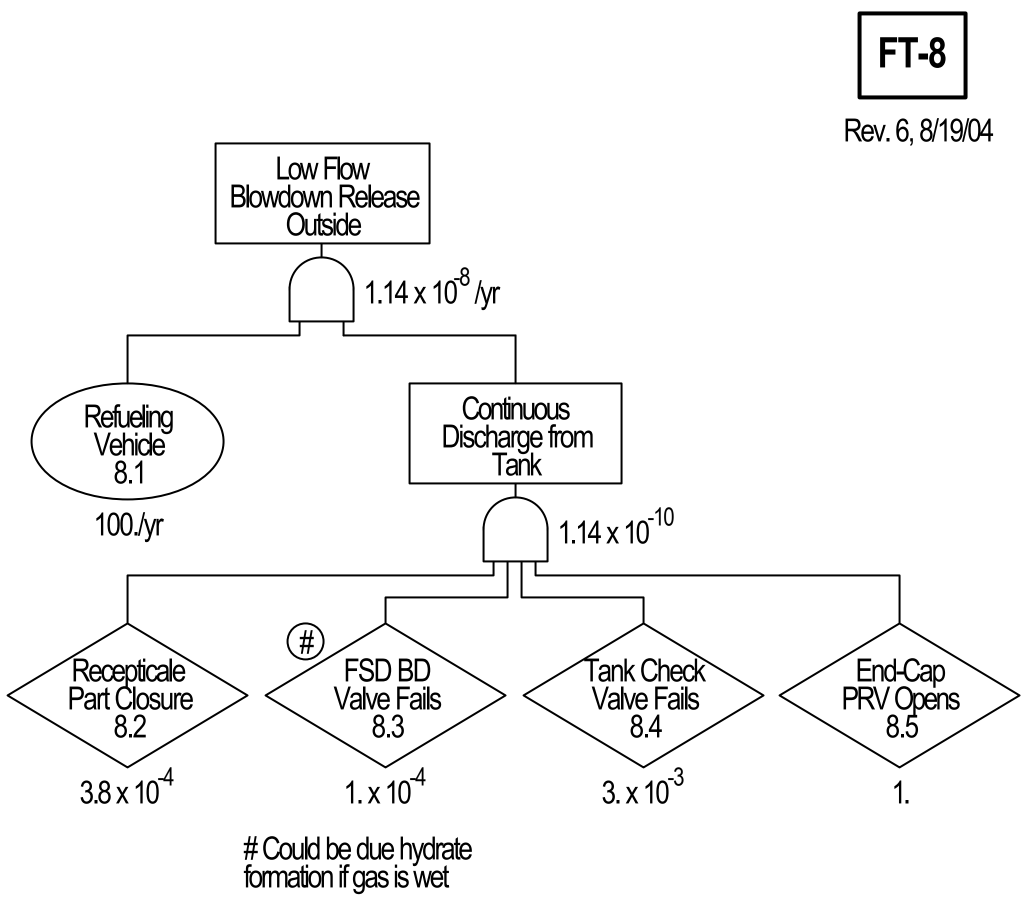
FT-5C
Rev. 9, 6/14/04
C
Check Valve Failures
3.9 x 10-7
Receptacle Check Fails 5.3
1.3 x 10-4
Tank Check Valve Fails 5.7
3. x 10-3

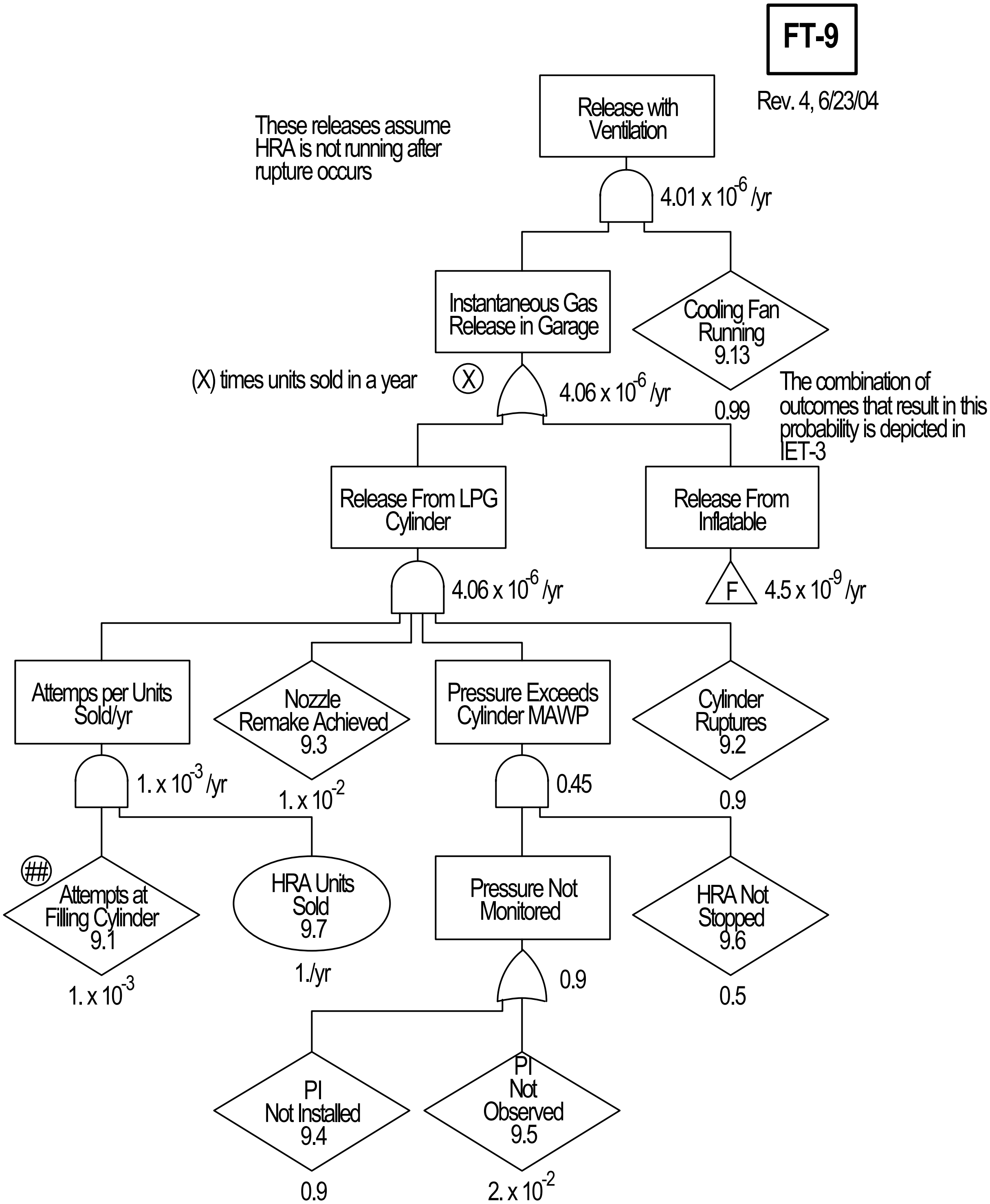


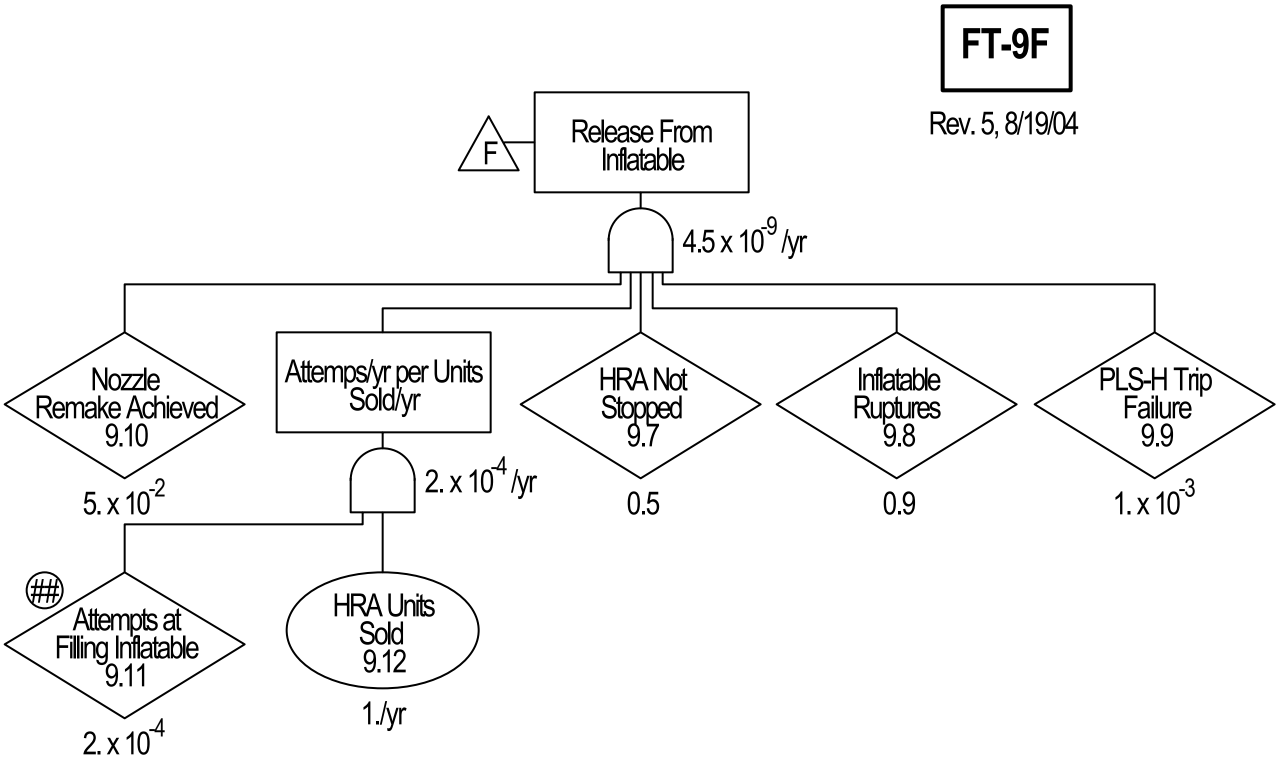
FT-5D
Rev. 9, 6/14/04
D
Hose Rupture or Open Breakaway
6. x 10-4
Refueling Completed 5.9
0.4
User Drives Away Connected 5.10
3. x 10-3
Hose Failure or Breakaway Open
1.
Vehicle Doesn't Exit 5.13
0.5
Breakaway Fails to Open 5.11
1.8 x 10-2
No Vehicle Side Shutoff 5.12
1.


FT-6
Rev. 10, 8/19/04
Blowdown Gas Release - Without Ventilation
2.83 x 10-10/yr
Assumes HRA is not running at time of release for both scenarios
Blowdown Gas Release In Garage
2.36 x 10-8 /yr
Fan/Sensor Malfunction 6.14
1.2 x 10-2
Cooling fan does not activate due to LEL detection or fan malfuction per IET-3
End Cap Overpressure Blowdown
7.34 x 10-11/yr
Blowdown From Hose/Breakaway
2.35 x 10-8 /yr
Refueling Vehicle 6.1
100./yr
PLS-H Stops Compressor 6.2
0.99
Check Valve Failures
C
3.9 x 10-7
Transfers C &D are the same a shown in FT-5A & B
Hose or Open Breakaway Release
6.02 x 10-4
Refueling Vehicle 6.6
100./yr
Ckeck Valve Failures 6.14
©
3.9 x 10-7
Overpressure Safeguards Fail
1.9 x 10-6
In Service Hose Rupture 6.8
2. x 10-6
Hose Rupture or Open Breakaway
D
6. x 10-4
FSD Doesn't Reenergize 6.5
3.8 x 10-3
PRV Fails to Open 6.4
5. x 10-4

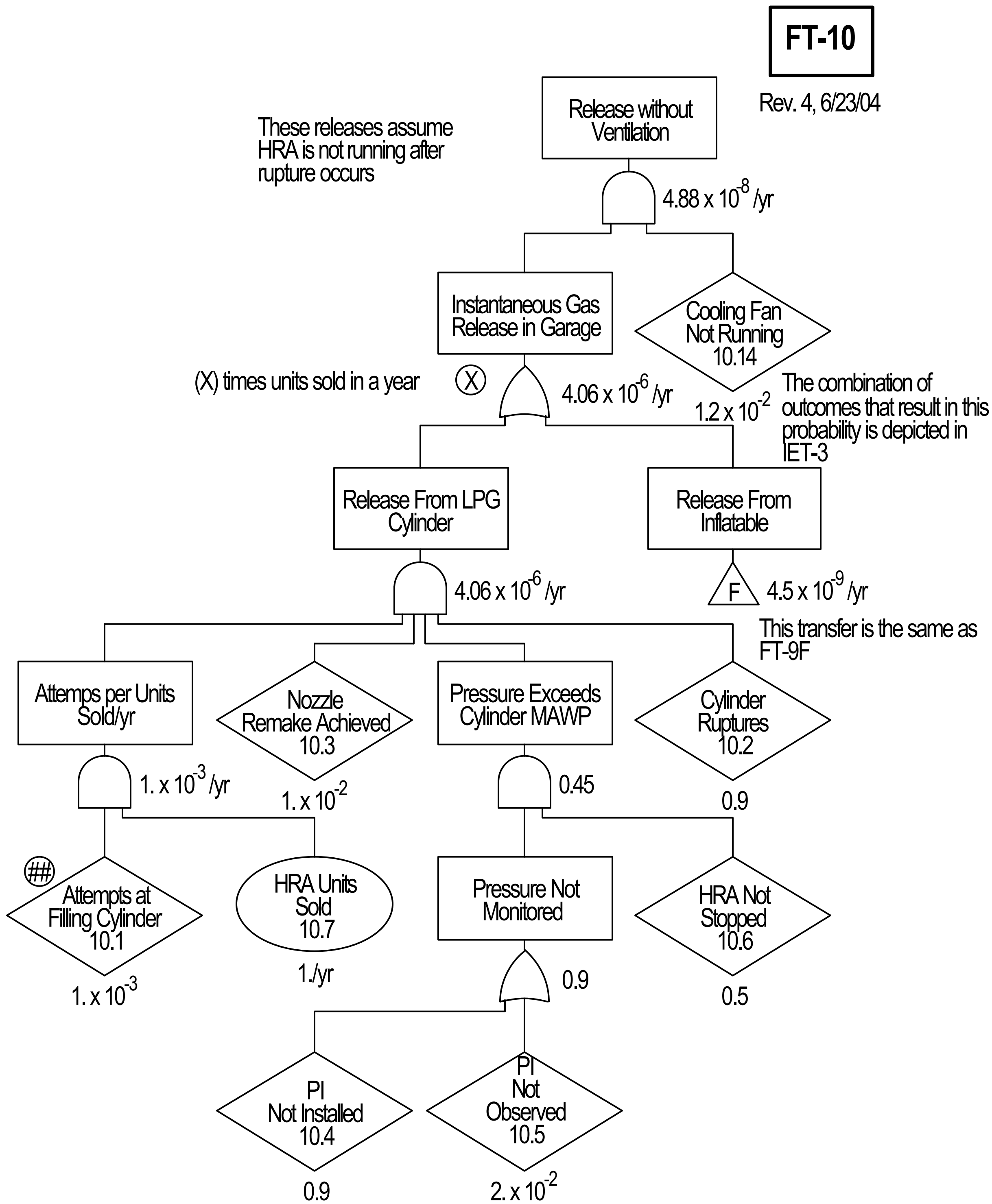

FT-7
Rev. 9 8/19/04
Blowdown Gas Release Outside
1.47 x 10-7 /yr
End Cap Overpressured
PRV Opens 7.4
1.
G
1.47 x 10-7 /yr
Refueling Vehicle 7.1
100./yr
PLS-H Stops Compressor 7.2
0.99
FSD de-energizes
FSD Doesn't Reenergize 7.5
3.8 x 10-3
Check Valve Failures
3.9 x 10-7
Recepticale CkV Fails 7.3
1.3 x 10-4
Tank Check Valve Fails 7.6
3. x 10-3


FT-8
Rev. 6, 8/19/04
Low Flow Blowdown Release Outside
1.14 x 10-8 /yr
Refueling Vehicle 8.1
100./yr
Continuous Discharge from Tank
1.14 x 10-10
Recepticale Part Closure 8.2
3.8 x 10-4
#
FSD BD Valve Fails 8.3
1. x 10-4
Tank Check Valve Fails 8.4
3. x 10-3
End-Cap PRV Opens 8.5
1.
Could be due hydrate formation if gas is wet


FT-9
Rev. 4, 6/23/04
Release with Ventilation
These releases assume HRA is not running after rupture occurs
4.01 x 10-6 /yr
Instantaneous Gas Release in Garage
Cooling Fan Running 9.13
(X) times units sold in a year
X
4.06 x 10-6 /yr
0.99
The combination of outcomes that result in this probability is depicted in IET-3
Release From LPG Cylinder
Release From Inflatable
4.06 x 10-6 /yr
F
4.5 x 10-9 /yr
Attemps per Units Sold/yr
Nozzle Remake Achieved 9.3
Pressure Exceeds Cylinder MAWP
Cylinder Ruptures 9.2
1. x 10-3 /yr
1. x 10-2
0.45
0.9
##
Attempts at Filling Cylinder 9.1
HRA Units Sold 9.7
Pressure Not Monitored
HRA Not Stopped 9.6
1./yr
1. x 10-3
0.9
0.5
PI Not Installed 9.4
PI Not Observed 9.5
0.9
2. x 10-2

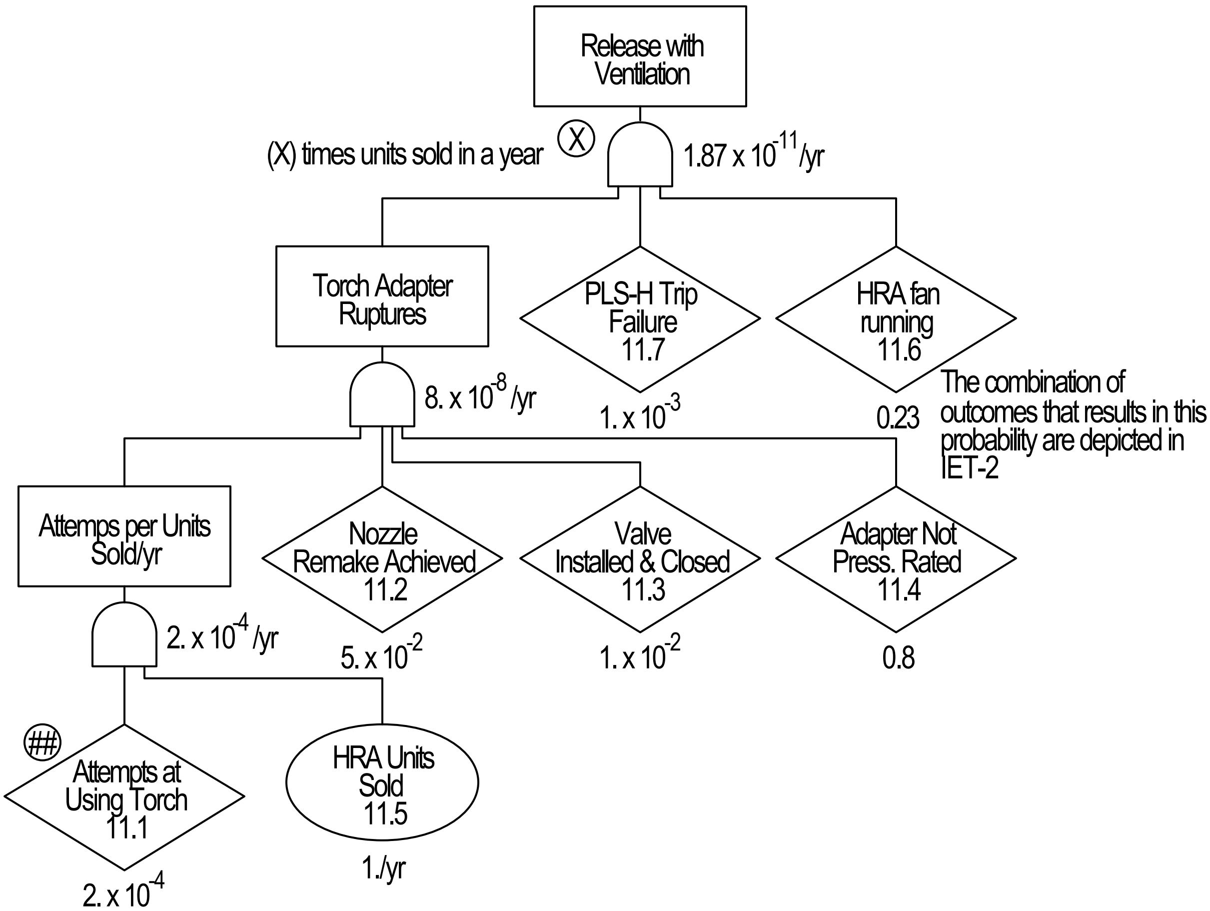


Assumes that 1 in 5000 owners will attempt within one year of purchase.

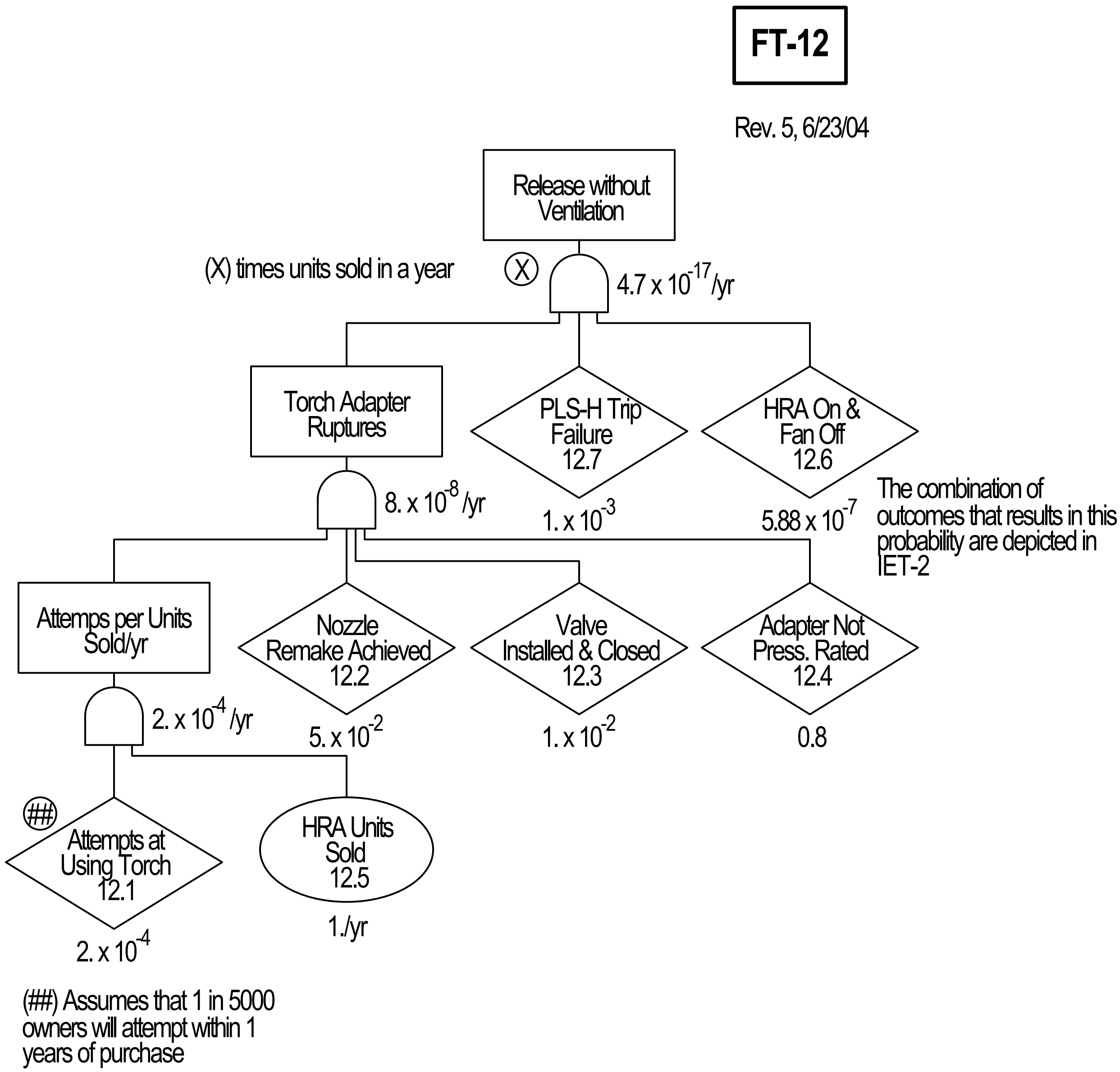

FT-10
Rev. 4, 6/23/04
Release without Ventilation
These releases assume HRA is not running after rupture occurs
4.88 x 10-8 /yr
Instantaneous Gas Release in Garage
Cooling Fan Not Running 10.14
(X) times units sold in a year
X
4.06 x 10-6 /yr
1.2 x 10-2
The combination of outcomes that result in this probability is depicted in IET-3
Release From LPG Cylinder
Release From Inflatable
4.06 x 10-6 /yr
F
4.5 x 10-9 /yr
This transfer is the same as FT-9F
Attemps per Units Sold/yr
Nozzle Remake Achieved 10.3
Pressure Exceeds Cylinder MAWP
Cylinder Ruptures 10.2
1. x 10-3 /yr
1. x 10-2
0.45
0.9
##
Attempts at Filling Cylinder 10.1
HRA Units Sold 10.7
Pressure Not Monitored
HRA Not Stopped 10.6
1./yr
1. x 10-3
0.9
0.5
PI Not Installed 10.4
PI Not Observed 10.5
0.9
2. x 10-2

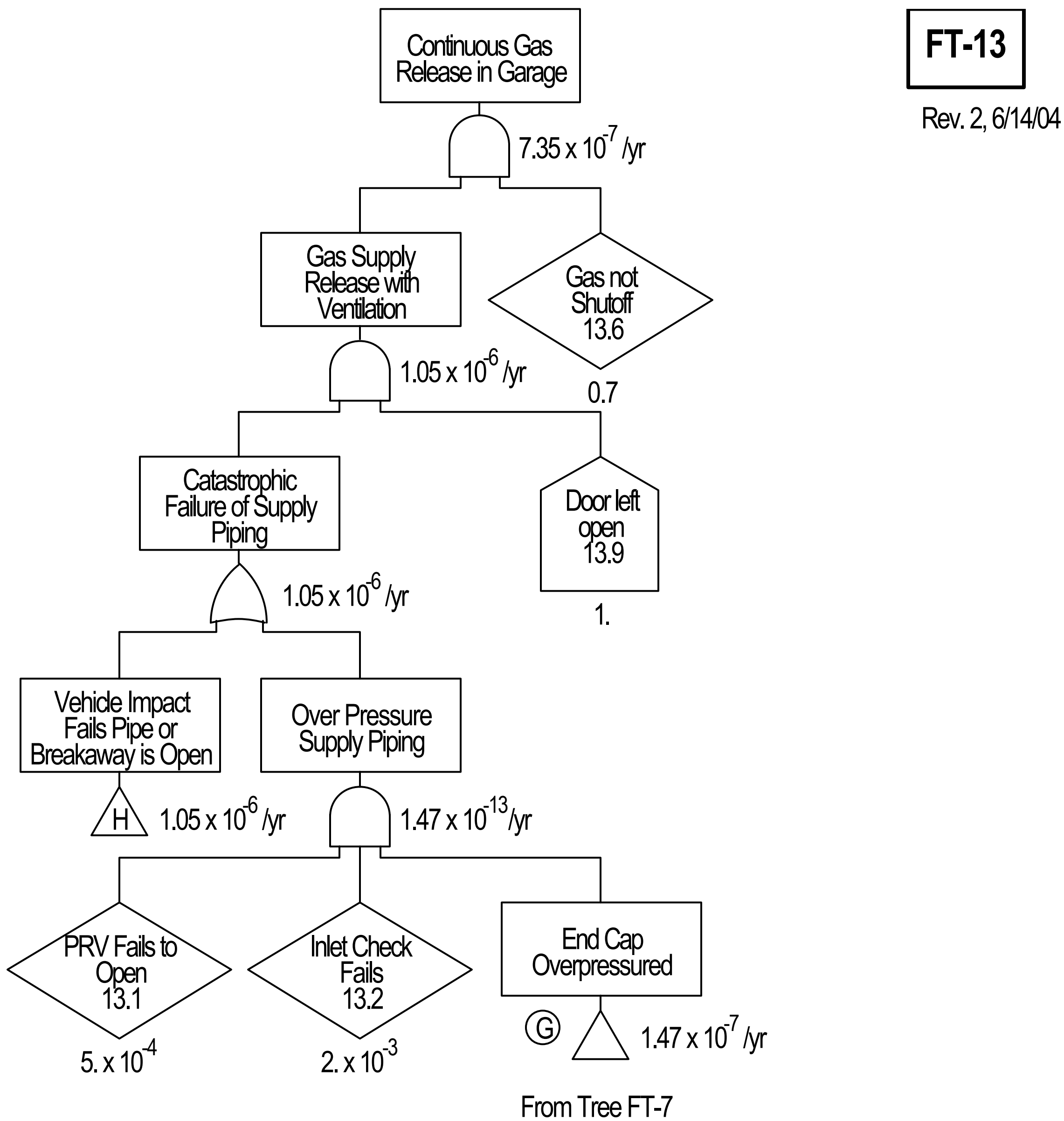
FT-11

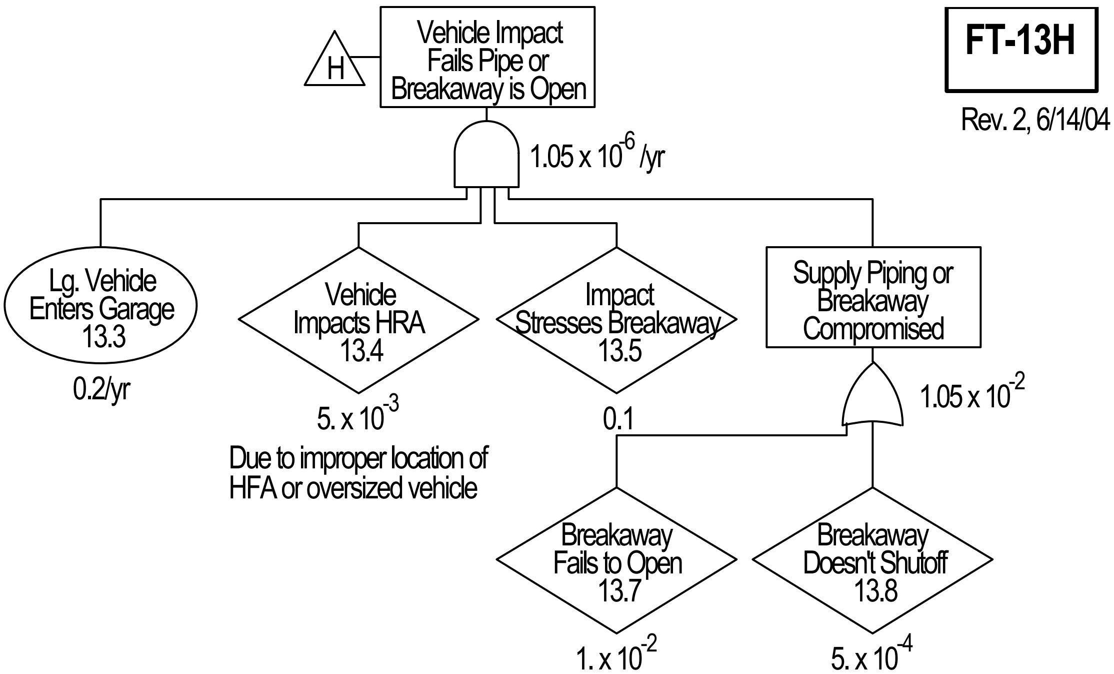
Rev. 6, 8/19/04

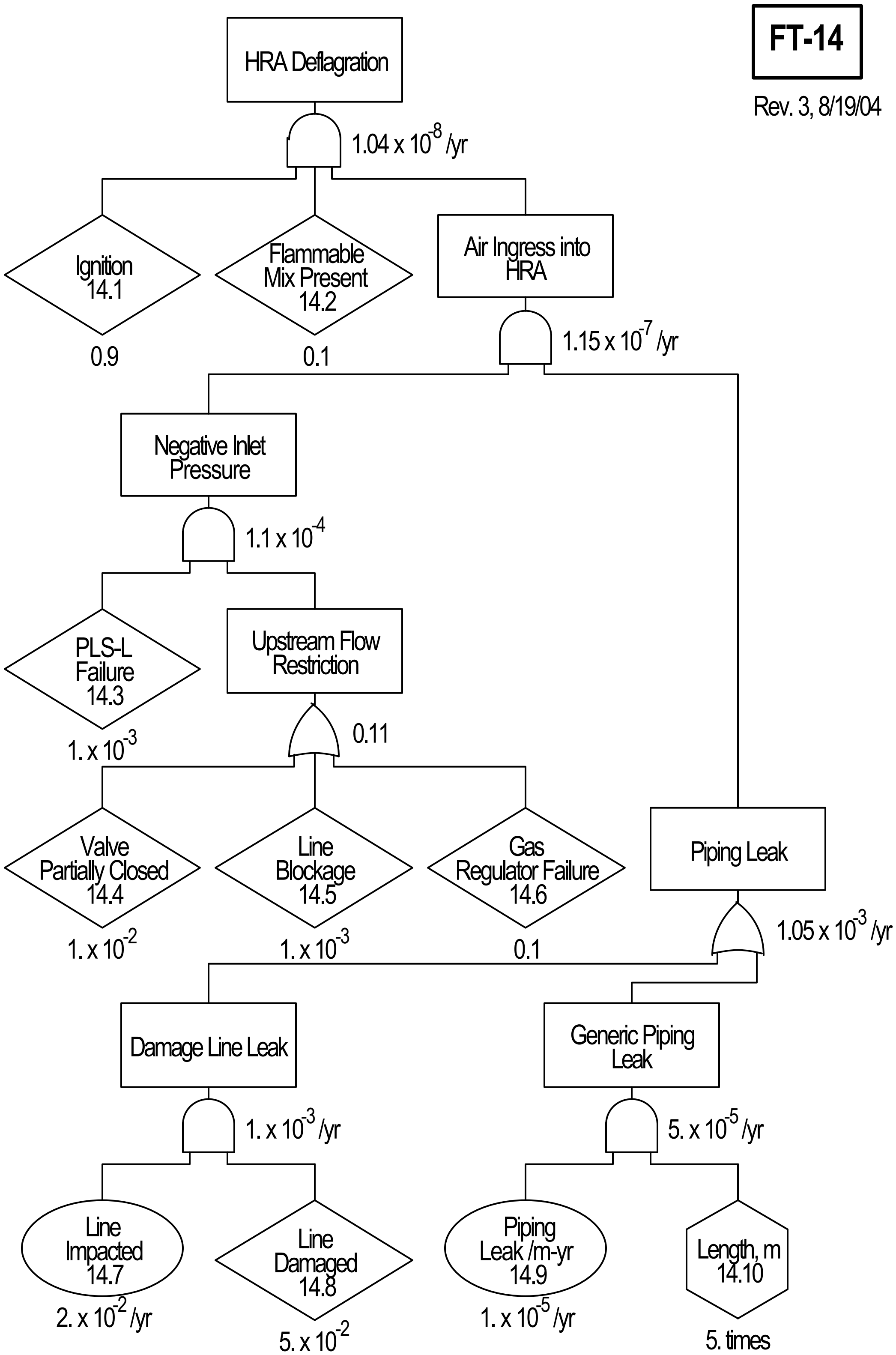


(##) Assumes that 1 in 5000 owners will attempt within 1 years of purchase


FT-12
Rev. 5, 6/23/04
Release without Ventilation
(X) times units sold in a year
X
4.7 x 10-17/yr
Torch Adapter Ruptures
PLS-H Trip Failure 12.7
1. x 10-3
HRA On & Fan Off 12.6
5.88 x 10-7
The combination of outcomes that results in this probability are depicted in IET-2
8. x 10-8 /yr
Attemps per Units Sold/yr
Nozzle Remake Achieved 12.2
5. x 10-2
Valve Installed & Closed 12.3
1. x 10-2
Adapter Not Press. Rated 12.4
0.8
2. x 10-4 /yr
##
Attempts at Using Torch 12.1
2. x 10-4
HRA Units Sold 12.5
1./yr
(##) Assumes that 1 in 5000 owners will attempt within 1 years of purchase

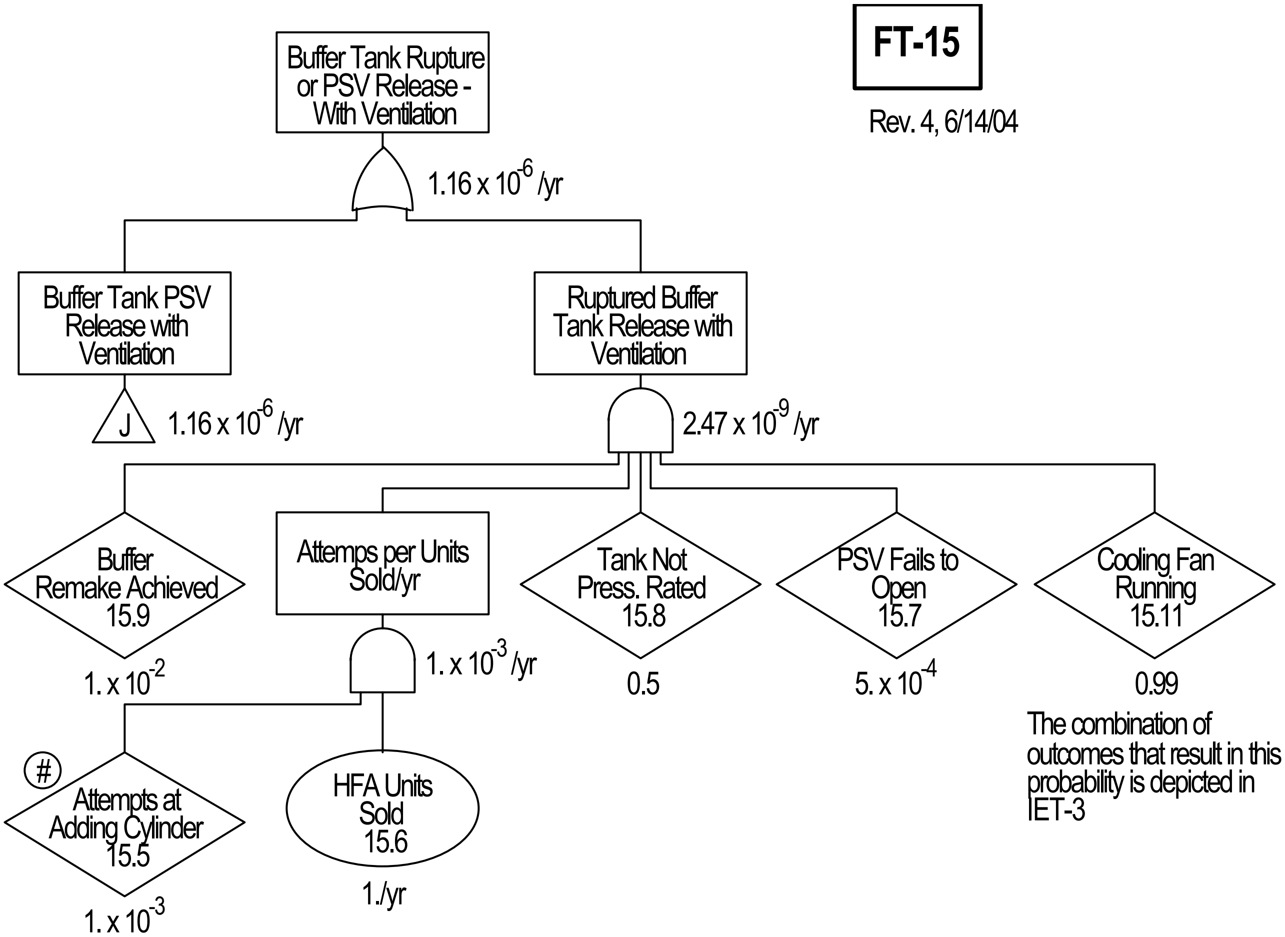

FT-13
Rev. 2, 6/14/04
Continuous Gas Release in Garage
7.35 x 10-7 /yr
Gas Supply Release with Ventilation
Gas not Shutoff 13.6
0.7
1.05 x 10-6 /yr
Catastrophic Failure of Supply Piping
Door left open 13.9
1.
1.05 x 10-6 /yr
Vehicle Impact Fails Pipe or Breakaway is Open
Over Pressure Supply Piping
H
1.05 x 10-6 /yr
1.47 x 10-13/yr
PRV Fails to Open 13.1
Inlet Check Fails 13.2
End Cap Overpressured
G
1.47 x 10-7 /yr
5. x 10-4
2. x 10-3
From Tree FT-7


FT-13H
Rev. 2, 6/14/04
H
Vehicle Impact Fails Pipe or Breakaway is Open
1.05 x 10-6 /yr
Lg. Vehicle Enters Garage 13.3
0.2/yr
Vehicle Impacts HRA 13.4
5. x 10-3
Due to improper location of HFA or oversized vehicle
Impact Stresses Breakaway 13.5
0.1
Supply Piping or Breakaway Compromised
1.05 x 10-2
Breakaway Fails to Open 13.7
1. x 10-2
Breakaway Doesn't Shutoff 13.8
5. x 10-4


FT-14
Rev. 3, 8/19/04
HRA Deflagration
1.04 x 10-8 /yr
Ignition 14.1
0.9
Flammable Mix Present 14.2
0.1
Air Ingress into HRA
1.15 x 10-7 /yr
Negative Inlet Pressure
1.1 x 10-4
PLS-L Failure 14.3
1. x 10-3
Upstream Flow Restriction
0.11
Valve Partially Closed 14.4
1. x 10-2
Line Blockage 14.5
1. x 10-3
Gas Regulator Failure 14.6
0.1
Piping Leak
1.05 x 10-3 /yr
Damage Line Leak
1. x 10-3 /yr
Generic Piping Leak
5. x 10-5 /yr
Line Impacted 14.7
2. x 10-2 /yr
Line Damaged 14.8
5. x 10-2
Piping Leak /m-yr 14.9
1. x 10-5 /yr
Length, m 14.10
5. times

FT-15

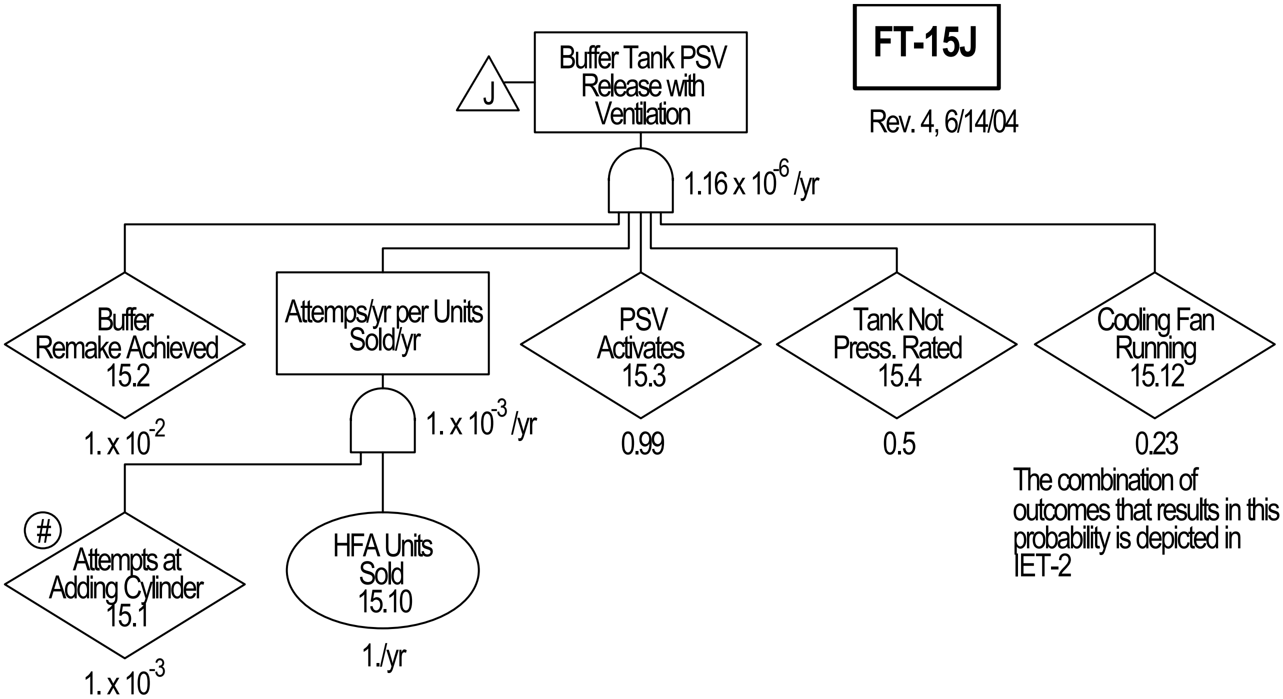
Rev. 4, 6/14/04

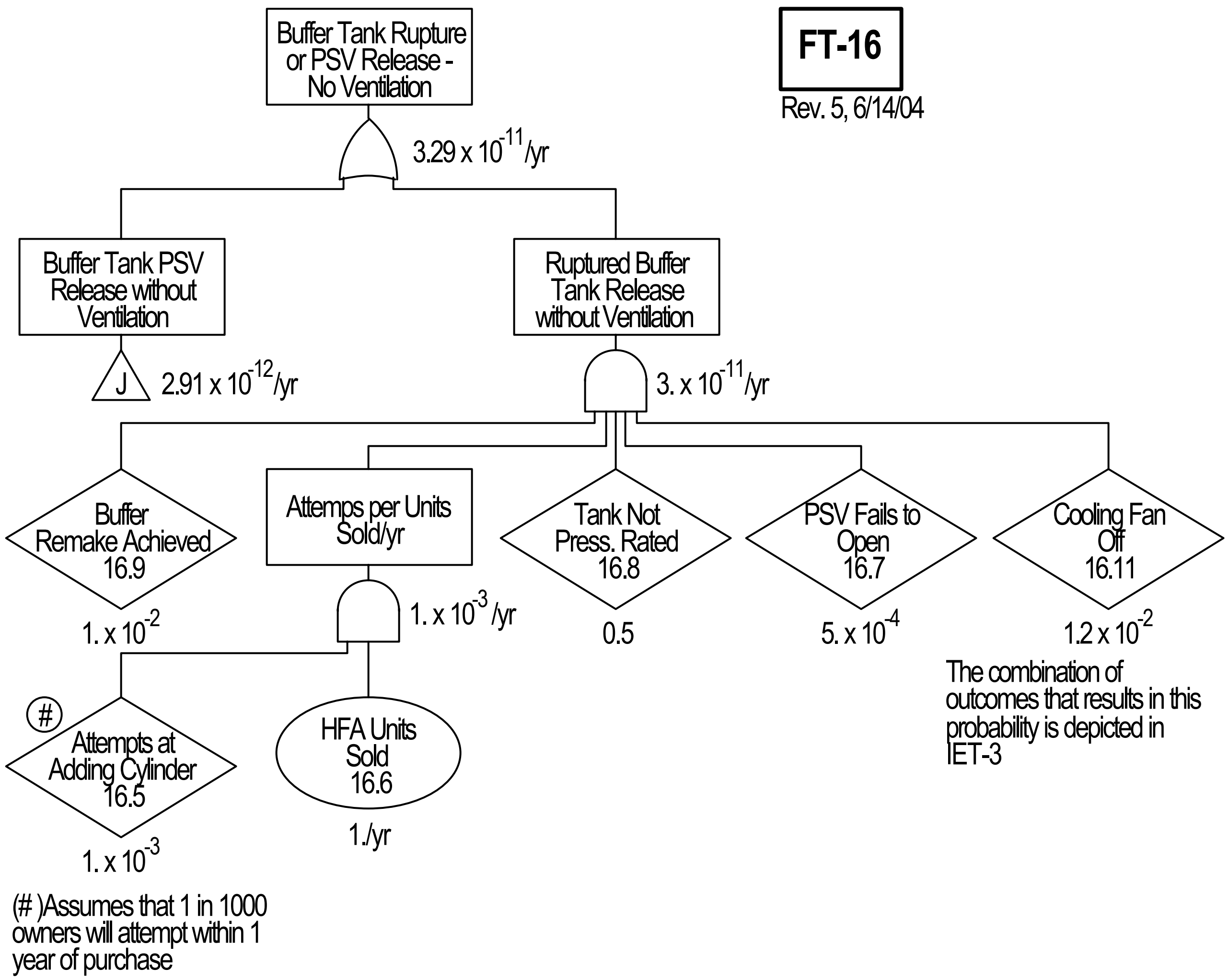


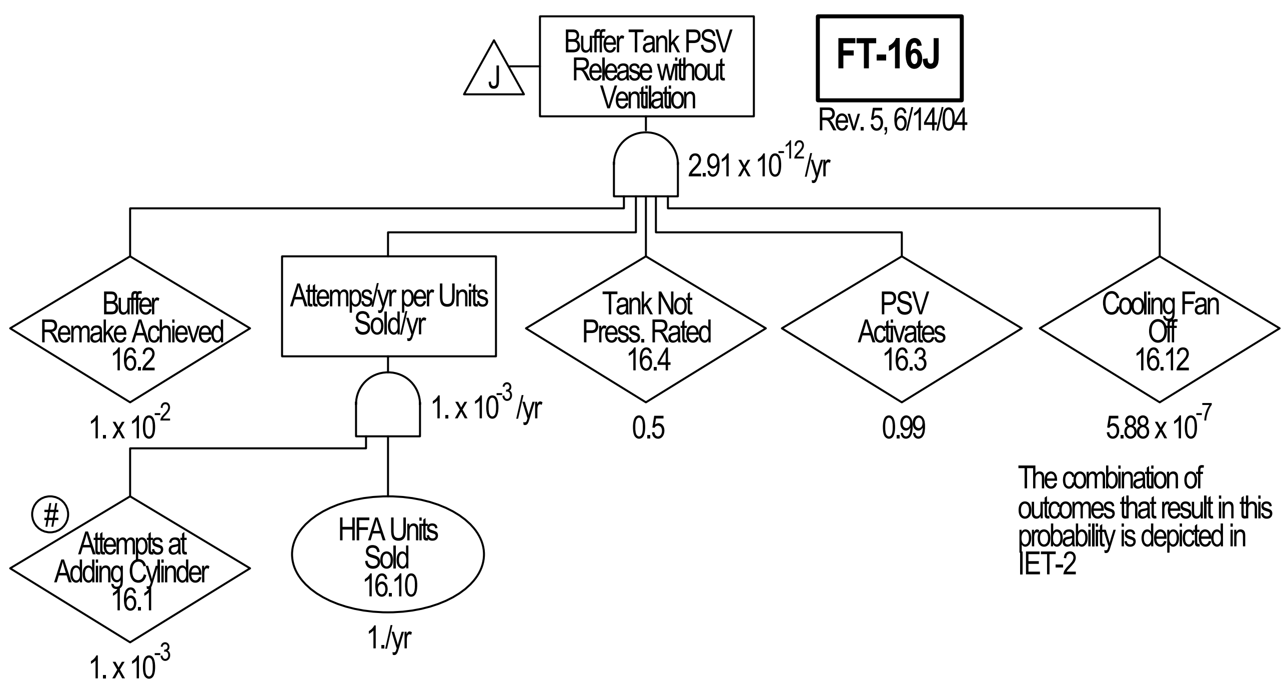
(#)Assumes that 1 in 1000 owners will attempt within 1 year of purchase

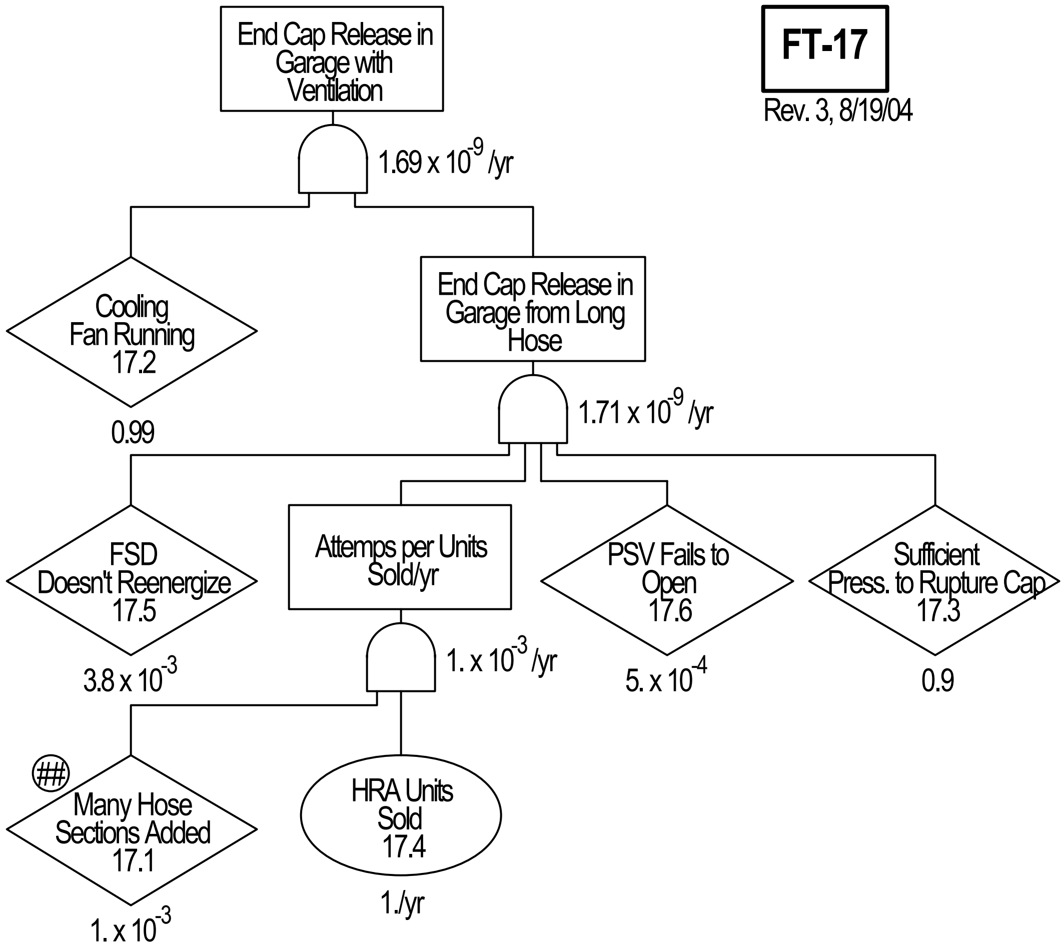
FT-15J

Rev. 4, 6/14/04

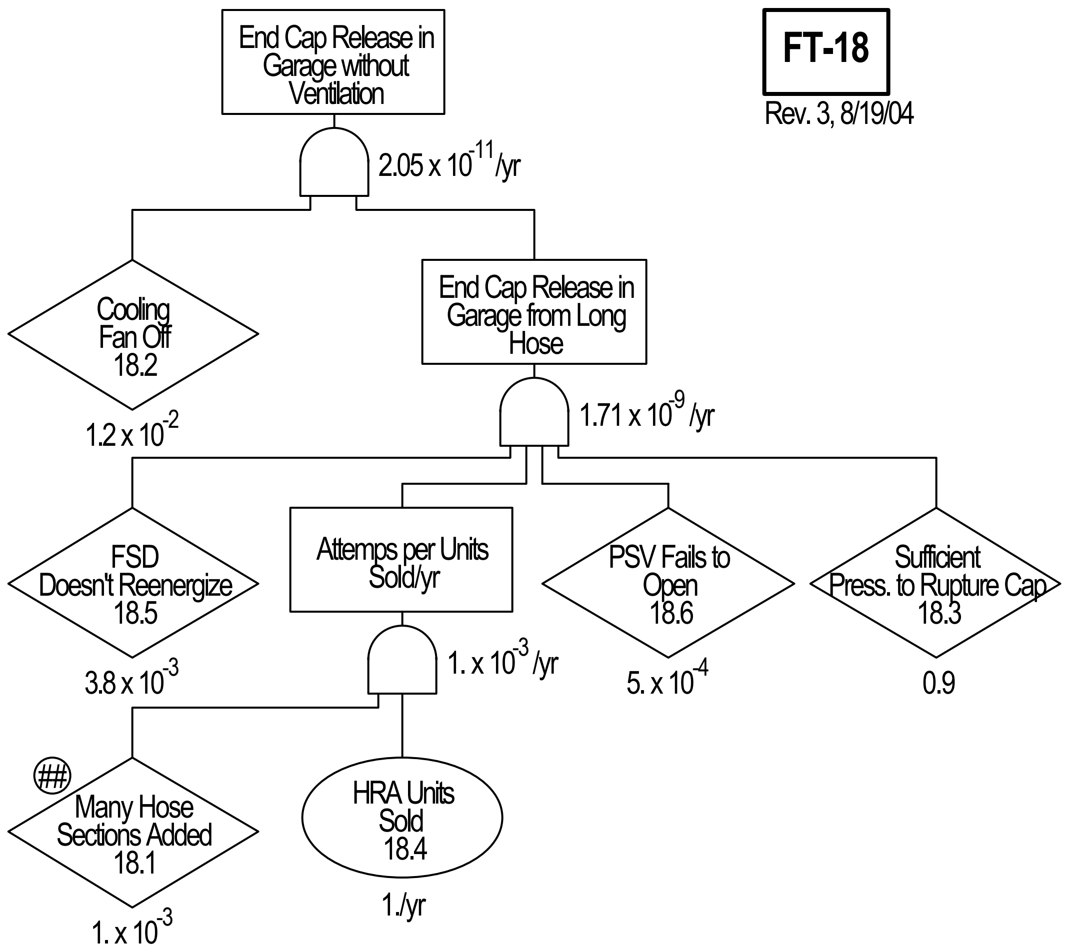



FT-16
Rev. 5, 6/14/04
Buffer Tank Rupture or PSV Release - No Ventilation
3.29 x 10-11/yr
Buffer Tank PSV Release without Ventilation
J
2.91 x 10-12/yr
Ruptured Buffer Tank Release without Ventilation
3. x 10-11/yr
Buffer Remake Achieved 16.9
1. x 10-2
Attemps per Units Sold/yr
1. x 10-3 /yr
Tank Not Press. Rated 16.8
0.5
PSV Fails to Open 16.7
5. x 10-4
Cooling Fan Off 16.11
1.2 x 10-2
The combination of outcomes that results in this probability is depicted in IET-3
#
Attempts at Adding Cylinder 16.5
1. x 10-3
HFA Units Sold 16.6
1./yr
(#)Assumes that 1 in 1000 owners will attempt within 1 year of purchase


J
Buffer Tank PSV Release without Ventilation
FT-16J
Rev. 5, 6/14/04
2.91 x 10-12/yr
Buffer Remake Achieved 16.2
1. x 10-2
Attemps/yr per Units Sold/yr
1. x 10-3 /yr
Tank Not Press. Rated 16.4
0.5
PSV Activates 16.3
0.99
Cooling Fan Off 16.12
5.88 x 10-7
The combination of outcomes that result in this probability is depicted in IET-2
#
Attempts at Adding Cylinder 16.1
1. x 10-3
HFA Units Sold 16.10
1./yr

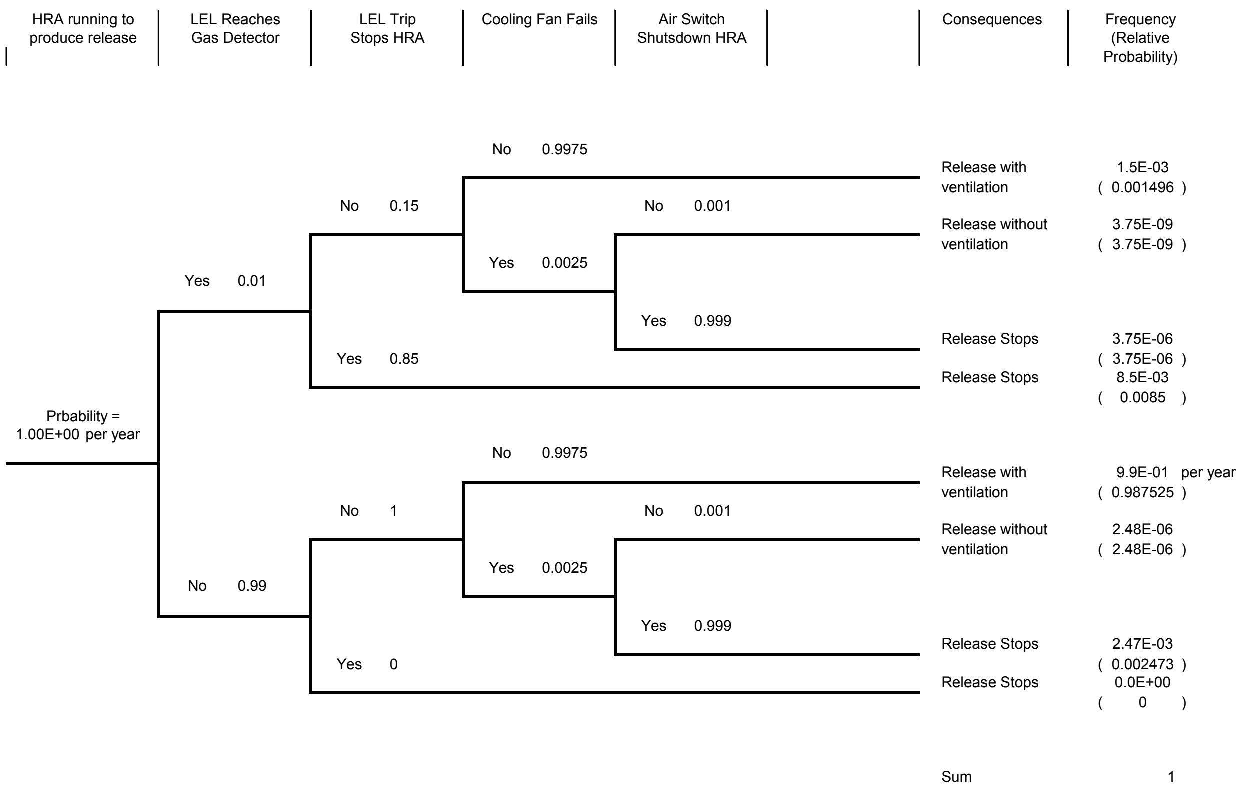


(##) Assumes that 1 in 1000 owners will attempt to add more than one hose within 1 year of purchase.

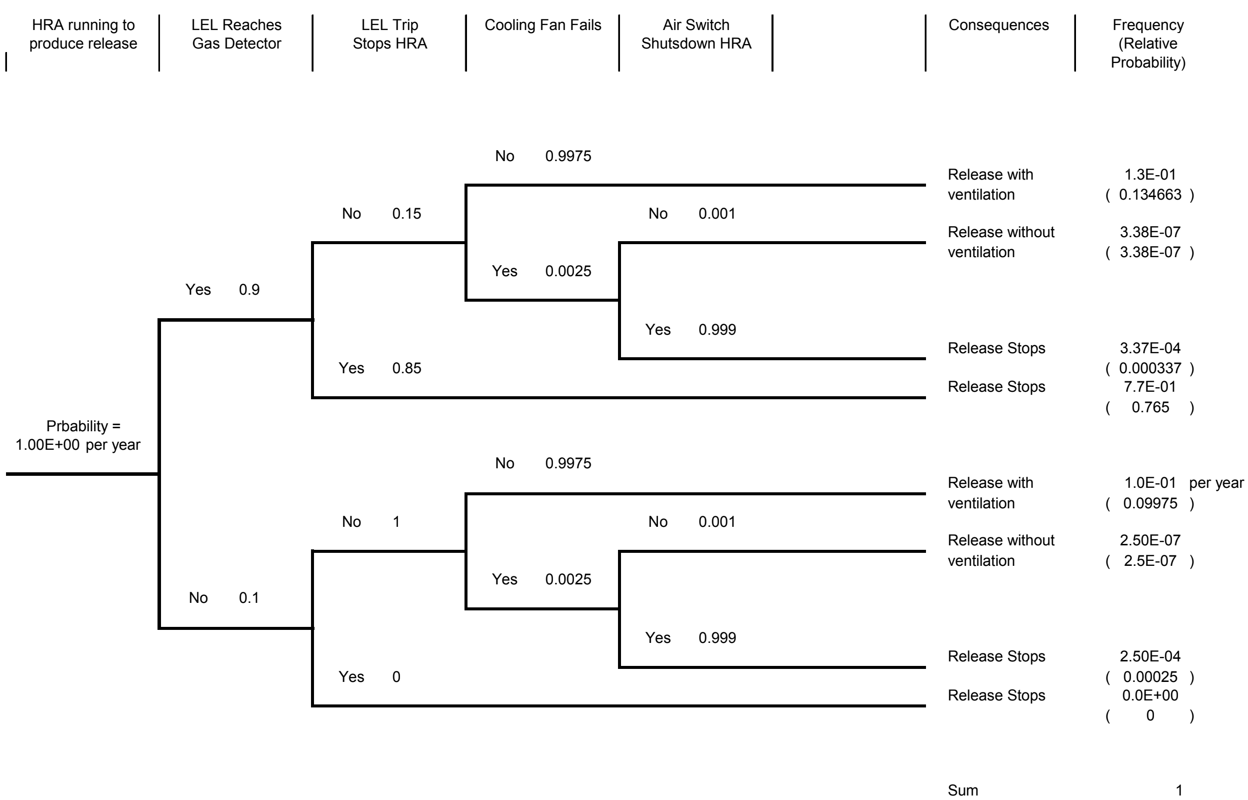


(##) Assumes that 1 in 1000 owners will attempt to add more than one hose within 1 year of purchase.

IET-1: Small (0.22 CFM or less) Continuous Release



IET-2: Larger (0.67CFM or greater) Continuous Release



IET-3: Tank Blowdown or Release Without HRA Running

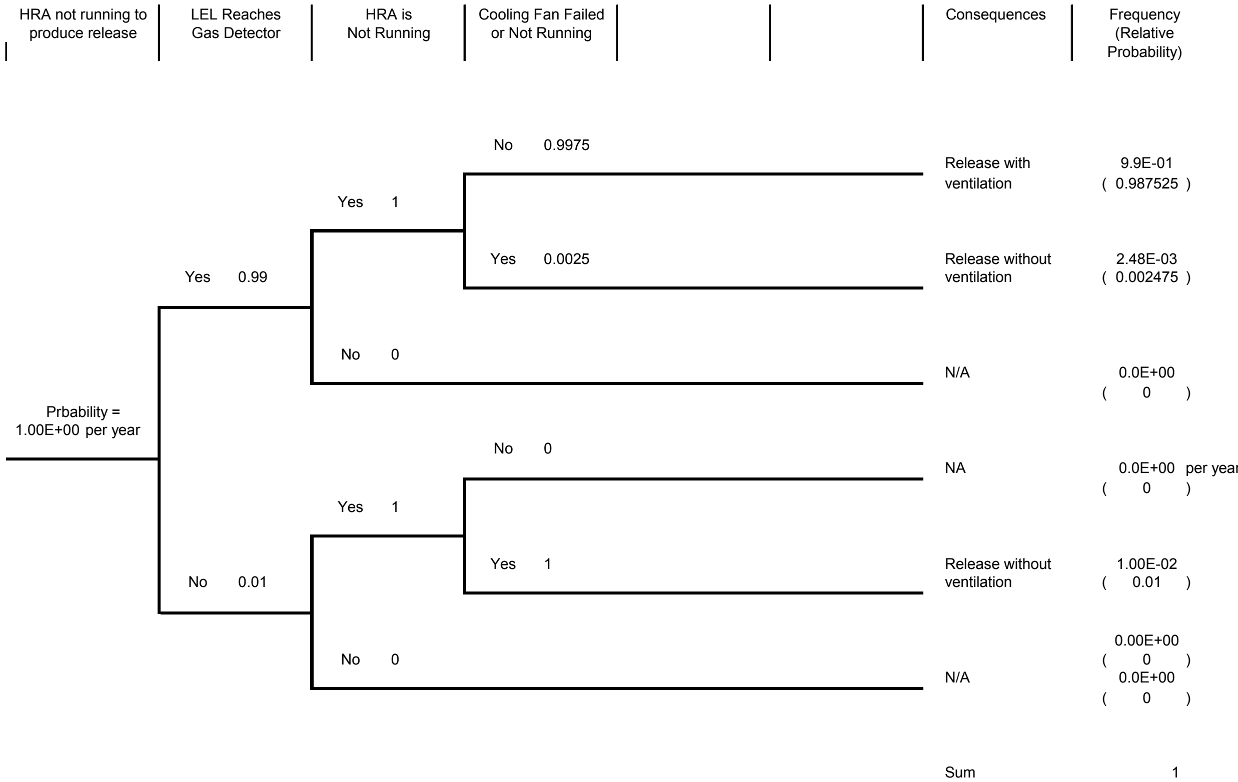


Table A-1: Frequency and Probability Data Summary

Item	Event	Statistic	Source/Discussion
1.1	Refueling Vehicle	0.14	See 1.9
1.2	Hose Leak in Service	$6x10^{-4}$/yr	See 3.5 A base rate of 10^{3}/yr is assumed with 80% of the failures being in-service and 75% will be leak failures.
1.3	HRA and cooling fan running	0.913	This values is the sum of all release outcomes with ventilation shown in intermediate event tree IET-1
1.4	Hose Leak Out of Service	$1.5x10^{-4}$/yr	See 3.4 A base rate of 10^{3}/yr is assumed with 20% of the failures being out of service and 75% will be leak failures.
1.5	Refueling Demands	100/yr	Estimate that vehicle will have to be refueled once or twice a week depending on use. Have selected conservative valve of 100 refuelings per year
1.6	No User Intervention	0.5	See 3.3
1.7	Leak Check Failure	$1x10^{-3}$	The HRA will periodically perform an on-line leak check and take itself out of service if static pressure cannot be maintained. A probability of failure of 1 in 1000 is applied, similar to the PLS-H safeguard failure (3.1).
1.8	No User Intervention	0.5	See 3.3
1.9	Fractional year per Refueling	$1.37x10^{-3}$	Assuming an average time of 12 hrs., the fractional year is 12/8760. The probability that a vehicle is refueling is the product of Item 1.5 times Item1.9 or 0.14.
1.10	Intentionally left blank		
1.11	No User Intervention	0.5	See 3.3
1.12	Fitting Leak	$5x10^{-4}$/yr	Hansen provides data for instrument (impulse) line connection to derive a frequency of $5x10^{-4}$/yr. This was selected because the HFA utilizes tubing connections.
1.13	Tubing leak	$1x10^{-5}$/m-yr	Rijnmond gives $1x10^{-5}$/m-yr for significant leakage for <2 inch pipe.
1.14	Coupling O-ring Leak	$1.8x10^{-3}$/yr	Lees gives a frequency for O-ring/seal failure in operation of $1.75x10^{-3}$/yr.
1.15	Hose Coupling Not Secured	$5x10^{-2}$/yr	Assumes coupling is tight enough to permit compressor to run for a time to build pressure before leakage occurs with a probability of 0.5. Human error rate for routine operations/jobs is 0.001. The refueling operation task is done 100 times per year.
1.16	Number of Fittings	6	It is estimated there are approximately 6 fittings including the drier and hose.
1.17	Length of Tubing	0.5m	Estimate of HRA tubing length

Table A-1: Frequency and Probability Data Summary (continued)

Item	Event	Statistic	Source/Discussion
2.1-2.17 ex 2.3	All statistics are the same as the corresponding values for 1.1-1.17, ex. 2.3		
2.3	HRA running and cooling fan off	2.48×10^{-6}	This values is the sum of all release outcomes without ventilation shown in intermediate event tree IET-1
3.1	High pressure limiting system (PLS-H) Fails to Trip	1×10^{-3}	Various sources (see Appendix A) give a range of from 3×10^{-3} to 1×10^{-4}/demand for pressure switch/transducer fails to operate or function when signaled. A value of 1×10^{-3}/ d is used for the entire trip circuit.
3.2	HRA and cooling fan running	0.234	This values is the sum of all release outcomes with ventilation shown in intermediate event tree IET-2
3.3	No User Intervention	0. 5	It is expected that a majority of the time no one will be present during the refueling period. However, the gas is odorized and in some leaks would be noticed in attached garages. We have estimated that the likelihood of intervention is 50%.
3.4	Hose Rupture Out of Service	5×10^{-5}/yr	CCPS gives 5×10^{-3}/yr for a mean value, with a low bound of 9×10^{-5}/yr. A proprietary source gives 1×10^{-3}/yr for transfer hoses in chemical service. The HFA hose is small diameter, relatively short and not highly stressed, and handling a non-corrosive material. A base rate of 10^{3}/yr is assumed with 20% of the failures being in-service and 25% will be full bore equivalent failures.
3.5	In Service Hose Rupture	2×10^{-4}/yr	CCPS gives 5×10^{-3}/yr for a mean value, with a low bound of 9×10^{-5}/yr. A proprietary source gives 1×10^{-3}/yr for transfer hoses in chemical service. The HFA hose is small diameter, relatively short, and handling a non-corrosive material. A base rate of 10^{3}/yr is assumed with 80% of the failures being in-service and 25% will be full bore equivalent failures.
3.6	PLS-H Fails to Trip	1×10^{-3}	See 3.1
3.7	No User Intervention	0. 5	See 3.3
3.8	Intentionally Blank		
3.9	Refueling Vehicle	1.4×10^{-1}	See 1.9
3.10	Partial Closure of Receptacle Check Valve	3.8×10^{-4}	Based on user survey results, a PFD value of 5×10^{-4} is indicated, and ¾ of the failures were assumed to be partial closure
3.11	Refueling Vehicle	100/yr.	See 1.5. Consistent with TNO value from prior study.

Table A-1: Frequency and Probability Data Summary (continued)

Item	Event	Statistic	Source/Discussion
3.12	User Drives Away Connected	$3x10^{-3}$	Human error rate for routine operations/jobs is 0.001. The rate for errors of omission is 0.003. Fleet user data gives a PDF between $1.1x10^{-3}$ to $1.5x10^{-4}$. Since there is a significant time gap between the start and end of refueling for HFA, the error rate is expected to be higher than for a routine task of short duration. Also, the person beginning and completing the refueling may be different.
3.13	Breakaway Coupling Fails to Disconnect and Hose Fails	$1.8x10^{-2}$	Proprietary source gives $2x10^{-2}$ for probability of failure on demand (PFD) of dry-break coupling. Further, we have assumed that 9 out of 10 times the hose will fail before the piping.
3.14	Breakaway Coupling Doesn't Shut Off Flow (HRA side)	$5x10^{-4}$	See 3.10. Statistic for breakaway not available. Used base failure rate for check valve.
3.15	PLS-H Fails to Trip	$1x10^{-3}$	See 3.1
3.16	Intentionally left blank		
3.17	No User Intervention	0.9	In the case of a drive away, the likelihood the driver will detect a problem is not very high.
3.18	Intentionally left blank		
3.19	Fitting Rupture	$1x10^{-4}$/yr	WASH 1400 gives $1x10^{-4}$/yr for small bore fitting rupture
3.20	Tubing Rupture	$1x10^{-6}$/m-yr	Rijnmond gives $1x10^{-6}$/m-yr for rupture of <2 inch pipe.
3.21	Refueling Vehicle	0.14	See 1.9
3.22	O-ring Popout	$3.7x10^{-2}$/yr	User data indicates O-ring blowouts occur about once every 3 months or 2700 refuelings. Assuming 100 refuelings/yr. using HFA gives $3.7x10^{-2}$/yr. (1/2700 x 100/yr.).
3.23	Intentionally Blank		
3.24	No User Intervention	0.0 5	Large leak is more likely to be noticed, particularly a missing O-ring at the start of refueling.
3.25	PLS-H Trip Failure	$1x10^{-3}$	See 3.1
4.1, 4.3-4.25	All statistics are the same as the corresponding values for 3.1, 3.3– 3.25		
4.2	HRA running and cooling fan off	$5.88x10^{-7}$	This values is the sum of all release outcomes without ventilation shown in intermediate event tree IET-2
5.1	Refueling Vehicle	100/yr	See 1.5
5.2	PLS-H Stops Compressor	0.999	1 minus 10^{-3}

Table A-1: Frequency and Probability Data Summary (continued)

Item	Event	Statistic	Source/Discussion
5.3	Receptacle Check Valve Sticks Open	$1.3x10^{-4}$	See 3.10 for base rate. ¼ * $5x10^{-4}$
5.4	End Cap Pressure Relief Valve (PRV) Fails to Open	$5x10^{-4}$	CCPS gives a mean value of $2x10^{-4}$/demand for failure to open, with a range of $8x10^{-4}$ to $8x10^{-6}$/d. Other sources (see Appendix A) give a range of $3x10^{-3}$ to $1x10^{-5}$/d for failure to open. A value of $5x10^{-4}$/d is used for PRV blockage or stuck closed valve.
5.5	Flow Switching Device (FSD) Doesn't Re-energize to Stop Flow	$3.8x10^{-3}$	CCPS give a mean value of $2.8x10^{-3}$ for failure of a solenoid valve to move on demand. For failure of the PLS-H to detect back flow we use $1x10^{-3}$ from item 3.1. Combining the two gives $3.8x10^{-3}$
5.6	Refueling Vehicle	100/yr	See 1.5
5.7	Fuel Tank Check Valve Fails Open	$3\ x10^{-3}$	The fuel tank solenoid valve acts as a check valve when deenergized. CCPS gives a PFD of $2.8x10^{-3}$ for no change in position of a solenoid valve. This was rounded to $3x10^{-3}$.
5.8	In Service Hose Rupture	$2x10^{-6}$	See 3.5. $2x10^{-4}$/yr. divided by 100 uses per year.
5.9	Refueling Completed	0.4	Assuming the cycle from start of refueling to next use of vehicle is 10 hrs and refueling a half full tank take about 6 hrs., the probability the HRA is connected to the vehicle with a full tank is about 40%.
5.10	User Drives Away Connected	$3x10^{-3}$	See 3.12
5.11	Breakaway Fails to Open	$1.8x10^{-2}$	See 3.13
5.12	No Vehicle Side Shutoff	1	The breakaway coupling does not have a poppet shutoff on the vehicle side so that the nozzle can be removed from the receptacle.
5.13	Vehicle Doesn't Exit Garage	0.5	The probability that the driver realizes the hose was not disconnected prior to driving off and stops the vehicle before exiting the garage is estimated at 50%.
5.14	Detection of LEL activates cooling fan	0.988	This values is the sum of all release outcomes with ventilation shown in intermediate event tree IET-3
6.1-6.13	All statistics are the same as the corresponding values for 5.1 – 5.13		
6.14	Detection or fan malfunction causes cooling failure	0.012	This values is the sum of all release outcomes without ventilation shown in intermediate event tree IET-3
7.1	Refueling Vehicle	100/yr	See 1.5
7.2	PLS-H Stops Compressor	0.999	1 minus $1x10^{-3}$

Table A-1: Frequency and Probability Data Summary (continued)

Item	Event	Statistic	Source/Discussion
7.3	Receptacle Check Valve Sticks Open	$1.3x10^{-4}$	See 5.3
7.4	End Cap Pressure Relief Valve Open	~1	1 minus 10^{-3}
7.5	FSD Doesn't Re-energize to Stop Flow	$3.8x10^{-3}$	See 5.5
7.6	Fuel Tank Check Valve Fails Open	$5x10^{-4}$	See 5.13
8.1	Refueling Vehicle	100/yr	See 1.5
8.2	Partial Closure of Receptacle Check Valve	$3.8x10^{-4}$	See 3.10
8.3	FSD Blowdown Valve Fails to Open	$3.8x10^{-4}$	See 5.5
8.4	Fuel Tank Check Valve Leaks	$3x10^{-3}$	See 5.7
8.5	End Cap Pressure Relief Valve Opens	0.999	Given that the end cap is overpressured, the probability of the PRV opening is 0.9995
9.1	Attempts at Filling of Cylinder	$1x10^{-3}$	Order of magnitude estimate, assumes that 1 in 1000 owners will attempt to fill an LPG cylinder within one year after purchasing a HRA unit. This couple with 9.7 gives a frequency of $1x10^{-3}$/yr per unit sold.
9.2	Cylinder Ruptures	0.9	LPG cylinders are rated for 250 psig. Given that the HRA can develop over 3000 psig and that other precautions have been ignored, failure is very likely.
9.3	Fill Nozzle Remake Achieved	$1x10^{-2}$	We assume it will take some ingenuity to successfully modify or make an attachment to the probe connector to allow filling an LPG cylinder.
9.4	Pressure Indicator not Installed	0.9	We assume a 1 in 10 chance that a PI would be considered
9.5	Pressure Indicator (PI) not Observed	$2x10^{-2}$	Given a 0.1 probability that the PI is installed, we assume a 20% probability that in wouldn't be used.
9.6	HRA not Stopped in Time	0.5	Given that the pressure is not monitored, we give a 50% chance that the HRA is not stopped in time.
9.7	HRA Units Sold Annually	1/yr	See 9.1. Analysis at this level is per single unit
9.8	Inflatable Ruptures	0.9	Given that the user has ignored pressure considerations at this point, rupture of the inflatable is likely.
9.9	PLS-H Trip Failure	$1x10^{-3}$	See 3.1

Table A-1: Frequency and Probability Data Summary (continued)

Item	Event	Statistic	Source/Discussion
9.10	Fill Nozzle Remake Achieved	$5x10^{-2}$	We assume it will take somewhat less ingenuity to successfully modify or make an attachment to the probe connector to allow filling an inflatable.
9.11	Attempts Filling of Inflatable	$2x10^{-4}$	Order of magnitude estimate, assumes that 1 in 5000 owners will attempt to inflate a basketball or other object within one year after purchasing a HRA unit. This couple with 9.12 gives a frequency of $2x10^{-4}$/yr per unit sold.
9.12	HRA Units Sold	1/yr	See 9.7
9.13	HRA cooling fan running	0.988	See 5.14
10.1 – 10.12	All statistics are the same as the corresponding values for 9.1 – 9.12		
10.13	HRA cooling fan not running	0.012	See 6.14
11.1	Attempts Using Torch	$2x10^{-4}$	Order of magnitude estimate, assumes that 1 in 5000 owners will attempt to configure a torch within one year after purchasing a HRA unit. This couple with 11.5 gives a frequency of $2x10^{-4}$/yr per unit sold.
11.2	Fill Nozzle Remake Achieved	$5x10^{-2}$	We assume it will take some ingenuity to successfully modify or make an attachment to the probe connector to allow using as a torch.
11.3	Nozzle Adapter Valve Closed	$1x10^{-2}$	We estimate that there is a 1 in ten chance the valve is installed, but given that, the likelihood that it is closed is 10%
11.4	Adapter Not Pressure Rated	0.8	In making the adapter, the user uses standard Schedule 40 pipe. We assumed that most individuals attempting to make such a modification would have some basic knowledge of plumbing and pipe. So the likelihood of being able to withstand the pressure is less than 50%.
11.5	HRA Units Sold Annually	1/yr	See 9.1. Analysis at this level is per single unit
11.6	HRA cooling fan running	0.234	See 3.2
11.7	PLS-H Trip Failure	$1x10^{-3}$	See 3.1
12.1 – 12.5, 12.7	All statistics are the same as the corresponding values for 11.1 – 11.5, 11.7		
12.6	HRA running and cooling fan off	$5.88x10^{-7}$	See 4.2
13.1	End Cap Pressure Relief Valve Fails to Open	$5x10^{-4}$	See 5.4
13.2	Inlet Check Valve Sticks Open	$2x10^{-3}$	CCPS gives a PFD of $2.2x10^{-3}$ for check valve failure to check.

Table A-1: Frequency and Probability Data Summary (continued)

Item	Event	Statistic	Source/Discussion
13.3	Oversized Vehicle Enters Garage	0.2/yr	Assumes that an oversized (RV, Van) vehicle enters a garage once in 5 years.
13.4	Vehicle Impacts (poor location) HRA	$5x10^{-3}$	Given detailed installation instructions provided by HRA manufacture, Assumes less than 1% of the installations would be vulnerable to impact due to improper installation
13.5	Impact Stresses Breakaway to Release	0.1	Given there is impact, we have assumed that 1 out of 10 would cause sufficient movement of the flexible gas connector and stress the breakaway coupling to the point of release.
13.6	Gas supply not shutoff	0.7	The two potential locations for shutting of the gas are the quarter turn valve at the HRA and the main gas supply. Give that gas is escaping at the HRA, this valve may not be safely accessed. The alternative shutoff location will not be known or appreciated by a majoring of home owners.
13.7	Breakaway fails to open and flexhose fails	$1x10^{-2}$	See 3.13 Using the base failure rate of $2x10^{-2}$ and a 1 out of 2 chance of failing the flexhose, given the hose has been stretched to the coupling release point.
13.8	Breakaway poppet doesn't shut off gas flow	$5x10^{-4}$	See 3.14
14.1	Ignition	0.9	Highly likely once flammable mixture is present. It actually happened at one of the test facilities
14.2	Flammable mixture present.	0.1	This will depend on the amount of air ingress. The flammable limit range for methane is about 10% of the total concentration range from 0 to 100%.
14.3	Low pressure limiting system (PLS-L) fails	$1x10^{-3}$	Same as PLS-H failure, see 3.1
14.4	Gas supply valve partially closed	$1x10^{-2}$	Assuming isolation of HRA for annual maintenance and a human error rate of 0.01 gives a frequency of $1x10^{-2}$/yr. Since the error would be found within a year, the PFD is the failed state duration divided by the time between failures (1 yr/100 yrs) or 0.01
14.5	Line Blockage	$1x10^{-3}$	Not very likely for natural gas. Estimated at an order of magnitude less likely than valve left partially closed
14.6	Gas Regulator Failure	0.1	Most likely cause of restriction. Estimated at an order of magnitude more likely than valve left partially closed
14.7	Line Impacted	$2x10^{-2}$/yr	Estimated at less that once in the life of the dwelling
14.8	Line damaged	$5x10^{-2}$	Assumes 5% of non-vehicle impacts by would result in line damage

Table A-1: Frequency and Probability Data Summary (continued)

Item	Event	Statistic	Source/Discussion
14.9	Piping leak	$1x10^{-5}$/m-yr	See 1.13
14.10	Length	5m	Assumes about 15 ft. of supply piping exposed to impact
15.1	Attempts at Adding Buffer Tank	$1x10^{-3}$	See 9.1.
15.2	Buffer tank remake is achieved	$1x10^{-2}$	We assume it will take some ingenuity to successfully install a buffer tank and re-plumb the system.
15.3	PRV activates	0.9995	1 minus the probability of failure to open
15.4	Buffer tank not pressure rated	0.5	Pressure tanks that would be readily available to individuals include LP Gas and compressed air, which are not rated for 4,000 psi. We assumed that some individuals attempting to make such a modification would have some knowledge of pressure ratings. So the likelihood of being able to withstand the pressure is about than 50%.
15.5	Attempts at Adding Buffer Tank	$1x10^{-3}$	See 9.1.
15.6	HRA Units Sold	1/yr	See 9.7
15.7	PRV Fails to Open	$5x10^{-4}$	See 5.4
15.8	Buffer tank not pressure rated	0.5	See 15.4
15.9	Buffer tank remake is achieved	$1x10^{-2}$	See 15.2
15.10	HRA Units Sold	1/yr.	See 9.7
15.11	HRA cooling fan running	0.988	This values is the sum of all release outcomes with ventilation shown in intermediate event tree IET-3
15.12	HRA and cooling fan running	0.234	See 3.2 Assumes release of 0.67 cfm.
16.1-16.10	All statistics are the same as the corresponding valves for 15.1 – 15.10		
16.11	HRA cooling fan not running	0.012	This values is the sum of all release outcomes without ventilation shown in intermediate event tree IET-3
16.12	HRA running with cooling fan off	$3.96x10^{-7}$	See 4.2 Assumes release of 0.67 cfm.
17.1	Many Hose Units Added	$1x10^{-3}$	Assumes that 1 in 1000 owners will attempt to add one hose segment within one year of purchasing a HRA unit.
17.2	HRA cooling fan running	0.988	See 15.11

Table A-1: Frequency and Probability Data Summary (continued)

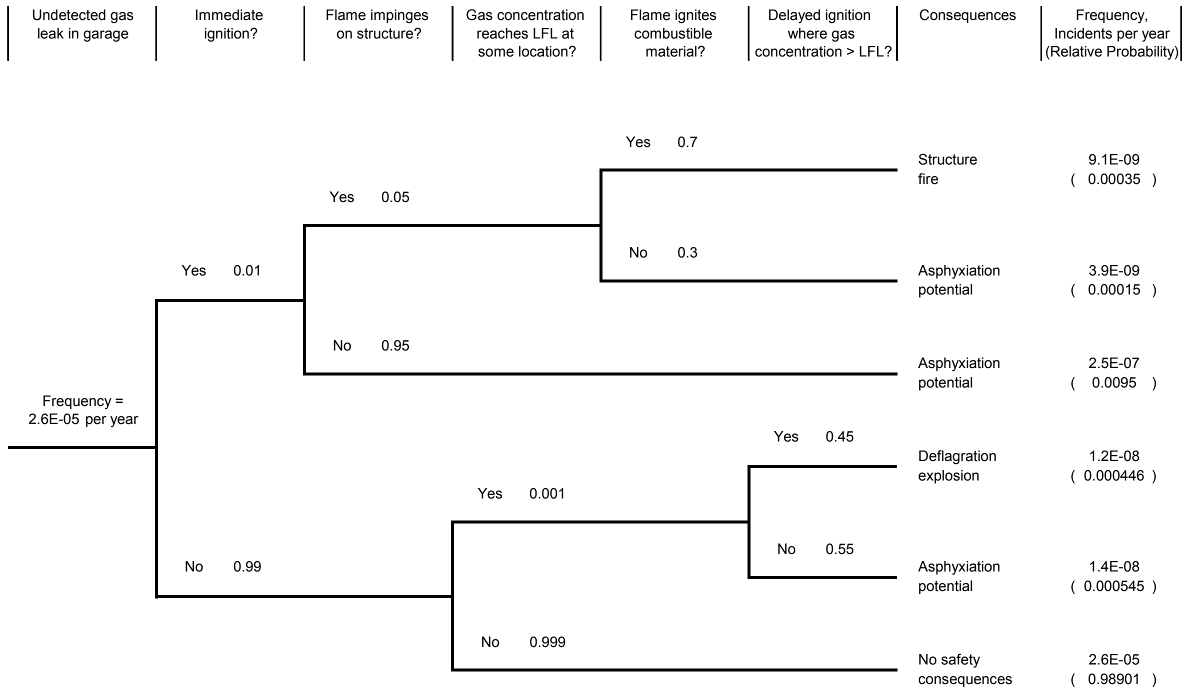
Item	Event	Statistic	Source/Discussion
17.3	Sufficient Pressure to Rupture End Cap	0.9	It is assumed that given many hoses were added, the probability of generating sufficient pressure is high.
17.4	HRA Units Sold	1/yr	See 9.7
17.5	FSD Doesn't Re-energize	$3.8x10^{-3}$	See 5.5
17.6	PRV Fails to Open	$5x10^{-4}$	See 5.4
18.1-18.6 ex 18.2	All statistics are the same as the corresponding valves for 17.1 – 17.6		
18.2	HRA cooling fan not running	0.012	This values is the sum of all release outcomes without ventilation shown in intermediate event tree IET-3
Probabilities for Event Trees IET-1, 2, 3			
	LEL not detected – small continuous discharge	0.99	Estimated probability of undetected gas discharges up to 0.22 cfm based on results of CFD calculations.
	LEL not detected – large continuous discharge	0.1	Estimated probability of undetected gas discharges of 0.67 cfm and greater based on results of CFD calculations.
	LEL Detection Shutdown Fails	0.15	Failure rate for gas detectors is about 1 in 3 years. FuelMaker is considering a change-out kit for gas detectors that would be replaced annually. We have used once/year replacement, which gives 0.33/yr x 0.5yr (FTD).
	Fan Failure on Demand or Vent Blocked	2.5×10^{-3}	CCPS gives a median value for PFD of 2×10^{-4} motor drive fan with a high of 0.001. WASH 1400 give a similar value to motor drive pump of 3×10^{-4}, with a high of 0.0008. A value of 5×10^{-4} was used for a commercial grade motor. The frequency of vent line blockage was estimated at 1 in 5 yrs. Give about 500 demands during that period, the PFD is 0.002. Combining the PFDs results in the value shown.
	Air Flow Shutdown Failure	1×10^{-3}	Lees gives a mean value for PFD of a limit switch of 3×10^{-4}, and WASH 1400 gives a similar value for a pressure switch. A value of 1×10^{-3} was selected because the data are not for a flow switch and to allow for other trip components.

References

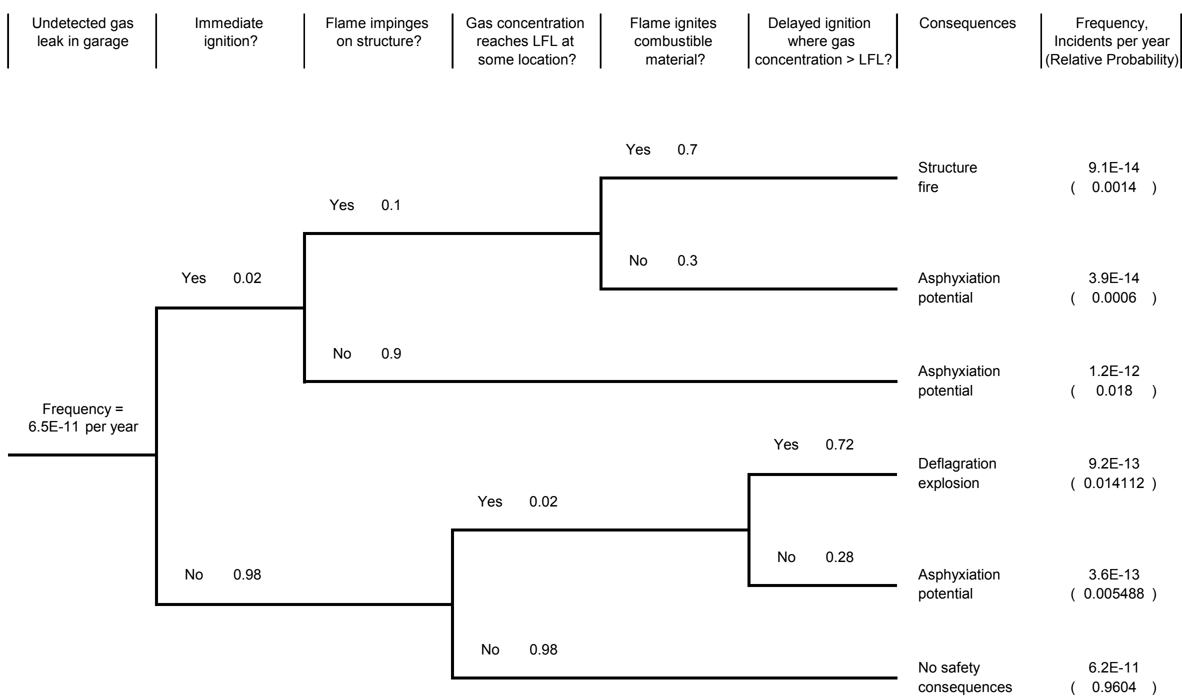
1. WASH1400 (NUREG-75/014), (1975)
2. Guidelines for Process Equipment Reliability Data, CCPS, AIChE, (1989)
3. Reliability and Maintenance in Perspective, D.J. Smith, 3rd.ed. (1988)
4. Risk Analysis Report to the Rijnmond Public Authority, 1981
5. Based on CNG user survey under NREL contract
6. Hansen, J., et al, *Comparative Risk Analysis of Processing Plant*, 3rd. Int. Loss Prev. Symp. (Basle), p.6-455 (1980).
7. Lees, F.P., Loss Prevention in the Process Industries, Vol. 3, Appendix A14 (1996)

Appendix B. Event Trees and Event Tree Probabilities Table

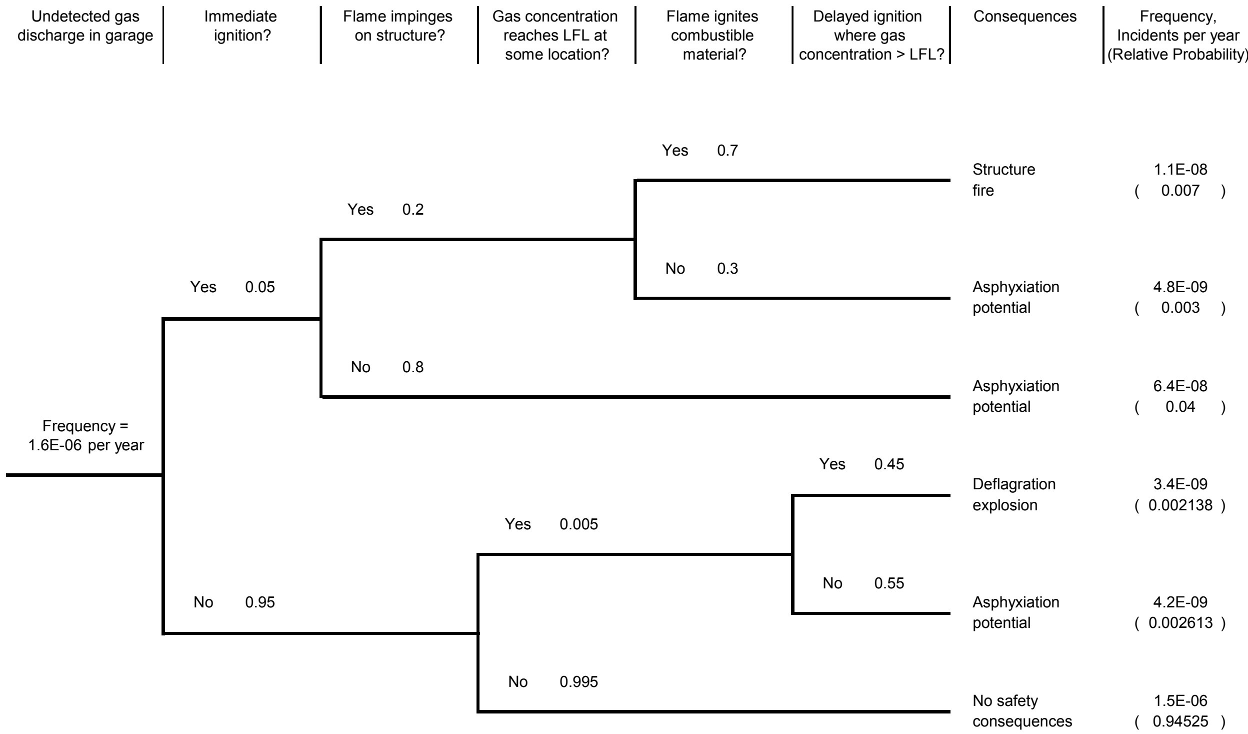
This appendix contains event trees ET-1 through ET-18. This appendix also contains a table (Table B-1) that summarizes the rationale for all the event tree “or” gate probability estimates.



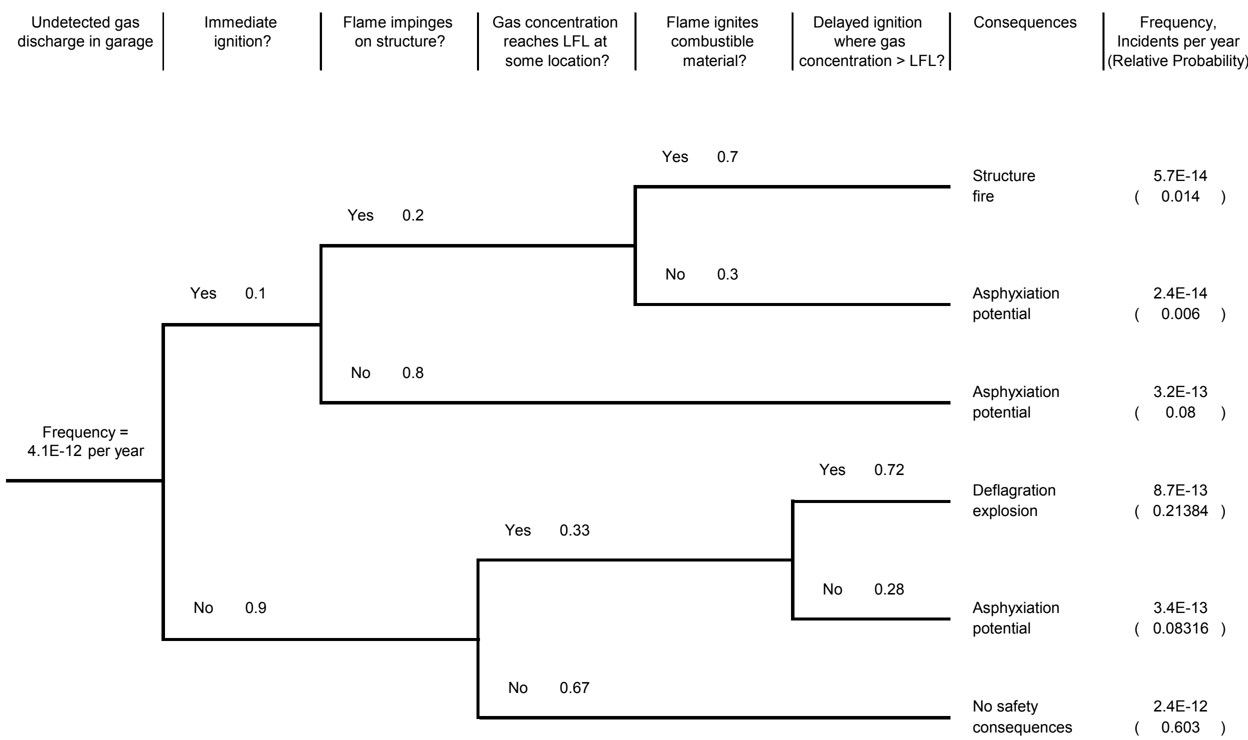
ET-1 Leak with ventilation



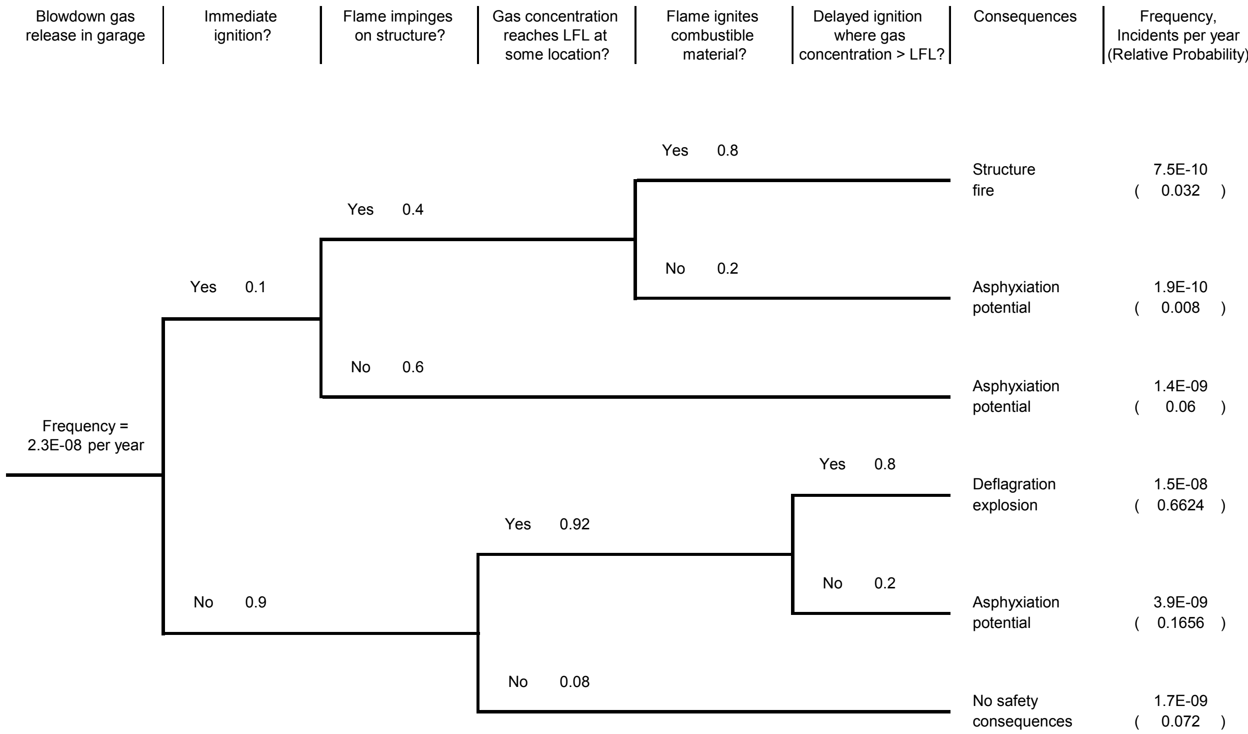
ET-2 Leak without ventilation



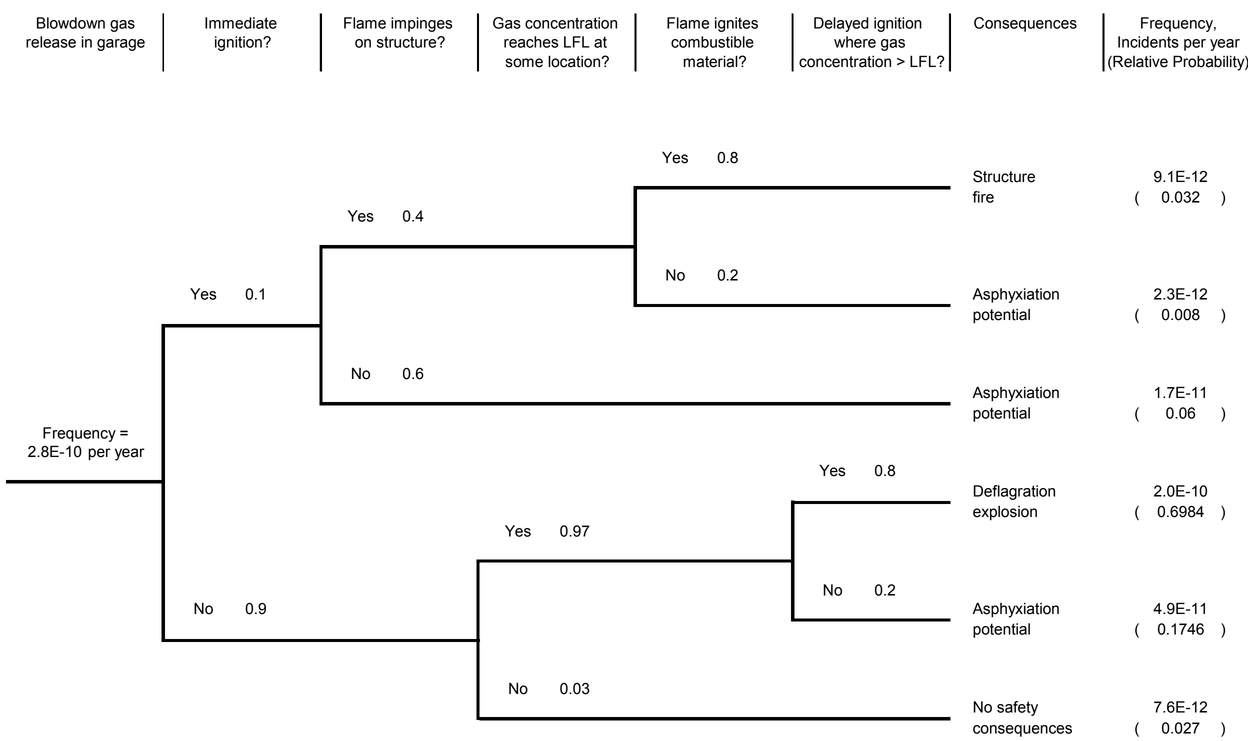
ET-3 Discharge with ventilation



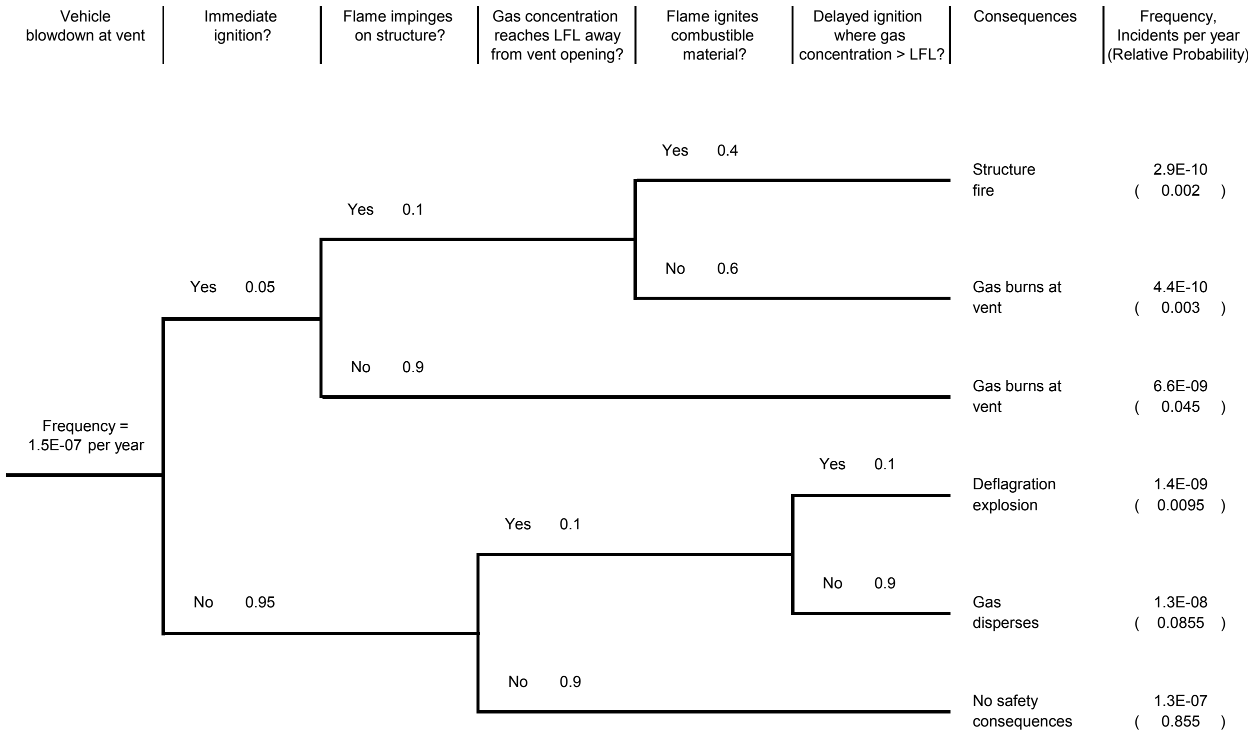
ET-4 Discharge without ventilation



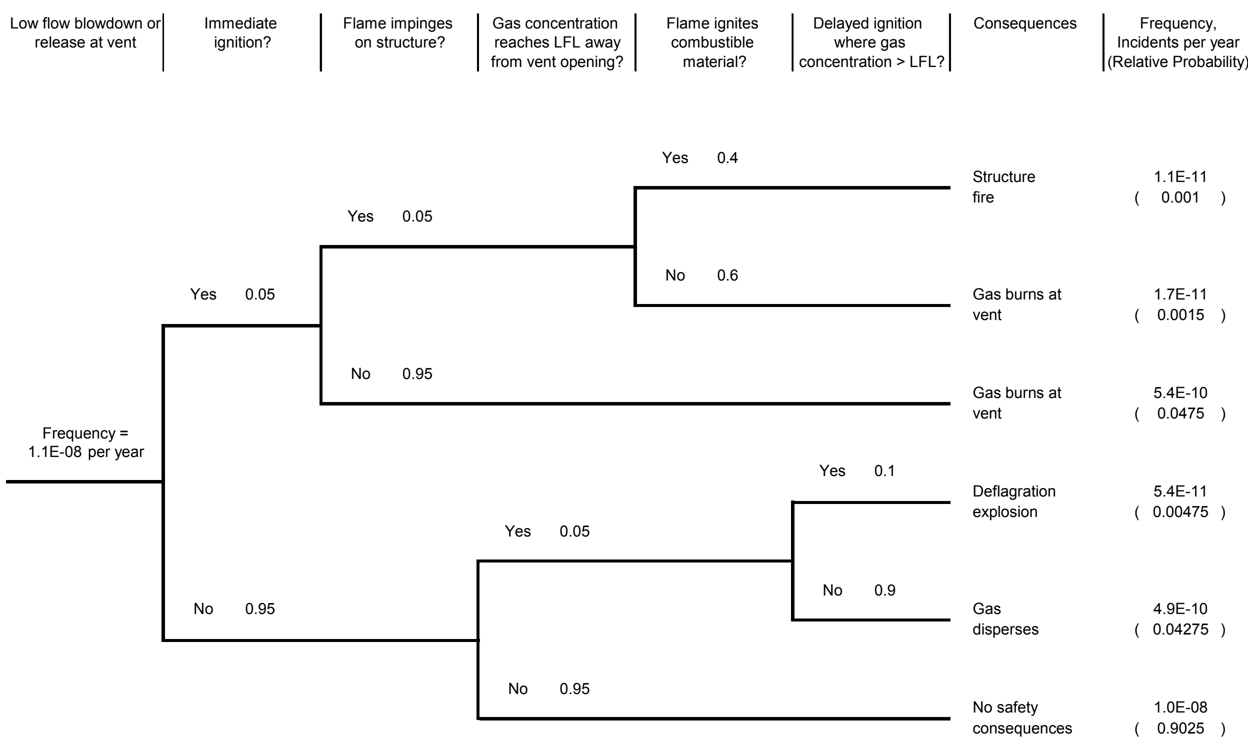
ET-5 Blowdown in with ventilation



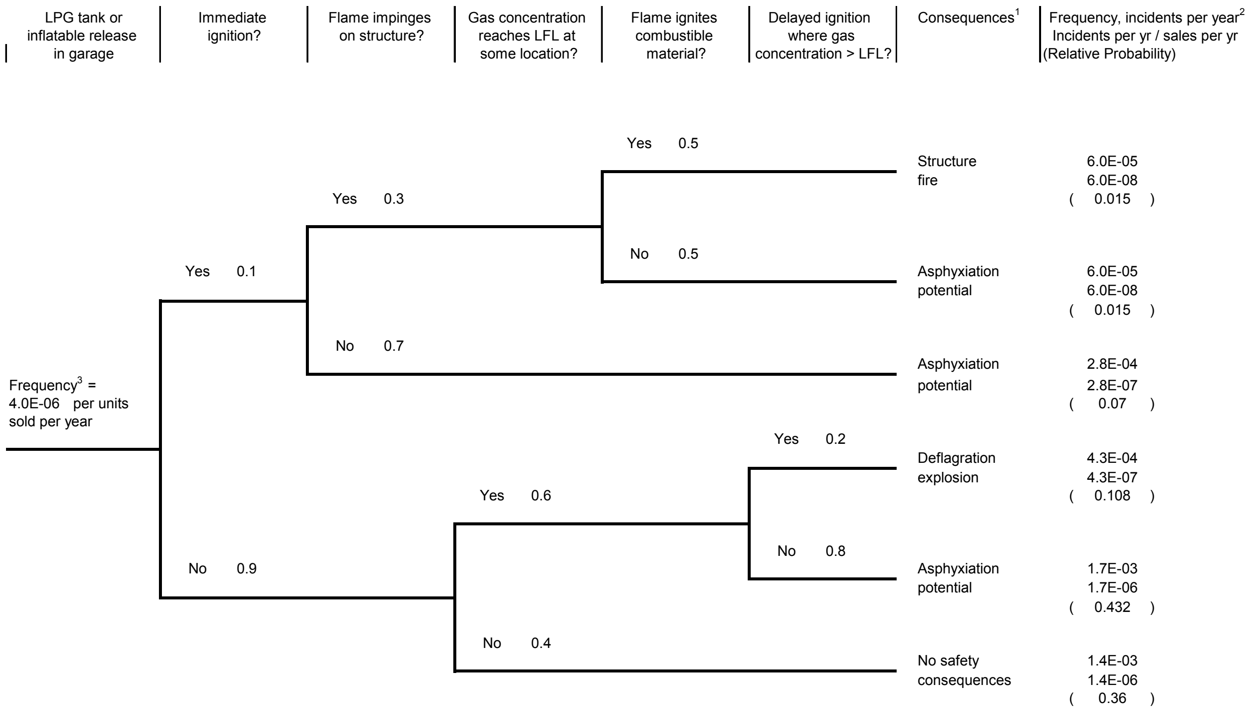
ET-6 Blowdown in without ventilation



ET-7 Blowdown outside

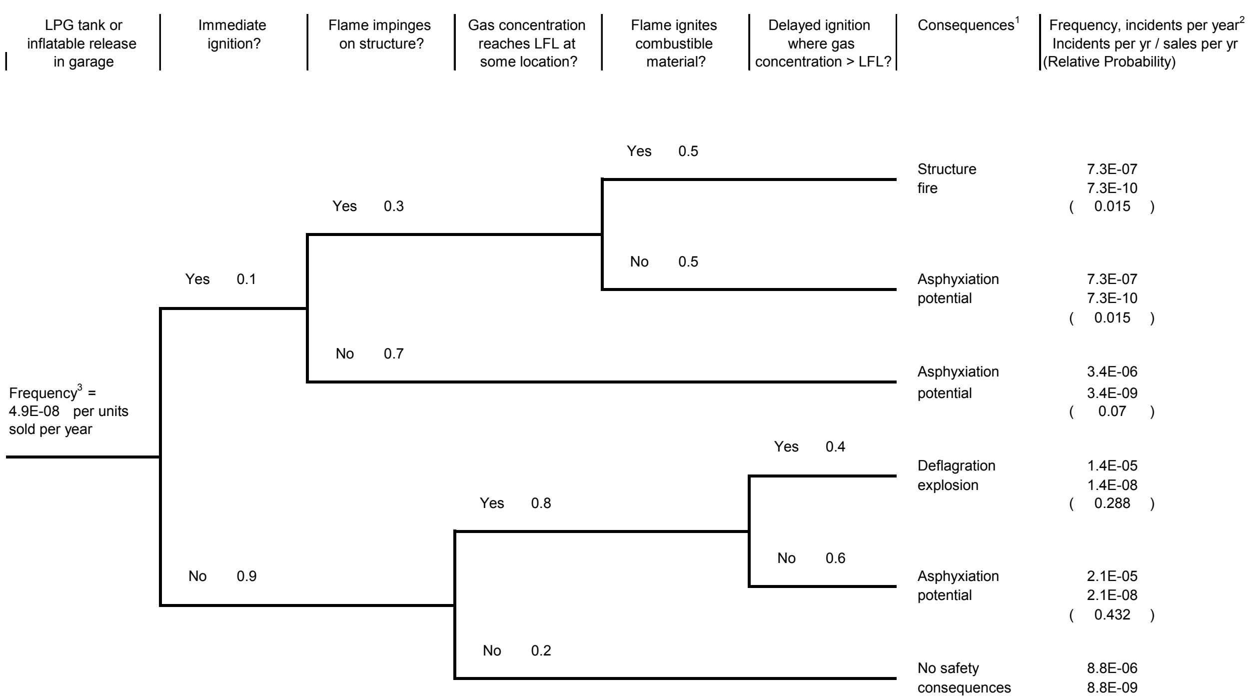


ET-8 Vent outside



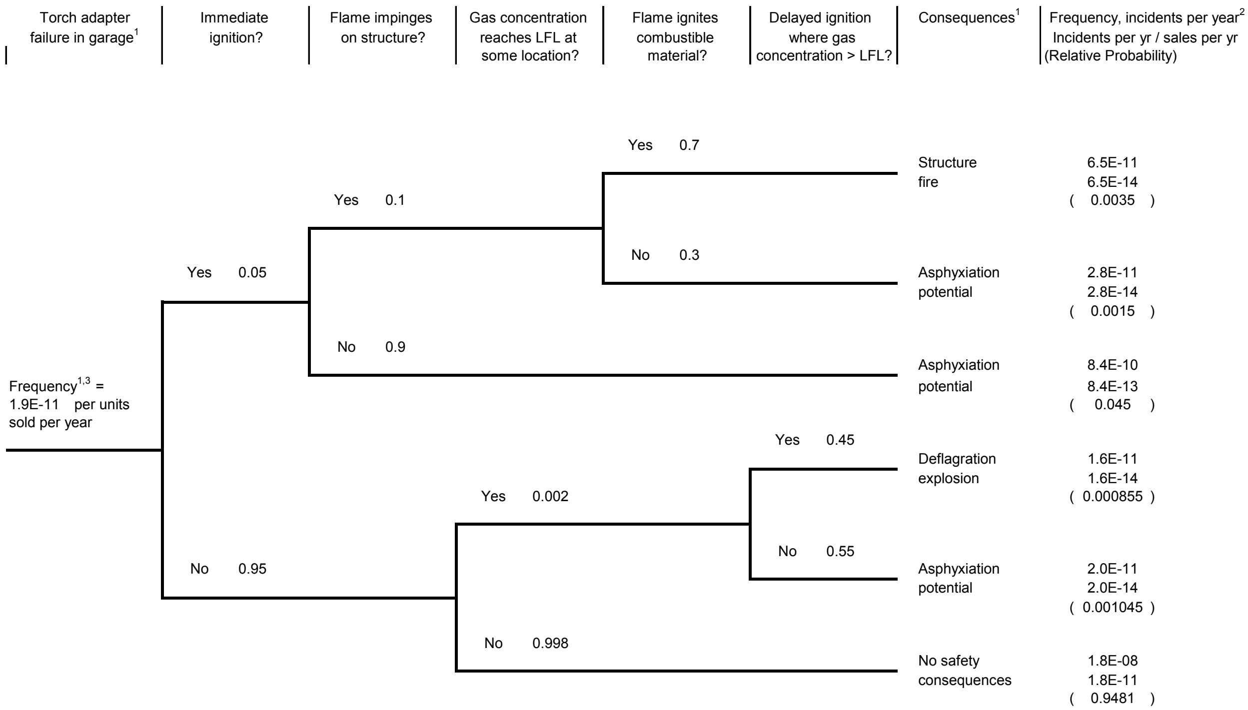
[1] Note that impact injury is also possible, even though there is no fire or explosion (e.g., person struct by rupturing LPG tank debris). This frequency was not estimated.
[2] Assumed HRA annual sales and installations = 1000 units sold per year.
[3] Note that these frequencies refer to the first year following installation.

ET-9 LPG and inflat with vent



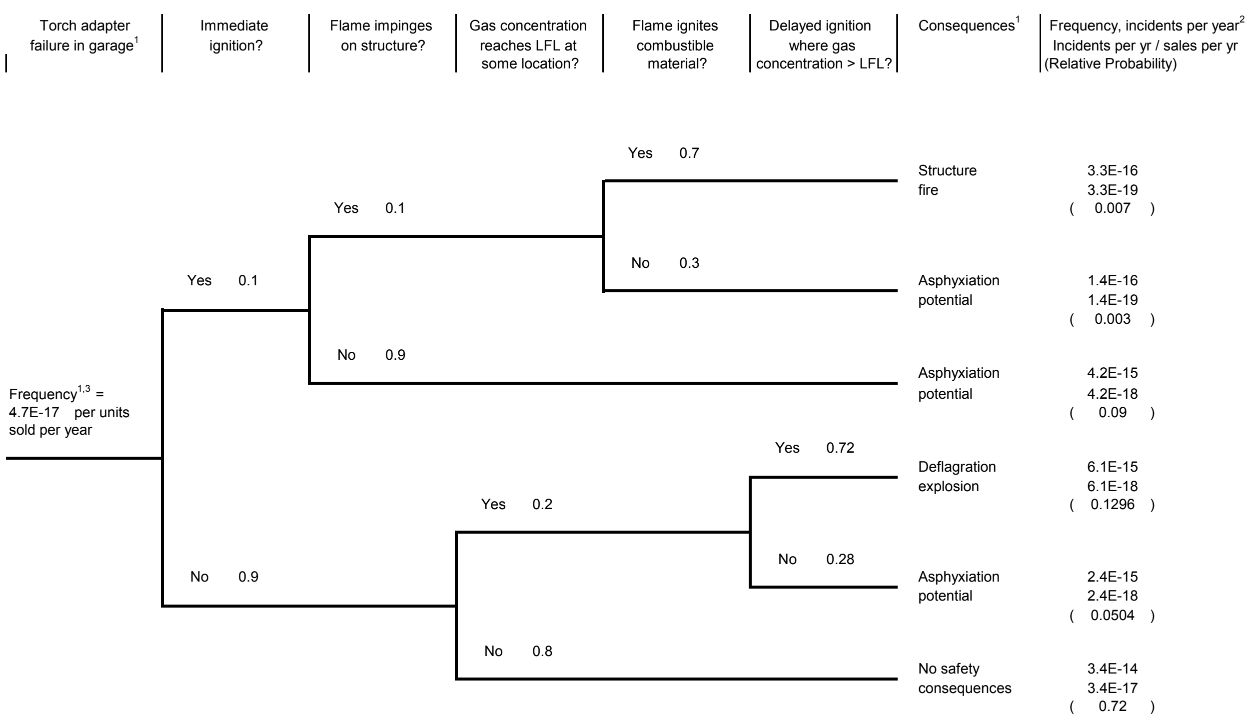
[1] Note that impact injury is also possible, even though there is no fire or explosion (e.g., person struct by rupturing LPG tank debris). This frequency was not estimated.
[2] Assumed HRA annual sales and installations = 1000 units sold per year.
[3] Note that these frequencies refer to the first year following installation.

ET-10 LPG and inflat without vent



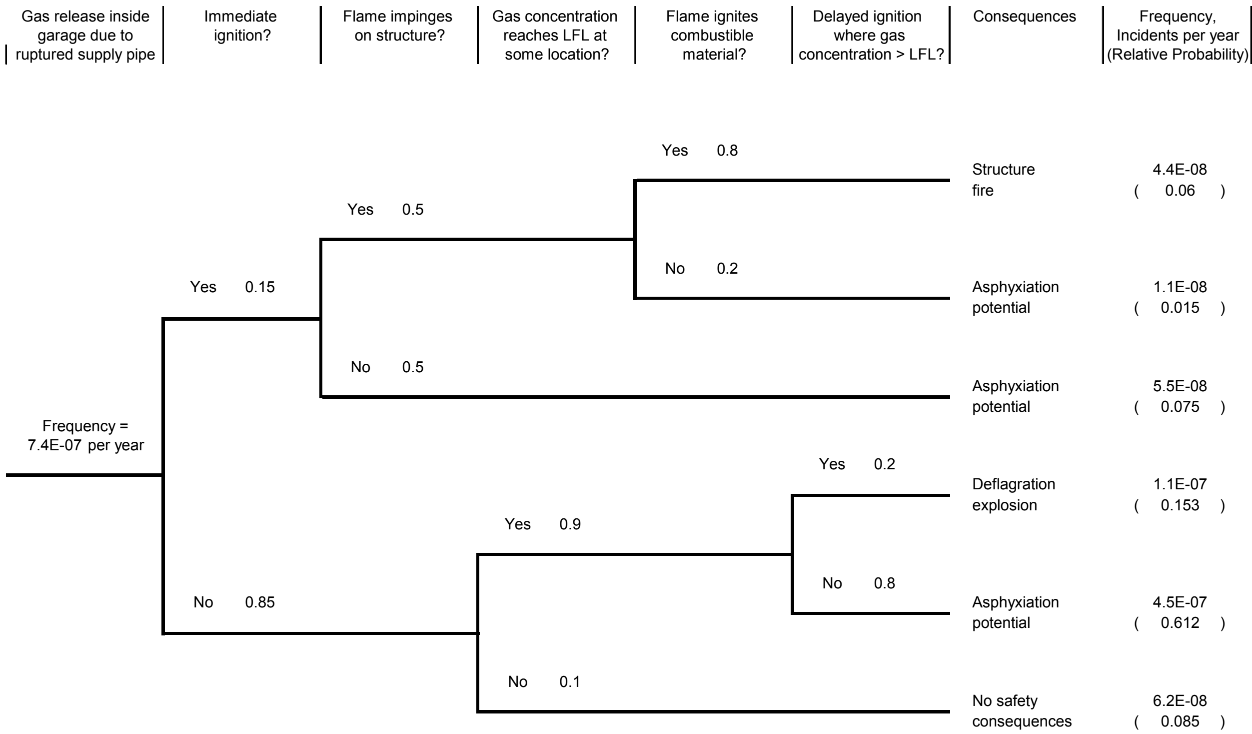
[1] These events correspond to failure of a torch adapter and do not consider accidents associated with successful fitting of an adapter and use of a torch.
It is asssumed that relevant HRA safeguards have been overridden as part of the work to fit the torch.
[2] Assumed HRA annual sales and installations = 1000 units sold per year.
[3] Note that these frequencies refer to the first year following installation.

ET-11 Torch fail with vent

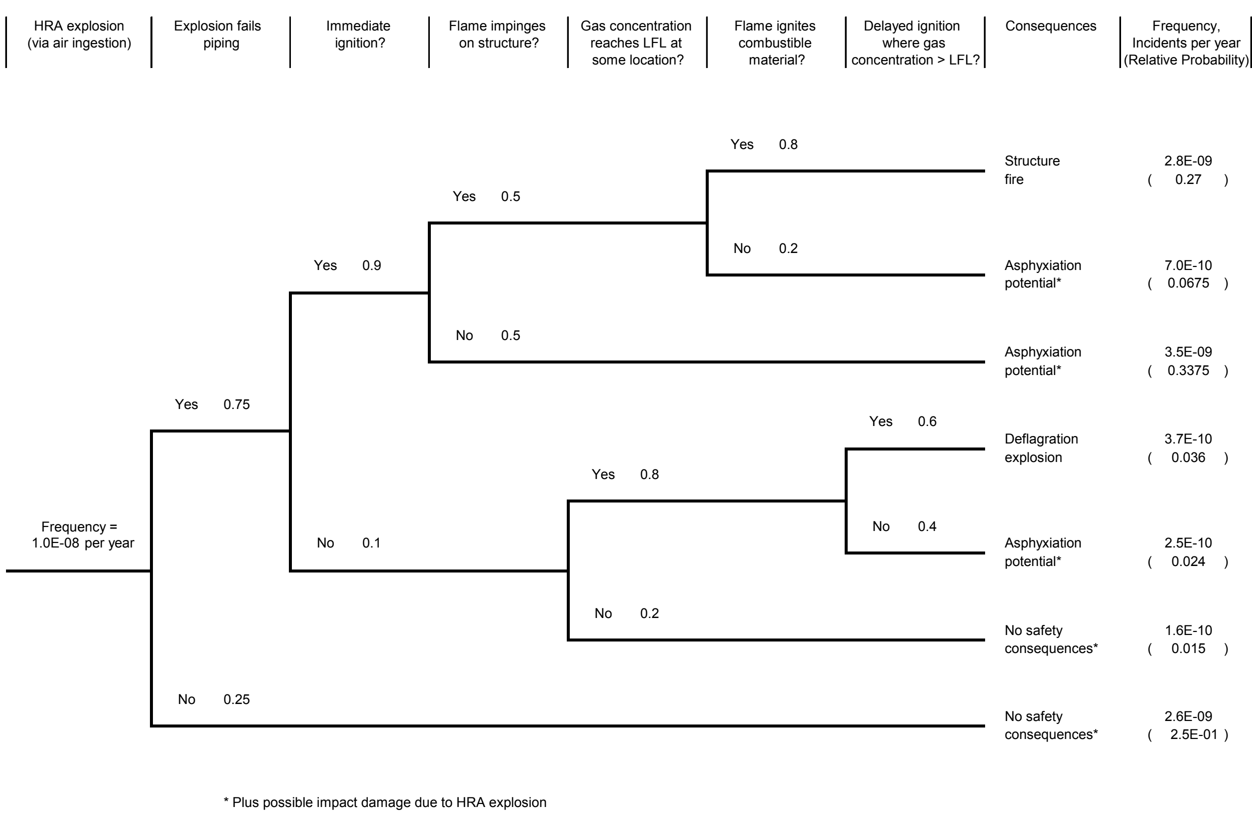


[1] These events correspond to failure of a torch adapter and do not consider accidents associated with successful fitting of an adapter and use of a torch.
It is asssumed that relevant HRA safeguards have been overridden as part of the work to fit the torch.
[2] Assumed HRA annual sales and installations = 1000 units sold per year.
[3] Note that these frequencies refer to the first year following installation.

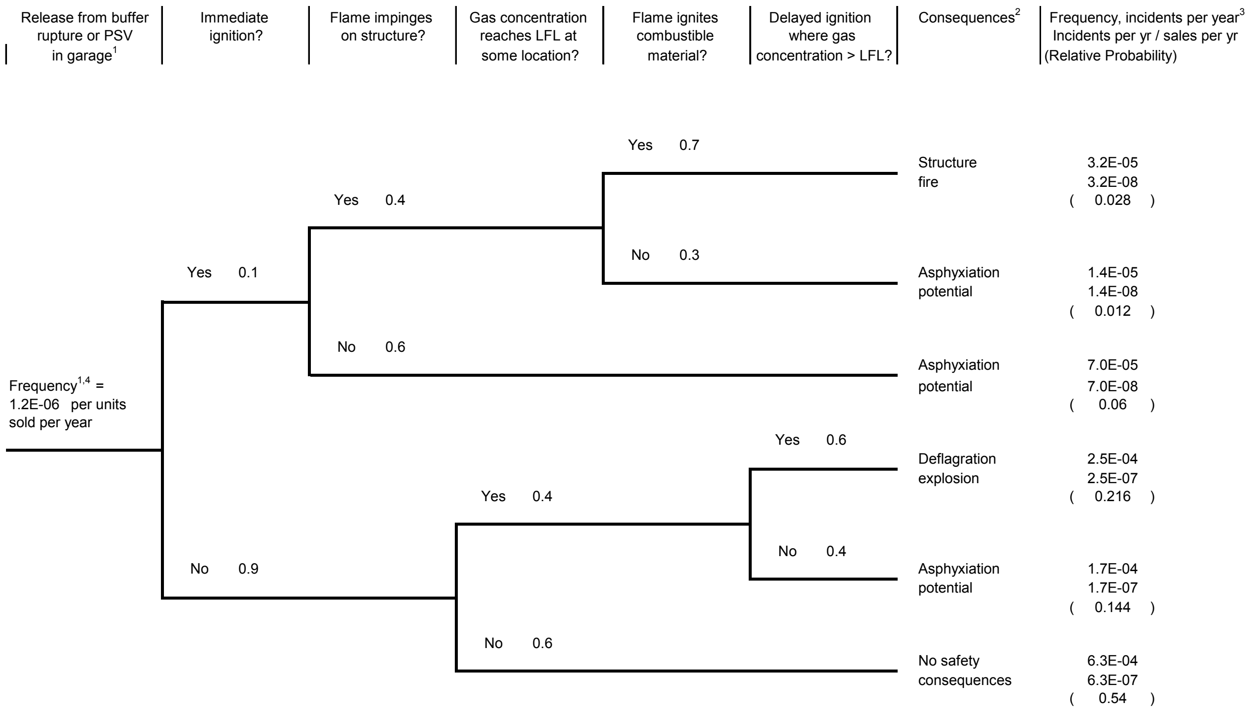
ET-12 Torch fail without vent



ET-13 Supply pipe fail

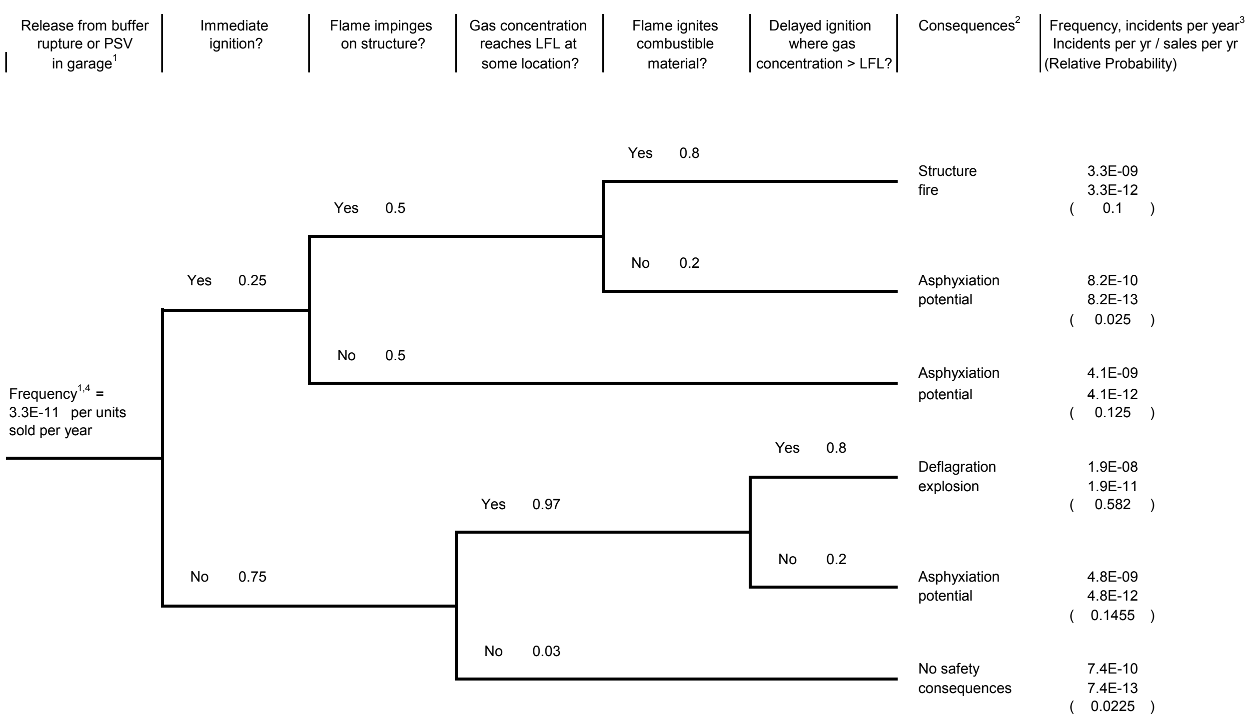


ET-14 HFA Expl.



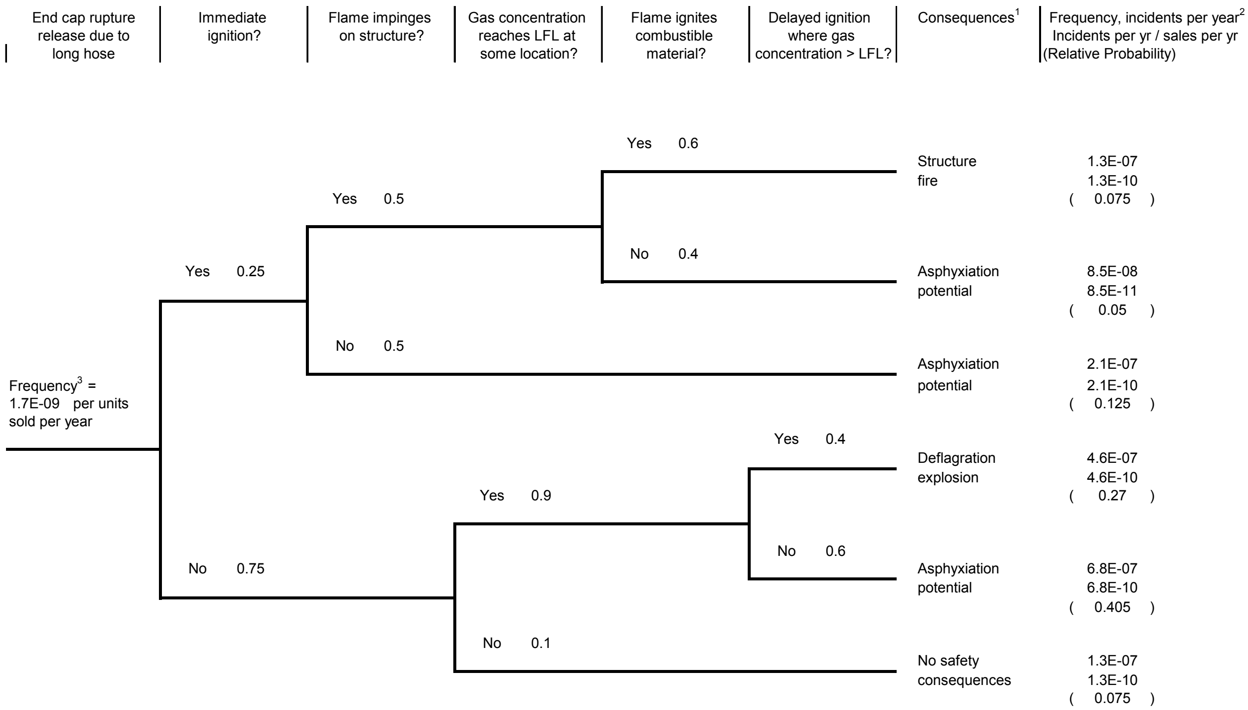
[1] These events correspond to rupture of or PSV venting from a buffer pressure vessel fitted to the HRA and not other accidents associated with use of an HRA with a buffer.
[2] Plus possible impact damage caused by rupturing buffer tank.
[3] Assumed HRA annual sales and installations = 1000 units sold per year.
[4] Note that these frequencies refer to the first year following installation.

ET-15 Buffer fail with vent



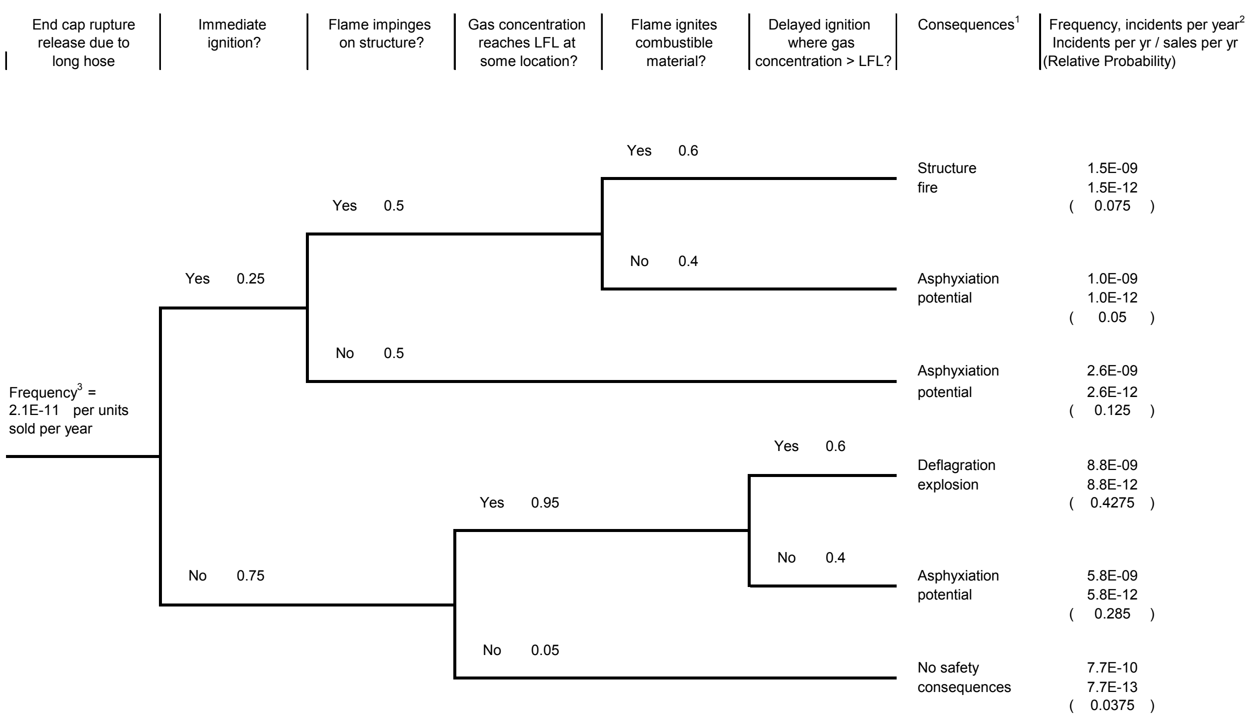
[1] These events correspond to rupture of or PSV venting from a buffer pressure vessel fitted to the HRA and not other accidents associated with use of an HRA with a buffer.
[2] Plus possible impact damage caused by rupturing buffer tank.
[3] Assumed HRA annual sales and installations = 1000 units sold per year.
[4] Note that these frequencies refer to the first year following installation.

ET-16 Buffer fail without vent



[1] Note that impact injury or damage is also possible, even though there is no fire or explosion (e.g., person struct by rupturing end cap debris). This frequency was not estimated. Also, an over-pressured end cap would normally vent outside through the PRV, but this scenario is very unlikely to cause a fire or deflagration.
[2] Assumed HRA annual sales and installations = 1000 units sold per year.
[3] Note that these frequencies refer to the first year following installation.

ET-17 Long hose EC rel. with vent



[1] Note that impact injury or damage is also possible, even though there is no fire or explosion (e.g., person struct by rupturing end cap debris). This frequency was not estimated. Also, an over-pressured end cap would normally vent outside through the PRV, but this scenario is very unlikely to cause a fire or deflagration.
[2] Assumed HRA annual sales and installations = 1000 units sold per year.
[3] Note that these frequencies refer to the first year following installation.

ET-18 Long hose EC rel. without vent

Table B-1. Event tree probability rationale

Event Tree	Gate	Probabilities	Rationale and Data Source
ET-1, Continuous gas leak (≤0.22 scfm) in garage, with ventilation (~80 scfm) plus infiltration	Immediate ignition?	Yes: 0.01 No: 0.99	Extremely unlikely because flammable plume from 0.22 scfm leak will be small particularly if 80 scfm air flow is near (e.g., if leak is inside HRA). However, the leak may persist for a long time and an ignition source might conceivably come into contact with it (e.g., someone smoking while trying to determine the source of the gas smell).
	Flame impinges on structure?	Yes: 0.05 No: 0.95	A flame supported by a gas flow of 0.22 scfm or less will be small (i.e., it will not extend far beyond the leak) and it may be extinguished by the 80 scfm air flow.. Depending on the leak location and angle, the flame could impinge on the garage structure, but the probability is low.
	Flame ignites combustible material?	Yes: 0.7 No: 0.3	Garage survey statistics indicate that approximately 88% of garages have wood framing and approximately 24% are all wood. This small flame could impinge on the garage structure in an area that is not wood or otherwise flammable.
	Gas concentration reaches LFL at some location?	Yes: 0.001 No: 0.999	Note that a median-size garage with 80 scfm ventilation has ACH ~ 1.1. The average gas concentration will reach 90% of its asymptotic level of 0.28% (about 6% of the LFL) in about 2 hours. The gas will be well mixed at locations away from the leak, which is consistent with CFD results. It is highly unlikely that there will be any concentration gradients adequate to result in the build up of LFL regions anywhere in the garage.
	Delayed ignition where gas concentration >LFL?	Yes: 0.45 No: 0.55	The garage survey statistics indicate that approximately 90% of garages have ignition sources such as electric garage door openers or gas water heaters. As noted above, the possibility of LFL regions is quite remote, and such regions will probably be small if they do exist. Therefore, assume that there is a 50% chance that that such an LFL region would be collocated with an ignition source if one exists in the garage: 0.9 x 0.5 = 0.45
ET-2, Continuous gas leak (≤0.22 scfm) in garage, with infiltration but no ventilation	Immediate ignition?	Yes: 0.02 No: 0.98	Extremely unlikely because flammable plume will be small, but more likely than ET-1 which had 80 scfm ventilation. This small leak may persist for a long time and an ignition source might conceivably come into contact with it (e.g., someone smoking while trying to determine the source of the gas smell). Assume that immediate ignition is twice as likely as for ET-1.
	Flame impinges on structure?	Yes: 0.1 No: 0.9	A flame supported by a gas flow of 0.22 scfm or less will be small, i.e., it will not extend far beyond the leak. This flame is less likely to be extinguished by air flow than ET-1. Depending on the leak location and angle, the flame could impinge on the garage structure, but the probability is low.
	Flame ignites combustible material?	Yes: 0.7 No: 0.3	Garage survey statistics indicate that approximately 88% of garages have wood framing and approximately 24% are all wood. This small flame could impinge on the garage structure in an area that is not wood or otherwise flammable.
	Gas concentration reaches LFL at some location?	Yes: 0.02 No: 0.98	The gas accumulation will take a long time (over 4 hours for 90% of asymptotic concentration for median ACH). Therefore, the gas will be well mixed at locations away from the leak, which is consistent with CFD results, and so it is assumed that the gas concentration can be as much as 20% greater than the average concentration at these locations. These locations would then reach LFL when the average concentration was 5%/1.2 = 4.2%. The ACH that provides this concentration for a median-size garage is approximately 0.074 air changes per hour. The garage survey statistics indicate that only about 8% of garages have ACH this low. Moreover, it would take an ACH = 0.074/hour garage approximately 30 hours to reach 90% of its steady average gas concentration. This would happen only if someone refueled their car for 30 hours or longer (e.g., forgot about it). We assume that this might happen 20% of the time (e.g., refuel each evening and drive each morning except Saturday). The yes probability is then 0.08 x 0.2 = 0.016 (which is rounded to 0.02).

Table B-1. Event tree probability rationale (continued)

Event Tree	Gate	Probabilities	Rationale and Data Source
	Delayed ignition where gas concentration >LFL?	Yes: 0.72 No: 0.28	The garage survey statistics indicate that approximately 90% of garages have ignition sources such as electric garage door openers or gas water heaters. Assume that there is an 80% chance that these ignition sources have adequate energy and are located where gas concentration >LFL.
ET-3, Continuous gas discharge (~0.67 scfm) in garage, with ventilation (~80 scfm) plus infiltration	Immediate Ignition?	Yes: 0.05 No: 0.95	It is very unlikely that an ignition source will be in the immediate vicinity of a full discharge gas release from HRA, hose, or nozzle. Ignition likelihood is decreased if 80 scfm air flow is near discharge. However, the discharge may persist for a long time and an ignition source might conceivably come into contact with it (e.g., someone smoking while trying to determine the source of the gas smell).
	Flame impinges on structure?	Yes: 0.2 No: 0.8	A 0.67 scfm release would not produce a long flame if ignited. Depending on the location and angle of the discharge, it could impinge on the garage structure, but the probability is not high.
	Flame ignites combustible material?	Yes: 0.7 No: 0.3	Garage survey statistics indicate that approximately 88% of garages have wood framing and approximately 24% are all wood. This relatively small flame could impinge on the garage structure in an area that is not wood or otherwise flammable.
	Gas concentration reaches LFL in some location?	Yes: 0.005 No: 0.995	Note that a median-size garage with 80 scfm ventilation has ACH ~ 1.1. The average gas concentration will reach 90% of its asymptotic level of 0.84% (about 17% of the LFL) in about 2 hours. The gas will be well mixed at locations away from the leak, which is consistent with CFD results. It is unlikely that there will be any concentration gradients adequate to result in the build up of LFL regions anywhere in the garage, but the probability will be greater than for ET-1.
	Delayed ignition where gas concentration >LFL?	Yes: 0.45 No: 0.55	The garage survey statistics indicate that approximately 90% of garages have ignition sources such as electric garage door openers or gas water heaters. As noted above, the possibility of LFL regions is quite remote, and such regions will probably be small if they do exist. Therefore, assume that there is a 50% chance that that such an LFL region would be collocated with an ignition source if one exists in the garage: 0.9 x 0.5 = 0.45
ET-4, Continuous gas discharge (~0.67 scfm) in garage, with infiltration but no ventilation	Immediate ignition?	Yes: 0.1 No: 0.9	Very unlikely because flammable plume will be small, but more likely than ET-3 which had 80 scfm ventilation. This discharge may persist for a long time and an ignition source might conceivably come into contact with it (e.g., someone smoking while trying to determine the source of the gas smell). Assume that immediate ignition is twice as likely as for ET-3.
	Flame impinges on structure?	Yes: 0.2 No: 0.8	A 0.67 scfm release would not produce a long flame if ignited. Depending on the location and angle of the discharge, it could impinge on the garage structure, but the probability is not high.
	Flame ignites combustible material?	Yes: 0.7 No: 0.3	Garage survey statistics indicate that approximately 88% of garages have wood framing and approximately 24% are all wood. This relatively small flame could impinge on the garage structure in an area that is not wood or otherwise flammable.
	Gas concentration reaches LFL at some location?	Yes: 0.33 No: 0.67	The gas accumulation will take a long time (over 4 hours for 90% of asymptotic concentration for median ACH). Therefore, the gas will be well mixed at locations away from the leak, which is consistent with CFD results, and so it is assumed that the gas concentration can be as much as 50% greater than the average concentration at these locations. These locations would then reach LFL when the average concentration was 5%/1.5 = 3.3%. The ACH that provides this concentration for a median-size garage is approximately 0.28 air changes per hour. The garage survey statistics indicate that roughly 33% of garages have ACH $\leq$ 0.28 per hour.

Table B-1. Event tree probability rationale (continued)

Event Tree	Gate	Probabilities	Rationale and Data Source
	Delayed ignition where gas concentration >LFL?	Yes: 0.72 No: 0.28	The garage survey statistics indicate that approximately 90% of garages have ignition sources such as electric garage door openers or gas water heaters. Assume that there is an 80% chance that these ignition sources have adequate energy and are located where gas concentration >LFL.
ET-5, Blowdown gas release in garage, with ventilation (~80 scfm) plus infiltration	Immediate Ignition?	Yes: 0.1 No: 0.9	Although the flammable gas plume is larger than for a discharge or leak release, it doesn't persist nearly as long, and it is unlikely that ignition sources will be in this vicinity.
	Flame impinges on structure?	Yes: 0.4 No: 0.6	If ignited, a blowdown release inside the garage will produce a relatively long jet/flame, which would be more likely to impinge on the garage structure compared to a discharge or leak flame.
	Flame ignites combustible material?	Yes: 0.8 No: 0.2	Garage survey statistics indicate that approximately 88% of garages have wood framing and approximately 24% are all wood. This relatively large flame would be likely to impinge on an area that includes wood or other flammable material.
	Gas concentration reaches LFL in some location?	Yes: 0.92 No: 0.08	The garage ventilation will be at least 80 scfm, and greater due to additional natural infiltration (which depends on many factors). An array of garage gas concentration calculations was carried out for CNG vehicle blowdown situations considering the following: typical CNG vehicle fuel tank full and near empty, garage size variations (10, 50, 90 percentile), and 80 scfm ventilation. Gas concentration gradients were estimated from CFD results. The estimated probabilities are weighted averages of these results.
	Delayed ignition where gas concentration >LFL?	Yes: 0.8 No: 0.2	The garage survey statistics indicate that approximately 90% of garages have ignition sources such as electric garage door openers or gas water heaters. The LFL region will be more likely to be collocated with an ignition source than for the leak and discharge scenarios.
ET-6, Blowdown gas release in garage, with infiltration but no ventilation	Immediate ignition?	Yes: 0.1 No: 0.9	Although the flammable gas plume is larger than for a discharge or leak release, it doesn't persist nearly as long, and it is unlikely that ignition sources will be in this vicinity.
	Flame impinges on structure?	Yes: 0.4 No: 0.6	If ignited, a blowdown release inside the garage will produce a relatively long jet/flame, which would be more likely to impinge on the garage structure compared to a discharge or leak flame.
	Flame ignites combustible material?	Yes: 0.8 No: 0.2	Garage survey statistics indicate that approximately 88% of garages have wood framing and approximately 24% are all wood. This relatively large flame would be likely to impinge on an area that includes wood or other flammable material.
	Gas concentration reaches LFL in some location?	Yes: 0.97 No: 0.03	An array of CNG vehicle blowdown garage average gas concentration calculations was carried out, which considered the following: typical CNG vehicle fuel tank full and near empty, garage size variations (10, 50, 90 percentile), ACH variations (10, 50, 90 percentile), and approximate concentration gradients (estimated from CFD results). The estimated probabilities are a weighted average considering these variations.
	Delayed ignition where gas concentration >LFL?	Yes: 0.8 No: 0.2	The garage survey statistics indicate that approximately 90% of garages have ignition sources such as electric garage door openers or gas water heaters. The LFL region will be more likely to be collocated with an ignition source than for the leak and discharge scenarios.

Table B-1. Event tree probability rationale (continued)

Event Tree	Gate	Probabilities	Rationale and Data Source
ET-7, Blowdown gas release outside of garage	Immediate ignition?	Yes: 0.05 No: 0.95	Even though this flammable gas plume may be relatively large, it is highly unlikely that there will be an ignition source near the outside vent. Also, the duration of this blowdown can be 10 minutes or more (after which it is less than about 1 scfm).
	Flame impinges on structure?	Yes: 0.10 No: 0.90	Even though the flame from a blowdown gas release outside will be relatively large, it will have a limited duration, and it should not impinge on any structure unless the outside gas vent was incorrectly installed.
	Flame ignites combustible material?	Yes: 0.4 No: 0.6	Garage survey statistics indicate that approximately 24% of garages are all-wood construction (but roughly 88% have wood framing). However, many other home construction materials are also flammable, and it is not clear where the flame might impinge if it did impinge (e.g., siding, roofing, roof overhang). This probability estimate is a weighted composite of these factors.
	Gas concentration reaches LFL away from vent opening?	Yes: 0.1 No: 0.9	This could only be due to an improperly installed outside gas vent, e.g., so that it allowed gas to collect under roof overhang or to leak back inside the garage or other structure.
	Delayed ignition where gas concentration >LFL?	Yes: 0.1 No: 0.9	This would be quite unlikely for a properly installed vent, because very few “natural” ignition sources exist for this situation. A potential “unnatural” ignition source might be a person smoking while climbing a ladder to determine where the gas smell was coming from.
ET-8, Low flow blowdown or release at vent outside	Immediate ignition?	Yes: 0.05 No: 0.95	Relative to ET-7, this release will be lower flow rate but it will persist for much longer, so assume that the small probability of immediate ignition is approximately the same.
	Flame impinges on structure?	Yes: 0.05 No: 0.95	This could happen only if the outside gas vent was incorrectly installed. Since the flame would be smaller than for ET-7, the probability of structure impingement would also be less.
	Flame ignites combustible material?	Yes: 0.4 No: 0.6	If there is a flame and if it impinges on a structure, then the probability that it would ignite a combustible material is approximately the same as for ET-7.
	Gas concentration reaches LFL away from vent opening?	Yes: 0.05 No: 0.95	Relative to ET-7, the gas flow rate would be lower and there would be more time for mixing and leakage (from a trapped space) to keep the concentration less than LFL, even if the gas did accumulate (e.g., under roof overhang) or leak back into garage. Assume the yes probability is 50% of that for ET-7.
	Delayed ignition where gas concentration >LFL?	Yes: 0.1 No: 0.9	This would be quite unlikely for a properly installed vent, because very few “natural” ignition sources exist for this situation. A possible “unnatural” ignition source might be a person smoking while climbing ladder to determine where the gas smell is coming from.
ET-9, Release of gas from LPG tank or small inflatable in garage, with ventilation (~80 scfm) plus infiltration	Immediate ignition?	Yes: 0.1 No: 0.9	The quantity of gas released is variable from the order of less than 1 scf (small inflatable bursting) up to 50 scf (LPG cylinder bursting). The probability of immediate ignition depends on the flammable gas plume size (small to large), its duration (very short), and the likelihood of an ignition source (person may be smoking or working near appliance with electric arc or pilot light).
(Note that the input frequency to ET-9 refers to the first year after installation, and this must be multiplied by installations/year to provide consequences with the units of incidents/year. Note also that impact injury is also possible for this scenario, which is not included in this ET.)	Flame impinges on structure?	Yes: 0.3 No: 0.7	The flame may be small or large as noted above. Assume that there is a 60% chance that the inflation would be carried out near a garage wall and a 50% chance that, if so, the flame would reach the wall.
	Flame ignites combustible material?	Yes: 0.5 No: 0.5	Garage survey statistics indicate that roughly 88% of garages have wood framing and 24% are all wood. The flame may or may not impinge on a combustible portion of the garage structure and its duration may or may not be adequate to ignite it.

Table B-1. Event tree probability rationale (continued)

Event Tree	Gate	Probabilities	Rationale and Data Source
	Gas concentration reaches LFL at some location?	Yes: 0.6 No: 0.4	As noted above, up to roughly 50 scf of gas may be released in this scenario. This would produce an average gas concentration of approximately 2.5% (i.e., 50 % of LFL) in a small garage. However, there will be significant gas concentration gradients in this abrupt-release scenario, the 80 scfm ventilation will have a secondary effect, and so the probability of reaching LFL at some location is estimated to be greater than 50%.
	Delayed ignition where gas concentration >LFL?	Yes: 0.2 No: 0.8	Garage survey statistics indicate that roughly 90% of garages have ignition sources such as garage door openers or gas water heaters. Because the volume of gas >LFL is likely to be small and the time duration >LFL is short, the probability that a >LFL volume will be co-located with an adequate-energy ignition source is relatively small.
ET-10, Release of gas from LPG tank or small inflatable in garage, with infiltration but no ventilation (Note that the input frequency to ET-10 refers to the first year after installation, and this must be multiplied by installations/year to provide consequences with the units of incidents/year. Note also that impact injury is also possible for this scenario, which is not included in this ET.)	Immediate ignition?	Yes: 0.1 No: 0.9	The quantity of gas released is variable from the order of less than 1 scf (small inflatable bursting) up to 50 scf (LPG cylinder bursting). The probability of immediate ignition depends on the flammable gas plume size (small to large), its duration (very short), and the likelihood of an ignition source (person may be smoking or working near appliance with electric arc or pilot light).
	Flame impinges on structure?	Yes: 0.3 No: 0.7	The flame may be small or large as noted above. Assume that there is a 60% chance that the inflation would be carried out near a garage wall and a 50% chance that, if so, the flame would reach the wall.
	Flame ignites combustible material?	Yes: 0.5 No: 0.5	Garage survey statistics indicate that roughly 88% of garages have wood framing and 24% are all wood. The flame may or may not impinge on a combustible portion of the garage structure and its duration may or may not be adequate to ignite it.
	Gas concentration reaches LFL at some location?	Yes: 0.8 No: 0.2	The probability that the gas concentration reaches LFL at some location is similar to ET-9, except that it is greater because the ventilation fan is not operating (unless the garage door is open, there is only natural infiltration, which depends on many factors), and therefore the average gas concentration will not decrease as fast.
	Delayed ignition where gas concentration >LFL?	Yes: 0.4 No: 0.6	Because the gas concentration does not decrease as fast as ET-9, there is an increased probability that an LFL region may be collocated with an ignition source.
ET-11, Gas release due to failed attempt to use HRA to support a torch, with ventilation (~80 scfm) plus infiltration (Note that the input frequency to ET-11 refers to the first year after installation, and this must be multiplied by installations/ year to provide consequences with the units of incidents/year. Note also that this scenario does not include consideration of accidents associated with successful fitting of an adapter and use of a torch.)	Immediate ignition?	Yes: 0.05 No: 0.95	Likelihood of ignition of 0.67 scfm gas flow from failed adapter will be similar to ET-3.
	Flame impinges on structure?	Yes: 0.1 No: 0.9	It is assumed that a person trying to use a torch will be less likely to be near a garage wall than a person trying to inflate something (i.e., ET-9).
	Flame ignites combustible material?	Yes: 0.7 No: 0.3	If the flame does impinge on a structure, the likelihood that it will ignite a combustible material is similar to ET-3.
	Gas concentration reaches LFL at some location?	Yes: 0.002 No: 0.998	This is similar to ET-3, except that it is highly likely that a person would be present and would turn off the gas supply or HRA before gas accumulates to LFL levels.
	Delayed ignition where gas concentration >LFL?	Yes: 0.45 No: 0.55	If the gas does in fact accumulate to LFL in some locations, the likelihood of ignition is similar to ET-3.

Table B-1. Event tree probability rationale

Event Tree	Gate	Probabilities	Rationale and Data Source
ET-12, Gas release due to failed attempt to use HRA to support a torch, with infiltration but no ventilation (Note that the input frequency to ET-12 refers to the first year after installation, and this must be multiplied by installations/ year to provide consequences with the units of incidents/year. Note also that this scenario does not include consideration of accidents associated with successful fitting of an adapter and use of a torch.)	Immediate ignition?	Yes: 0.1 No: 0.9	Likelihood of ignition of 0.67 scfm gas flow from failed adapter will be similar to ET-4.
	Flame impinges on structure?	Yes: 0.1 No: 0.9	It is assumed that a person trying to use a torch will be less likely to be near a garage wall than a person trying to inflate something (i.e., ET-10).
	Flame ignites combustible material?	Yes: 0.7 No: 0.3	If the flame does impinge on a structure, the likelihood that it will ignite a combustible material is similar to ET-4.
	Gas concentration reaches LFL at some location?	Yes: 0.2 No: 0.8	This is similar to ET-4, except that it is likely that a person would be present and would turn off the gas supply or HRA before gas accumulates to LFL levels.
	Delayed ignition where gas concentration >LFL?	Yes: 0.72 No: 0.28	If the gas does in fact accumulate to LFL in some locations, the likelihood of ignition is similar to ET-4.
ET-13, Gas release from failed gas-supply pipe due to vehicle-HRA impact or gas overpressure	Immediate ignition?	Yes: 0.15 No: 0.85	Force of impact is assumed to be more likely to trigger ignition compared to ET-3 or ET-5.
	Flame impinges on structure?	Yes: 0.5 No: 0.5	Because flame is relatively large and located at the garage wall, the likelihood of it impinging on the wall is estimated to be 50%.
	Flame ignites combustible material?	Yes: 0.8 No: 0.2	Garage survey statistics indicate that approximately 88% of garages have wood framing and 24% are all wood. This relatively large flame is likely to impinge on an area that is wood or otherwise combustible.
	Gas concentration reaches LFL at some location?	Yes: 0.9 No: 0.1	The ruptured gas line discharge rate is estimated to be on the order of 5 scfm, or less if the line is crimped or squashed. The effective ACH is very high (estimated 10 to 100/hr magnitude range) because the garage door is assumed to be open, and it depends on many factors such as the wind speed and direction. Substantial gas concentration gradients will exist. Taking these factors into account, the probability of an LFL gas region is estimated to be 90%.
	Delayed ignition where gas concentration >LFL?	Yes: 0.2 No: 0.8	The garage survey statistics indicate that approximately 90% of garages have ignition sources such as electric garage door openers or gas water heaters. In this scenario, it is unlikely that a large fraction of the garage volume will reach LFL because the door is open. The duration of a flammable gas region (assuming the gas reaches LFL in some location) is judged to be relatively brief because a person is likely to be present, observe the problem and/or smell gas, and shut off the gas supply. Taking these factors into account, the probability that a >LFL volume will become co-located with an adequate-energy ignition source is estimated to be 20%.
ET-14, HRA deflagration (explosion) due to air ingestion	Explosion fails piping?	Yes: 0.75 No: 0.25	We assume that the explosive force of the HRA deflagration is more than 50% but less than 100% likely to sever the gas supply line.
	Immediate ignition?	Yes: 0.9 No: 0.1	Immediate ignition of gas flowing from a severed line is judged to be highly likely because the flammable region is large and the flame from the exploding HRA will provide an ignition source.
	Flame impinges on structure	Yes: 0.5 No: 0.5	This ignited broken gas supply line situation is similar to ET-13.
	Flame ignites combustible material?	Yes: 0.8 No: 0.2	This situation is similar to ET-13.

Table B-1. Event tree probability rationale (continued)

Event Tree	Gate	Probabilities	Rationale and Data Source
	Gas concentration reaches LFL at some location?	Yes: 0.8 No: 0.2	This depends on many factors including the nature of the gas line break (and resultant gas discharge rate), is the garage door open or shut, what is the infiltration rate if the door is shut, and did the exploding HRA increase the garage leakage area? Taking these uncertainties into account, the probability of an LFL region is eatimated to be more than 50% but less than 100%
	Delayed ignition where gas concentration >LFL?	Yes: 0.6 No: 0.4	This depends on how big the LFL region is, how it moves, and how long it persists. The upper limit is the probability that the garage contains an ignition source, approximately 90% (note that because this is delayed ignition, the exploding HRA is assumed to no longer be an ignition source).
ET-15, Buffer (pressure vessel) tank venting or rupture, with ventilation (~80 scfm) plus infiltration (Note that the input frequency to ET-15 refers to the first year after installation, and this must be multiplied by installations/year to provide consequences with the units of incidents/year. Note also that a rupturing buffer tank could cause impact damage, which is not included in this ET.)	Immediate ignition?	Yes: 0.1 No: 0.9	A PSV release is more likely than a tank rupture for this scenario, and this is assumed to be similar to ET-3. However, there is an additional small probability that the escaping gas will be immediately ignited by metal tearing if the tank does rupture or by electrical devices added to the system by the person who added the buffer. Therefore, immediate ignition is estimated to be twice as probable as ET-3.
	Flame impinges on structure?	Yes: 0.4 No: 0.6	Because a PSV release is more likely than a tank rupture for this scenario, this situation is similar to ET-3 except that the buffer tank is more likely to be located near a structure (garage wall).
	Flame ignites combustible material?	Yes: 0.7 No: 0.3	This situation is similar to ET-3.
	Gas concentration reaches LFL at some location?	Yes: 0.4 No: 0.6	The rate and duration of gas release can range from throttled for a venting release to abrupt if tank ruptures. This affects the probability that an LFL region will be formed, which is assumed to be between ET-3 (which is weighted more because a PSV release is more likely) and ET-5.
	Delayed ignition where concentration >LFL?	Yes: 0.6 No: 0.4	The garage survey statistics indicate that approximately 90% of garages have ignition sources such as electric garage door openers or gas water heaters. The probability of an LFL region being collocated with an ignition source is assumed to be between ET-3 (which is weighted more because a PSV release is more likely) and ET-5.
ET-16, Buffer (pressure vessel) tank venting or rupture, with infiltration but no ventilation (Note that the input frequency to ET-16 refers to the first year after installation, and this must be multiplied by installations/year to provide consequences with the units of incidents/year. Note also that a rupturing buffer tank could cause impact damage, which is not included in this ET.)	Immediate ignition?	Yes: 0.25 No: 0.75	There is a moderate probability that the escaping gas will be immediately ignited by metal tearing if the tank ruptures (which is more likely than a PSV release for this scenario), or electrical devices added to the system by the person who added the buffer, or from other nearby ignition sources.
	Flame impinges on structure?	Yes: 0.5 No: 0.5	This situation is similar to ET-6 except that the buffer tank is more likely to be located near a structure (garage wall).
	Flame ignites combustible material?	Yes: 0.8 No: 0.2	This situation is similar to ET-6.
	Gas concentration reaches LFL at some location?	Yes: 0.97 No: 0.03	This situation is assumed to be similar to ET-6, except the gas will be released at a faster rate if the buffer tank ruptures and a slower rate if the PRV opens.
	Delayed ignition where concentration >LFL?	Yes: 0.8 No: 0.2	This situation is assumed to be similar to ET-6.

Table B-1. Event tree probability rationale (concluded)

Event Tree	Gate	Probabilities	Rationale and Data Source
ET-17, End cap release resulting from hose addition(s), with ventilation (~80 scfm) plus infiltration (Note that the input frequency to ET-17 refers to the first year after installation, and this must be multiplied by installations/year to provide consequences with the units of incidents/year.)	Immediate ignition?	Yes: 0.25 No: 0.75	There is a moderate chance that the escaping gas will be ignited by the rupturing end cap or other sources.
	Flame impinges on structure?	Yes: 0.5 No: 0.5	The HRA is mounted on the garage wall
	Flame ignites combustible material?	Yes: 0.6 No: 0.4	Garage survey statistics indicate that approximately 88% of garages have wood framing and 24% are all wood. However the gas discharge (and flame, if ignited) duration will be very brief.
	Gas concentration reaches LFL at some location?	Yes: 0.9 No: 0.1	High concentration gradients will be associated with this abrupt release. Even though the average gas concentration will be much less than LFL, a volume near the discharge is highly likely to exceed LFL for a brief period.
	Delayed ignition where concentration >LFL?	Yes: 0.4 No: 0.6	The volume with gas concentration > LFL will be small and its duration will be brief. The probability that this region will ever be collocated with an ignition source is estimated to be slightly less than 50%.
ET-18, End cap release resulting from hose addition(s), with infiltration but no ventilation (Note that the input frequency to ET-18 refers to the first year after installation, and this must be multiplied by installations/year to provide consequences with the units of incidents/year.)	Immediate ignition?	Yes: 0.25 No: 0.75	There is a moderate chance that the escaping gas will be ignited by the rupturing end cap or other sources.
	Flame impinges on structure?	Yes: 0.5 No: 0.5	The HRA is mounted on the garage wall
	Flame ignites combustible material?	Yes: 0.6 No: 0.4	Garage survey statistics indicate that approximately 88% of garages have wood framing and 24% are all wood. However the gas discharge (and flame, if ignited) duration will be very brief.
	Gas concentration reaches LFL at some location?	Yes: 0.95 No: 0.05	This probability will be somewhat higher than for ET-17 because there is no fan-driven ventilation and so the ACH will be lower.
	Delayed ignition where concentration >LFL?	Yes: 0.6 No: 0.4	This probability will be somewhat higher than for ET-17 because there is no fan-driven ventilation and so any region with gas concentration > LFL will persist for a longer time and therefore be more likely to encounter an ignition source.

Appendix C. Residential Garage Infiltration Survey Form

RESIDENTIAL GARAGE INFILTRATION SURVEY

PURPOSE

We are collecting information to aid in determining the issues associated with potential use of natural gas (or possibly hydrogen) vehicle refueling devices inside of residential garages. We will use the information you provide on this form to estimate the range of air infiltration (i.e., natural ventilation) rates in residential garages. We do not need to know your name or address, but we do need to know your city in order to estimate local weather conditions.

WHAT WE ARE ASKING YOU TO DO

Please inspect your garage, fill out this form, and send (FAX, mail, e-mail) it to the address noted at the end. Your answers and measurements do not need to be precise.

EXAMPLE

An example completed survey form is attached.

LOCATION

Garage location

City: ________________________________

State: ________________________________

Country: ________________________________

Nearest large city: ________________________________

SKETCH

Please sketch the basic floor-plan layout of your garage in the box below. Please indicate the location of: adjoining structures, garage "vehicle" doors, "people" doors, windows, vents, and any significant openings to the outside. Please also indicate the "north" direction. A rough sketch is fine.

GENERAL CONFIGURATION

How many vehicles does this garage accommodate?: __________

Number of vehicles that you normally park in the garage: __________

- ☐ Garage is free standing (not attached to another structure)
- ☐ Garage is attached on one or more sides to another structure. Number of attached sides: __________ (please indicate in sketch)
- ☐ Garage is below another structure
- ☐ Garage is attached in some other way: ____________________________

Type of structure attached to garage: __________________. Approximate area of attached structure: _____ ft^2. Number of stories: _____.

Basement? ☐ No ☐ Yes

The basic construction of this garage is:

- ☐ Wood
- ☐ Wood framing with stucco or similar
- ☐ Wood framing with siding
- ☐ Brick, concrete block, or other masonry
- ☐ Other: ______________________________

Garage ceiling/roof configuration:

- ☐ Approximately flat and level
- ☐ Slightly sloped
- ☐ Significantly sloped
- ☐ Slightly peaked
- ☐ Significantly peaked
- ☐ Other: ________

DIMENSIONS

What are the approximate garage dimensions?

Width: _________, Depth: _________, Height (to lowest ceiling): _________

- ☐ Unusual shape (please indicate in sketch)

GARAGE "VEHICLE" DOOR(S)

Number of garage doors: _________

Approximate total dimensions of garage doors: ___________ x ___________

Type of garage doors:

- ☐ Solid one-piece door(s)
- ☐ Paneled door(s)
- ☐ Slatted door(s)
- ☐ Other: ______________________________

Garage door opening type:

- ☐ Retracts to overhead position using glider wheels in track
- ☐ Swing-up type opens to overhead position using hinges and springs
- ☐ Slides sideways (usually suspended from overhead track)
- ☐ Side-hinged, opens outward
- ☐ Other: ______________________________

Garage door opener:

- ☐ Manual
- ☐ Electric, motor location:
  - ☐ Overhead
  - ☐ Other: ______________________________

Air gaps around closed garage doors:

- ☐ Garage doors have weather stripping or other features to seal out air flow
- ☐ Garage doors have no weather stripping, but they fit tightly, and any air gaps are too small to measure
- ☐ Obvious air gaps around garage door(s). Measured or estimated average gap widths:
  - Bottom:______________
  - Top:______________
  - Sides: ______________
- ☐ None of the above apply to my garage door: ______________

GARAGE "PEOPLE" DOOR(S)

Number of people doors:

Garage to outside: ________

Garage to house: ________

Garage to structure other than house: ________

Garage to basement or crawl space: ________

If any of these doors are normally left open, please note: ______________

Air gaps around closed garage people doors:

- ☐ Doors fit tightly or have weatherstripping
- ☐ Doors don't fit real tight, but any air gaps are too small to measure
- ☐ Doors have obvious air gaps. Measured or estimated average gap with:

  ____

GARAGE WINDOWS

Number of garage windows: ________________________

Normally open or closed? __________________________

Air gaps around closed windows:

- ☐ They close pretty tight
- ☐ They don't close tight, but any air gaps are too small or impractical to estimate
- ☐ Air gaps. Measured or estimated average gap widths and locations: _________
  ____
  ____

INTENTIONAL VENTILATION OPENINGS

Does garage have any intentional ventilation openings?: ☐ Yes ☐ No

If yes, please note on sketch and describe:

Number, approximate area, and location (e.g., near floor or near ceiling): _______

____

Is garage equipped with a fan, blower, or similar?: ☐ No ☐ Yes

If yes, please describe: ____

WIND CONDITIONS/SHIELDING

We will apply weather databases to estimate typical wind speeds and directions in your area. But we need you to estimate how much your garage is shielded from prevailing winds by nearby structures, solid fences, trees, hedges, etc.:

- ☐ No significant wind shielding (e.g., mostly "out in the open")
- ☐ Light wind shielding (e.g., a few trees nearby)
- ☐ Moderate wind shielding (e.g., thick hedges, solid fence, near other houses)
- ☐ Substantial wind shielding (e.g., buildings or other obstructions within 30 ft in most directions)
- ☐ Very substantial wind shielding (e.g., downtown and mostly surrounded by nearby large obstructions)

IGNITION SOURCES

What types of obvious potential ignition sources are inside your garage?:

- ☐ Water heater: ☐ Gas ☐ Oil ☐ Electric
- ☐ Space heater: ☐ Gas ☐ Oil ☐ Electric
- ☐ Clothing dryer: ☐ Gas ☐ Electric
- ☐ Clothing washer
- ☐ Electric garage door opener
- ☐ Various electric tools
- ☐ Other: ____

OTHER

Please note any additional features of your garage that might affect air infiltration:

____

____

RETURN AND QUESTIONS

Thank you for your help. Please return this form by mail, FAX, or e-mail (and direct any questions) to:

Charles Powars
561 Thain Way
Palo Alto, CA 94306
Phone (650) 424-0426
FAX (650) 857-0291
CAPCAP@aol.com

Appendix D. Residential Garage Infiltration Rate Estimation Methodology

This appendix describes the methodology that was used to estimate the air infiltration rates of a sample of 33 garages from a variety of locations in the U.S. and Canada. The sample was obtained from respondents to a survey form that was distributed as discussed in Section 5.2 in the main text. A copy of this form is shown in Appendix C. The entries in this form are keyed to the methodology that, in turn, is adapted from the so-called LBL (Lawrence Berkeley Laboratory) model described in the ASHRAE Handbook (Reference D-1).

The LBL method is based on a lumped parameter and fully mixed single-zone model of a structure. There are other methods available, including comparable single-zone models by Canadian and Swedish workers as well multi-zone models, like that developed at the National Institute of Standards and Technology and available in the form of a computer code called CONTAM (Reference D-2). However, the selection of the LBL method was determined by several factors, the main being the practical matter of getting a reasonably consistent set of data from survey respondents without imposing a burden that would affect their willingness and ability to respond. Thus, CONTAM is not suitable for this purpose because it requires inputs at a very detailed level that would not generally be available from the respondents. In addition, the LBL method is perhaps the most widely used and well understood of the readily available methods.

We used the LBL model by applying it to a garage and ignoring the rest of the structure except for a leakage area assigned to any door between the house and the attached garage and the stratification effects associated with multi-storied structures. We also used a detailed method based on gap geometry to calculate the effective leakage area of car doors (i.e., the garage doors through which vehicles pass) since, in most cases, this is likely to be the dominant infiltration path for a garage.

The essential features of the LBL model are a basic equation for the air leakage rate of a structure as a function of wind speed and indoor-outdoor temperature difference, a set of tabular data for the effects of local wind shielding and building height, and the effective leakage areas of specific features like windows and doors. These are described below.

The basic equation is:

$$Q = L\left(C\Delta T + Dv^{2} \right)^{0.5}$$

Where:

Q = airflow rate, scfm
L = total effective leakage area, in^2
C = stack coefficient, $scfm^2/(in^4\ °F)$
ΔT = indoor-outdoor temperature difference °F

D = wind coefficient, scfm^2 (in^4 mph^2)
v = wind speed, mph

The required wind speed and temperature difference were taken from Table 1, United States, and Table 2, Canada, in Chapter 24, WEATHER DATA, of the ASHRAE Handbook (Reference D-1). These parameters vary with geographical location and we applied the data from the location nearest the reporting location. We used only the "Prevailing Wind" (Column 9) speed data because, unfortunately, the LBL model does not directly account for the obvious effect of wind direction. Also, we used half the "Mean Daily Range" (Column 7) of temperature as a representative value of ΔT, since during the summer at least, the late night and morning temperatures in a garage are typically less than ambient and more than ambient in the afternoon and early evening.

The airflow rate, Q, calculated using the LBL model is in fact the infiltration, I, defined in Section 5.1 of the main text. As discussed in Section 5.1, the garage air changes per hour (ACH) is simply the infiltration rate divided by the garage volume, V:

$$ACH = \frac{I}{V}$$

Ranges of values for the coefficients in the LBL equation are tabulated in Chapter 23 of the ASHRAE Handbook. The stack coefficient, C, which is simply a function of the number of stories of the garage structure, is taken from Table 6. The wind coefficient, D, is taken from Tables 7 and 8 as determined by the corresponding entries on the survey form.

The effective leakage area, L, is the sum of the following components:

1. Each outside door is assigned a value of 3.3 in^2
2. Each inside door is assigned a value of 1.9 in^2
3. Windows are assigned a value of 0.4 in^2/linear ft of sash
4. Vents and gaps around car doors are assigned values calculated by the Baker method described below.

The effective leakage areas for items 1 and 2 of this list are the "Best Estimate" values from Table 3 of the ASHRAE Handbook, and the effective leakage area for item 3 is a typical value from that table.

The ASHRAE Handbook does not give effective leakage values for vents or gaps around car doors, so we chose to calculate these with the method developed by Baker, et al., (Reference D-2), as described by Dols and Walton (Reference D-3). The Baker method is essentially a means for relating the geometry of an opening to the discharge coefficient. Our application of the Baker method is summarized below:

1. We follow the normalization approach, which uses a reference pressure difference of 4 Pa (0.016 in of water) and a reference discharge coefficient of 1.0, and first solve a quadratic equation for the flowrate through the opening at the reference pressure difference. This equation is:

$$4 = aQ + bQ^2$$

With:

$$a = \frac{12\mu Z}{\ell d^2}$$

And:

$$b = \frac{\rho E}{2d^2 \ell^2}$$

Where:

μ = viscosity
ρ = density
Z = distance along the direction of flow
d = gap width
ℓ = gap length
E = 1.5 + number of turns in flow path

2. The next step is to convert this flowrate to an effective leakage area at unity discharge coefficient using Eqn. 27 of the ASHRAE Handbook (Reference B-1):

$$L = \frac{C_6 Q(\rho / 2\Delta P)^{0.5}}{C_D}$$

Where

ΔP = reference pressure difference (0.016 in of water)
C_D = 1.0, reference discharge coefficient
C_6 = 0.186, unit conversion factor

The Baker method gives values of effective leakage area that are always less than the geometrical area of the gap or vent and therefore predicts an effective discharge coefficient that is typically between 0.5 and 0.7. This is a reasonable range for a low Reynolds number flow, and it appears that the relative ranking of predictions using this method along with the following interpretation of the survey forms gives a rational ordering of the survey data.

As a practical matter in the application of these methods, it is necessary to apply some judgement in the interpretation of the data from the survey form. In particular we discovered that respondents were not necessarily consistent in their interpretation of the question on "Air gaps around closed garage doors." In particular, we think that even a well-sealed car door has some leakage, even though there is no visible gap between the door and the jamb. So, after several trials, we concluded it is reasonable to make the following associations between car door gap dimensions and the responses to this question:

1. Garage door with weather striping: d=3/64 = 0.046875 in
2. Garage door without weather striping: d = 3/32 = 0.09375 in
3. Garage door with obvious air gaps: d = as reported, typically > 0.125 in

Similarly, we note that an interpretation is necessary to quantify the response to the survey question "Garage ceiling/roof configuration." In this case, we adopted the convention that "slightly sloped/peaked" has a slope of 2/12 and "significantly sloped/peaked" has a slope of 4/12. This is roughly consistent with architectural practice. Also, where lateral dimensions are necessary to calculate the volume of the roof, we used the average of the length and the width, since no information about the orientation of the roof slope is available.

References:

D-1. 1993 ASHRAE Handbook – Fundamentals, I-P Edition, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, GA

D-2. Baker, P.H., Sharples, S., and Ward, I. C., "Air Flow through Cracks," *Building and Environment*, Pergamon, 22(4): 293-304, 1987

D-3. Dols, W. S. and Walton, G. N., CONTAMW 2.0 User Manual, NISTIR 6921, November 2002

Appendix E. Average Gas Concentrations Caused by Blowdowns, Discharges, and Leaks for Various Garage Ventilation and Infiltration Situations

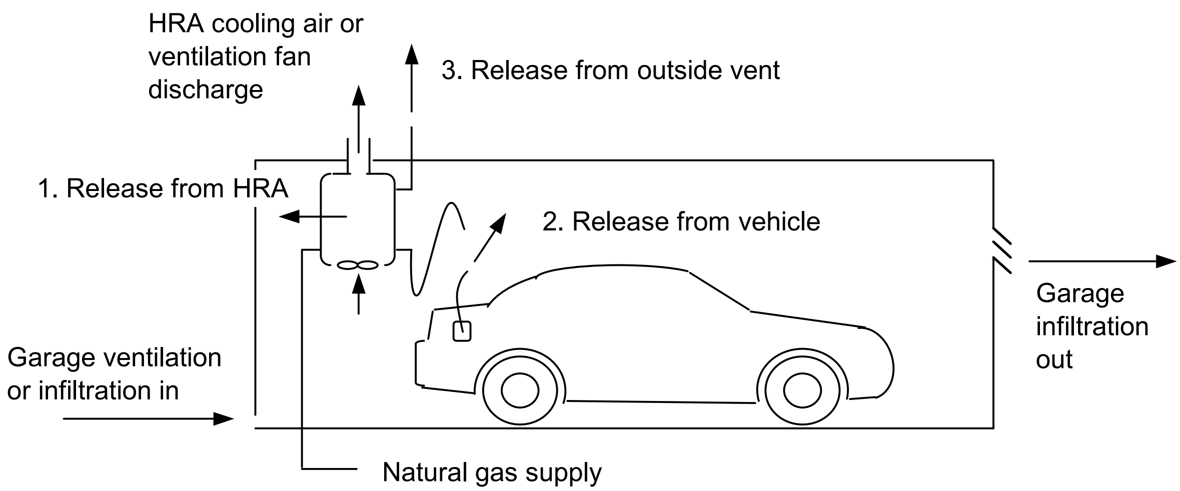


Figure E-1. Types of Gas Releases and Ventilation/Infiltration Flow Paths

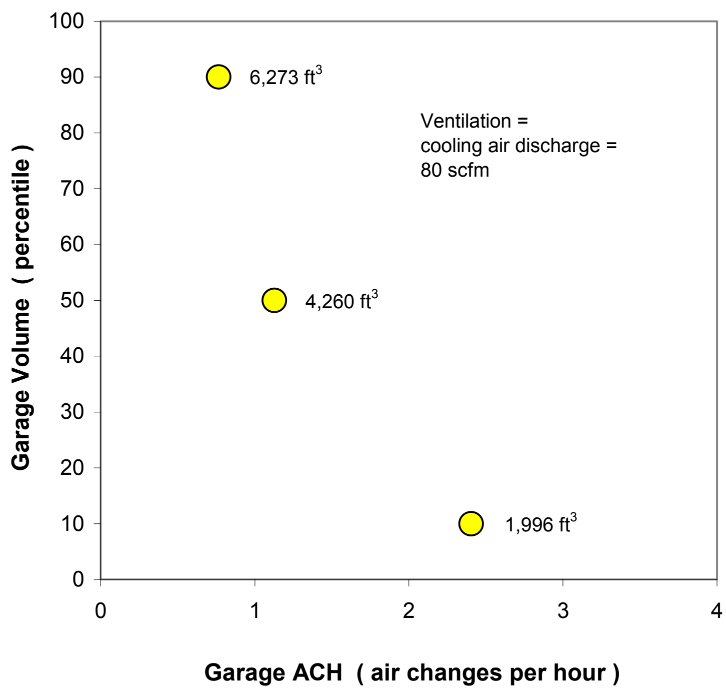


Figure E-2. Figures E-3 through E-5 show average gas concentrations for 80 scfm ventilation and three garage sizes

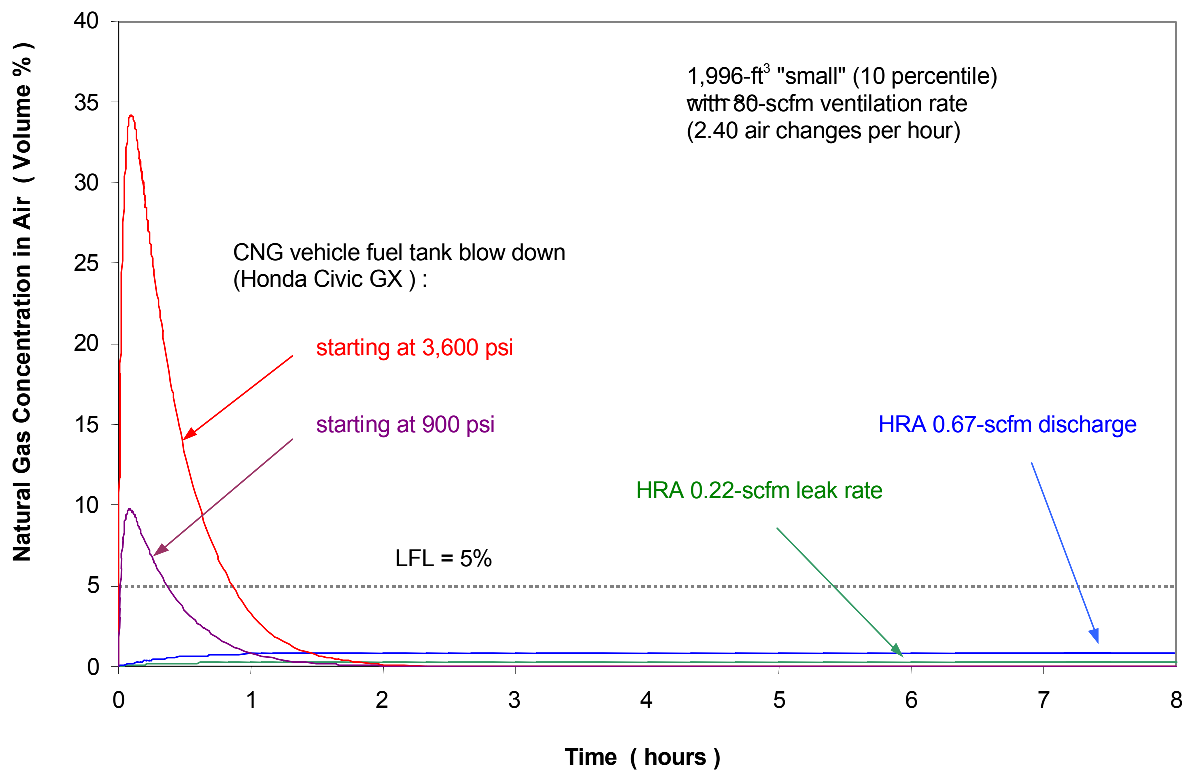


Figure E-3. Average gas concentrations with 80 scfm ventilation in a small garage

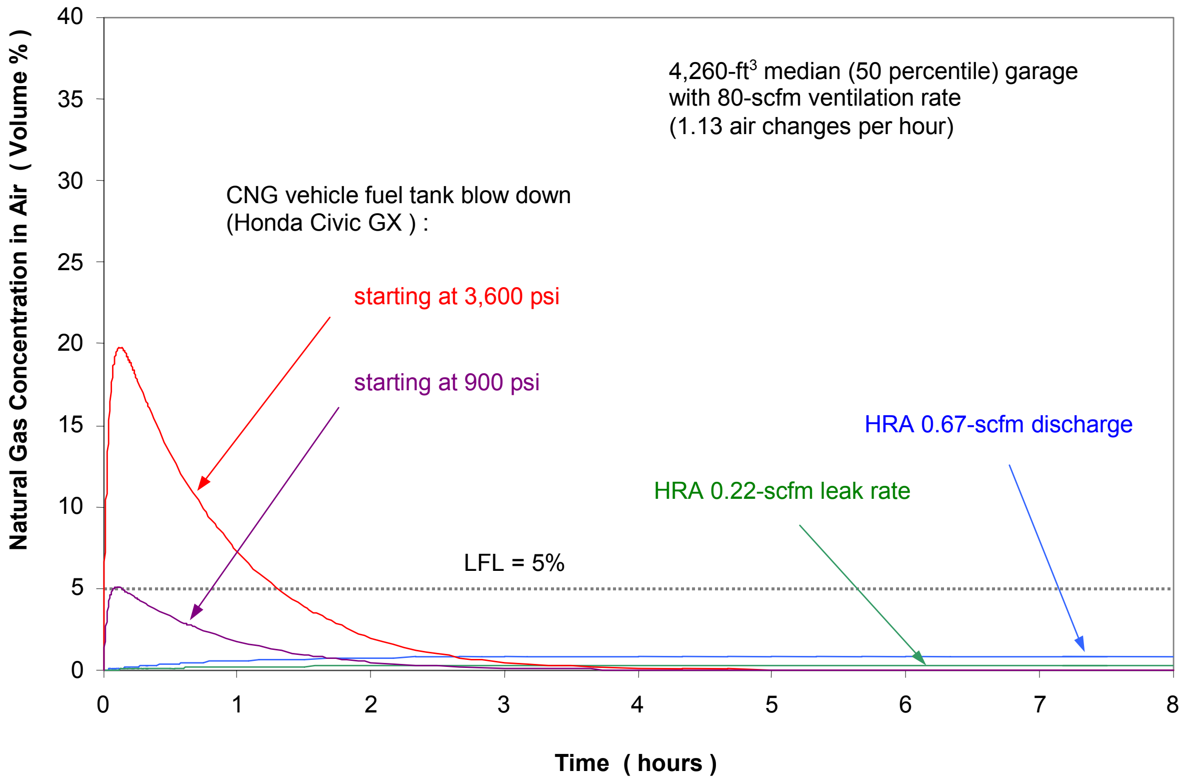


Figure E-4. Average gas concentrations with 80 scfm ventilation in a medium garage

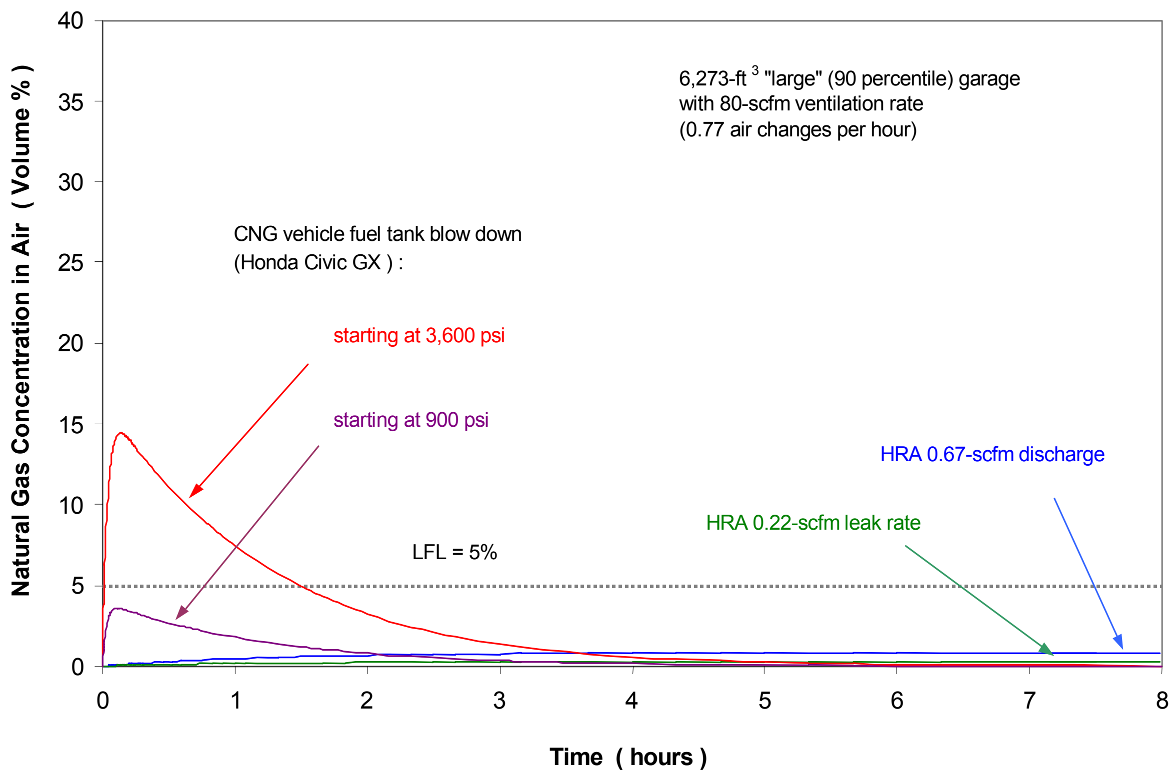


Figure E-5. Average gas concentrations with 80 scfm ventilation in a large garage

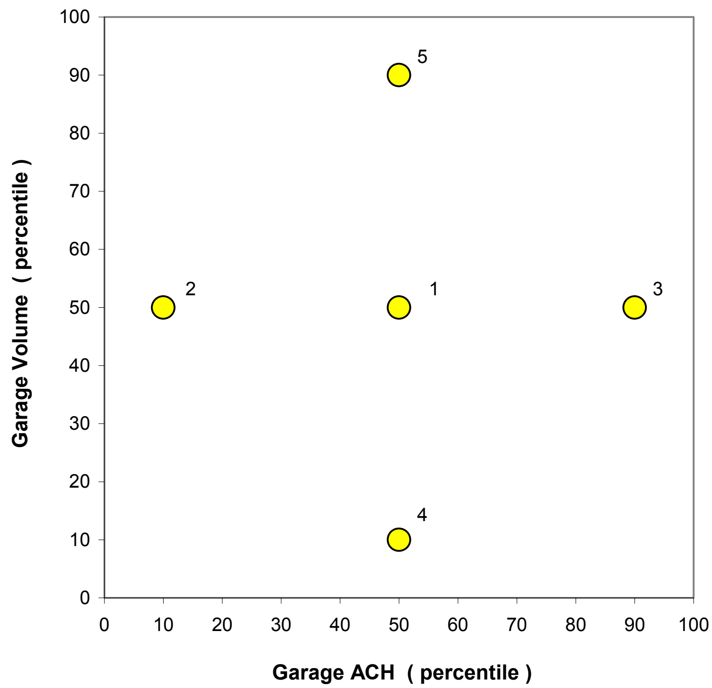


Figure E-6. Figures E-7 through E-11 show average gas concentrations for infiltration corresponding to five garage size and ACH combinations

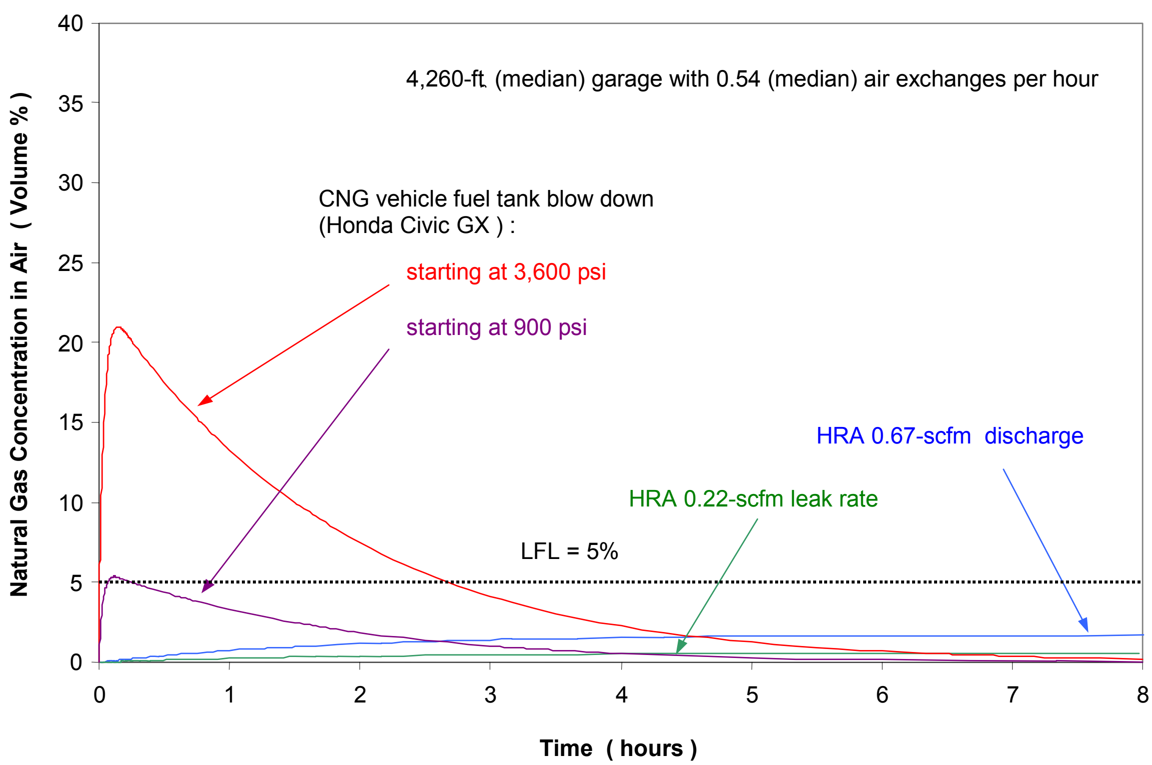


Figure E-7. Average gas concentrations for infiltration into medium garage with medium ACH

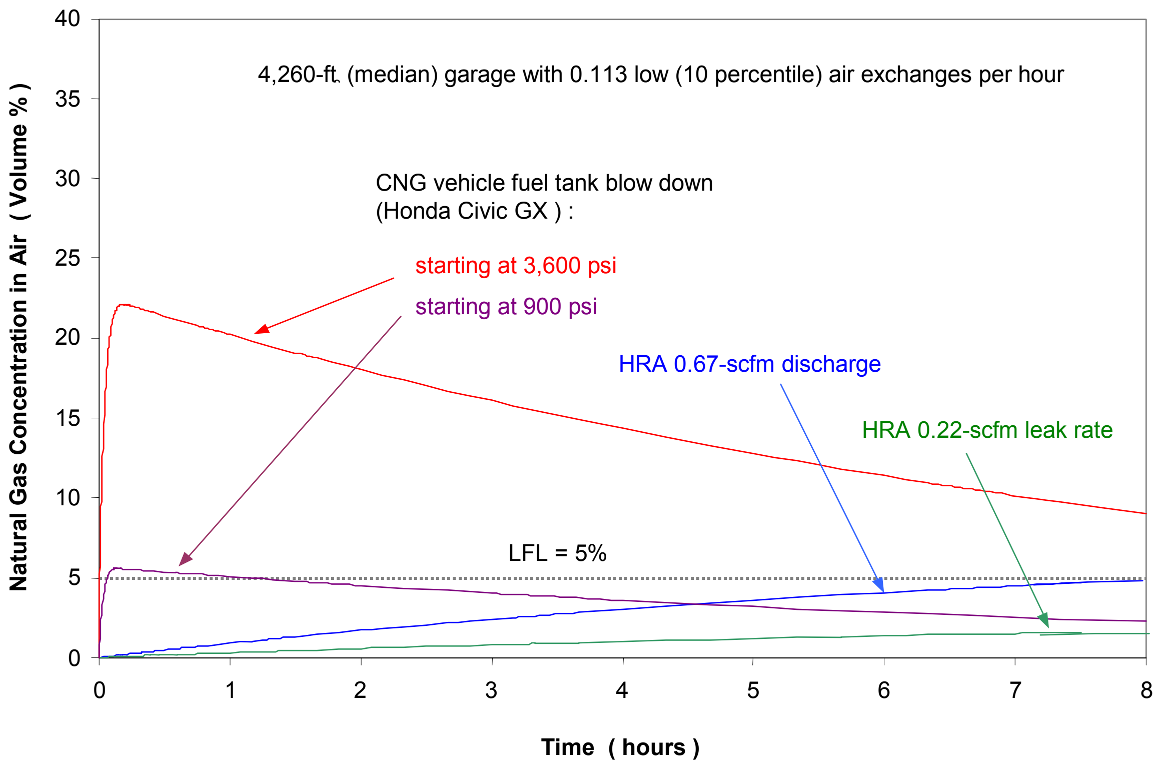


Figure E-8. Average gas concentations for infiltration into medium garage with low ACH

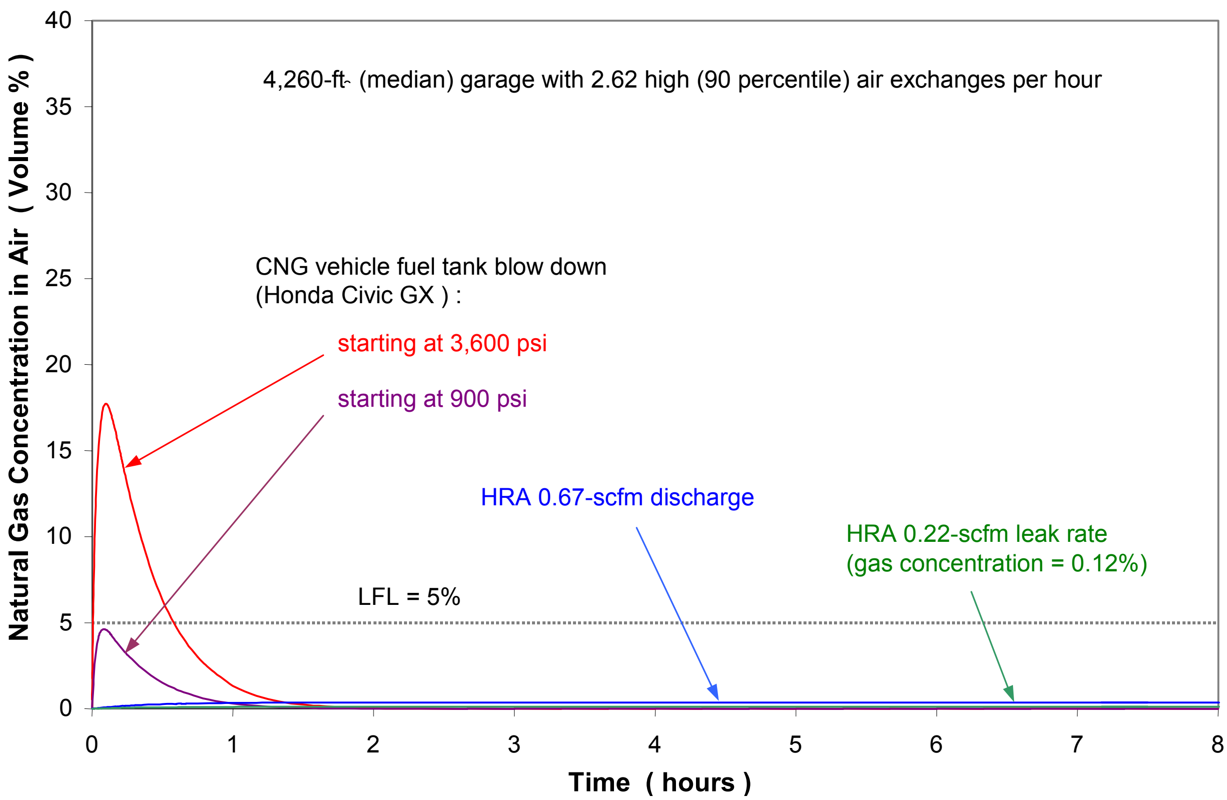


Figure E-9. Average gas concentations for infiltration into medium garage with high ACH

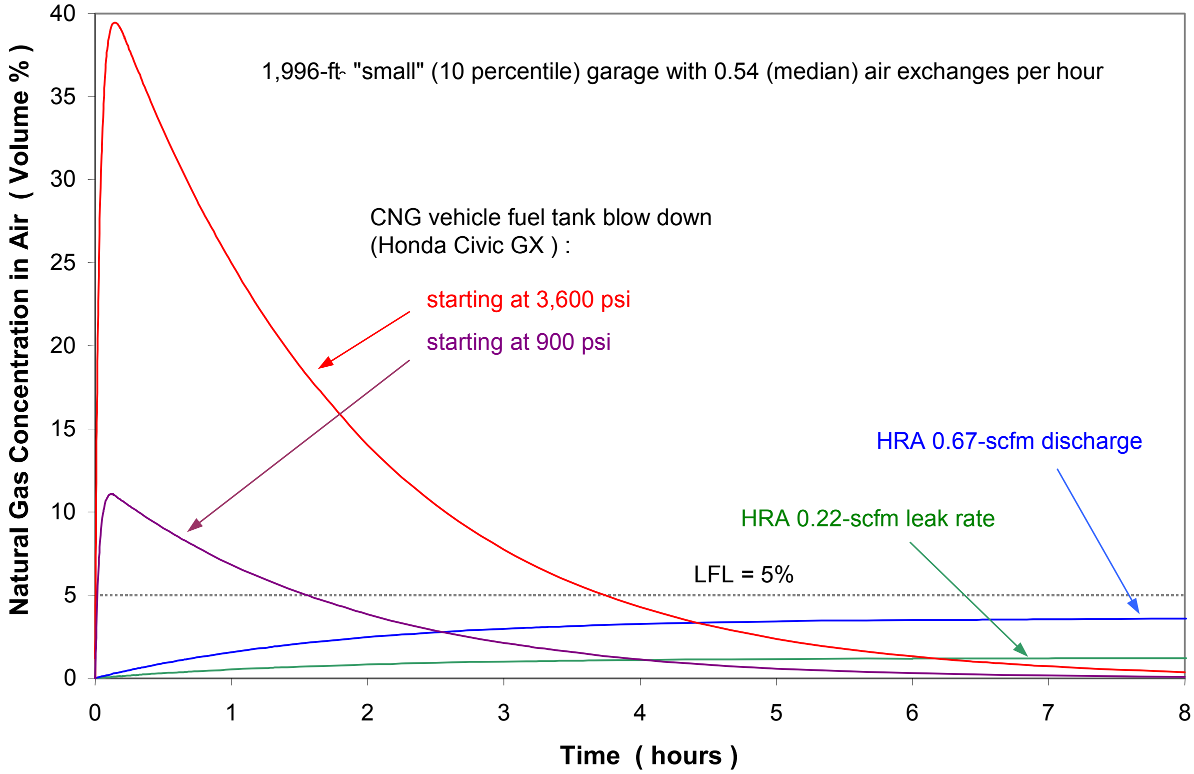


Figure E-10. Average gas concentations for infiltration into small garage with medium ACH

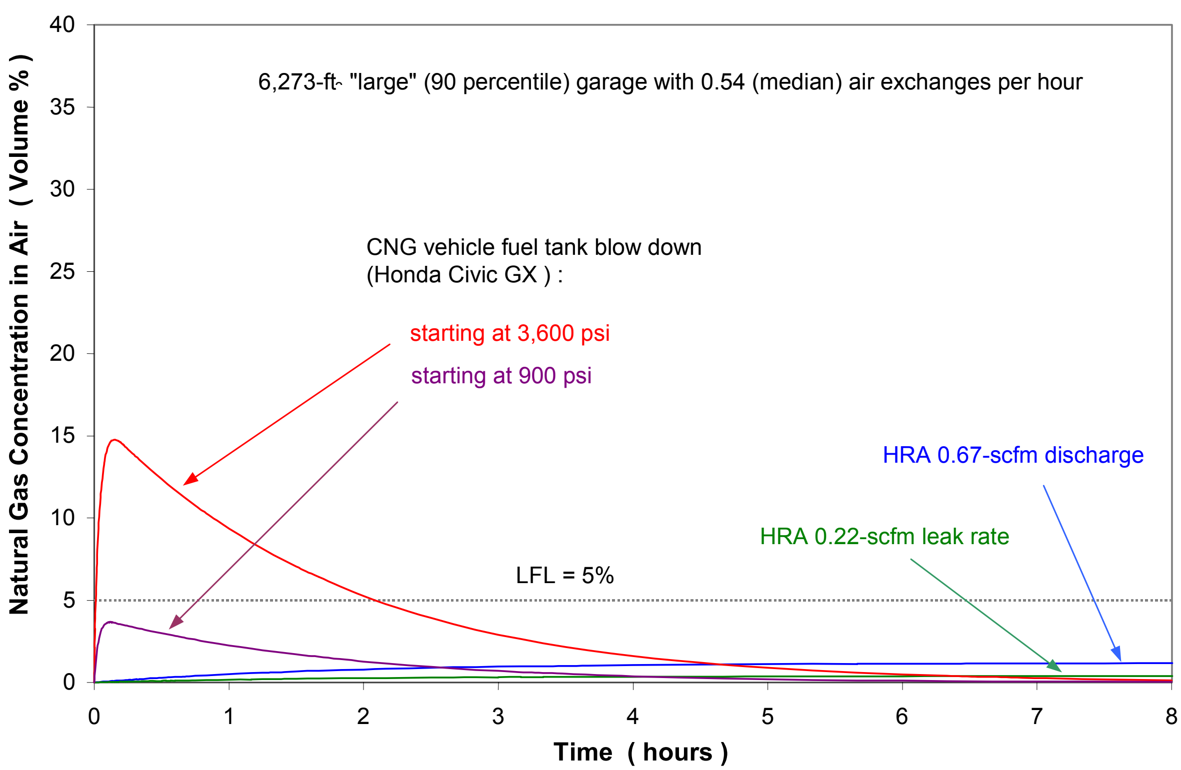


Figure E-11. Average gas concentrations for infiltration into large garage with medium ACH

Appendix F. Garage Geometry

A typical two-car garage was selected for computational fluid dynamics simulation. The side and top views of the garage solid model, with various key dimensions, are presented in Figures F-1 and F-2. The garage is 25-feet long, 20-feet wide and 9-feet high. The FuelMaker HRA is located on a side wall 10-feet inside from the garage door and 5-feet high from the floor. An additional section of about 6 feet was modeled outside the garage as shown in the figures. The additional section allows continuity between the flow field developing outside the garage door and inside the garage.

As shown in Figure F-3, infiltration into and out of the garage occurs through the gaps on three sides around the garage vehicle door. The bottom of the garage door was modeled as well sealed with no infiltration. A rear "people" door was present but it was not considered as an infiltration route. A porous zone was utilized to vary flow resistance in the gap along the top and sides of the garage door and adjust for the correct air exchange rate.

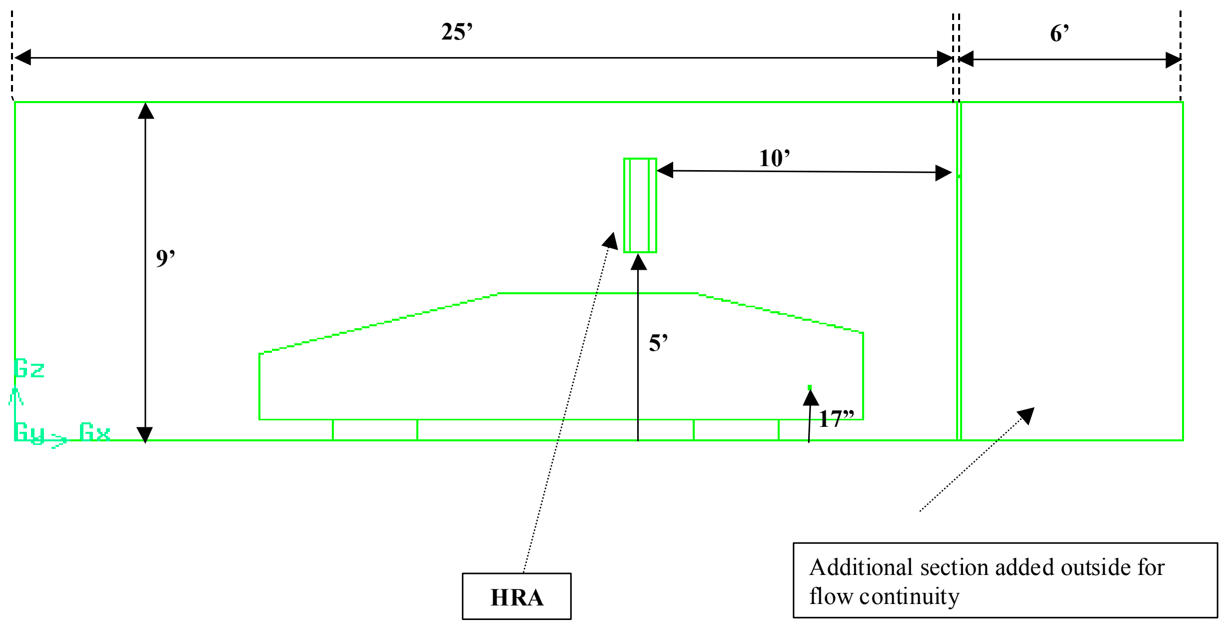


Figure F-1. Garage CFD Solid Model Side View

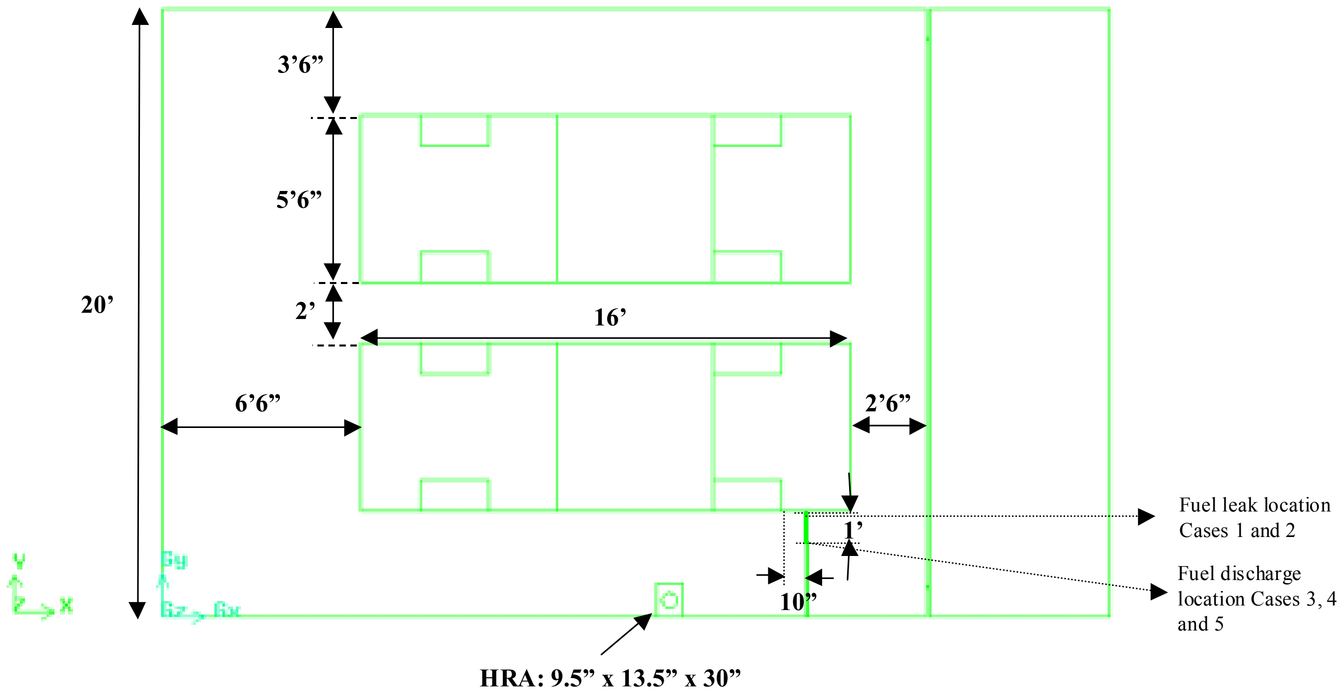


Figure F-2. Garage CFD Solid Model Top View

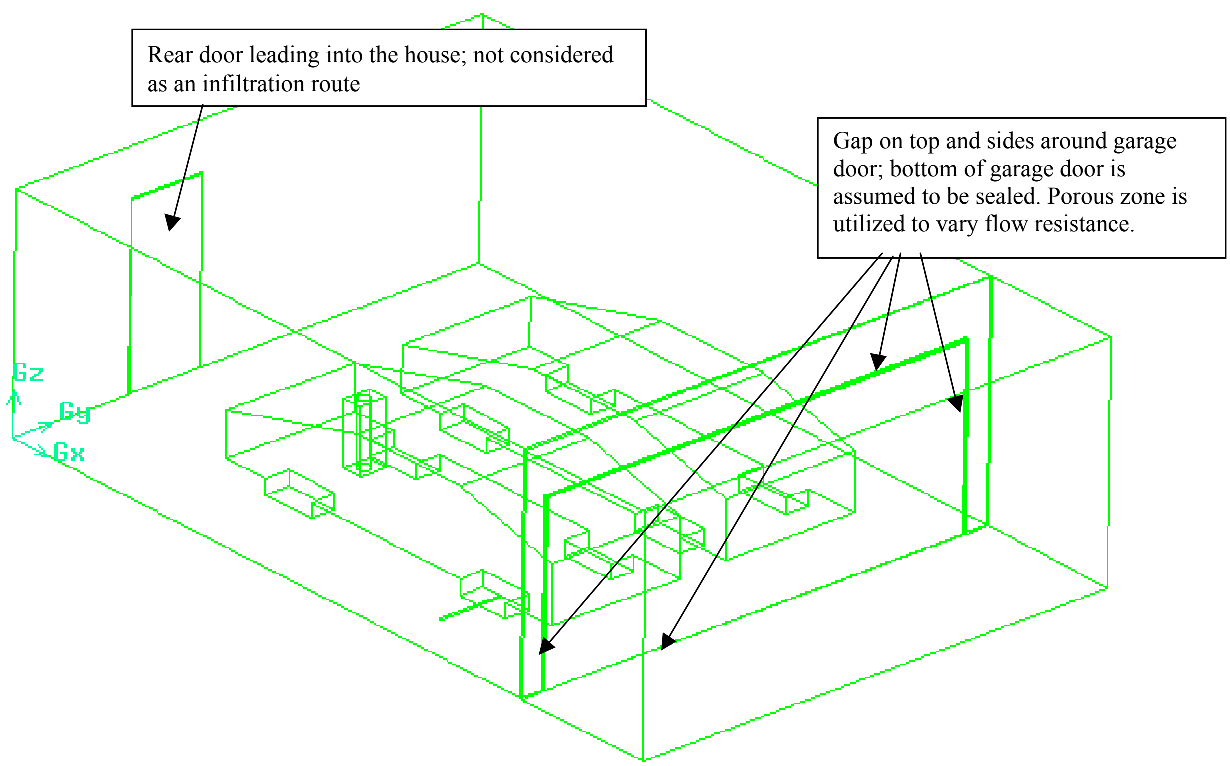


Figure F-3. Infiltration Locations

Computational Grid

The computational grid consisted of approximately 500,000 elements. A map of the grid is presented in Figure F-4. As can be seen from the grid map below, a combination of element types/shapes was selected to obtain computational efficiency as well as accuracy. Also, for the reasons of efficiency and accuracy, the grid density varied with location. In areas where there was significant flow activity and the relative physical scale was smaller – such as the infiltration zone along the border of the garage door and the inlet and outlet zones of the HRA – the grid was refined and the element sizes were smaller. In other areas of the solid model, the grid was sparse and the element sizes were larger. While the overall features of the computational grid were the same, some fine differences were introduced into the grid depending on the calculation case.

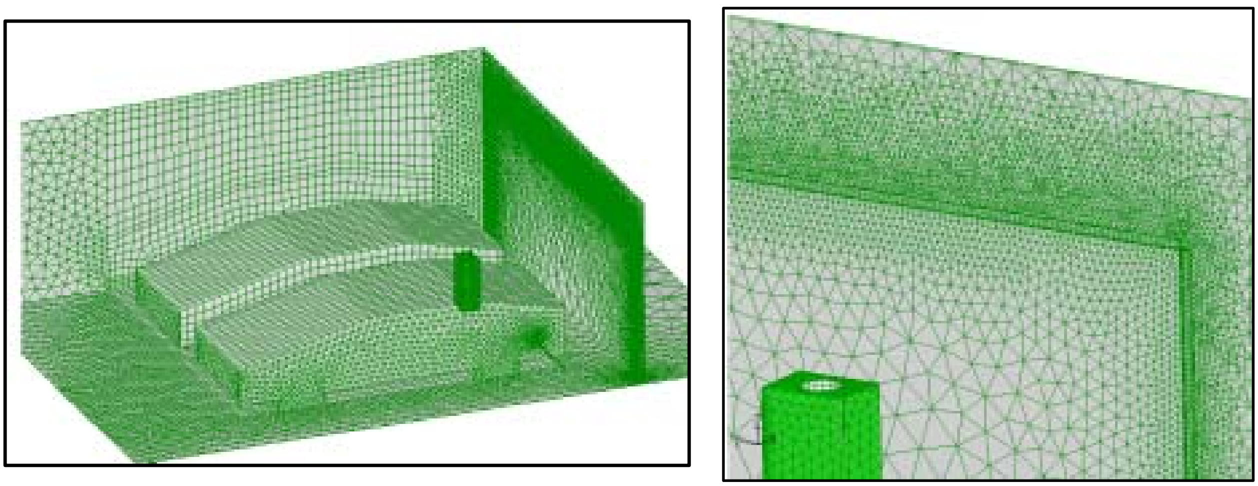


Figure F-4. Computational Grid Map

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