CRC Project No. CM-138-12-1

A RISK ANALYSIS/HAZARD ASSESSMENT OF HIGH ETHANOL CONTENT FUELS AT SERVICE STATIONS

June 2014

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Abbreviations and Acronyms

AIT	Auto-Ignition Temperature
ANSI	American National Standards Institute
APEA	UK Association for Petroleum and Explosives Administration
API	American Petroleum Institute
AST	Atmospheric Storage Tank
ASTM International	American Society for Testing and Materials, International
ATM	Automatic Tank Gauging
BTU	British Thermal Unit
CARBOB	California Reformulated Blendstock for Oxygen Blending
CCPS	Center for Chemical Process Safety
CFR	Code of Federal Regulations
COMAH	Seveso II Directive; Control of Major Accident Hazards
DOD	US Department of Defense
DVPE	Dry Vapor Pressure Equivalent
EPA	US Environmental Protection Agency
EVR	Enhanced Vapor Recovery
FTA	Fault Tree Analysis
GM	General Motors
GPM	Gallons per Minute
HAZOP	Hazard and Operability Study
HSE	UK Health and Safety Executive
IEC	International Electrical Code
ISA	International Society of Automation
LD	Light-Duty(Vehicle)
LFL	Lower Flammability Limit
MAWP	Maximum Allowable Working Pressure
MD	Medium-Duty(Vehicle)
MESG	Minimum Experimental Safe Gap
NFPA	National Fire Protection Association
NREL	National Renewable Energy Laboratory
ORVR	Onboard Vapor Recovery
OSHA	US Occupational Safety and Health Administration
PHA	Process Hazard Analysis
PHAST	Process Hazards Analysis Software Tool
PSI	Pounds per Square Inch
PSM	Process Safety Management
PVAP	PHAST Pool Vaporization Model
QRA	Quantitative Risk Assessment
RA/HA	Risk Assessment/Hazard Analysis
RBOB	Reformulated Blendstock for Oxygen Blending

RMP	Risk Management Program
RP	Recommended Practice
SRI	Societal Risk Index
TNO	Netherlands Organization for Applied Scientific Research
UDM	PHAST Unified Dispersion Model
UFL	Upper Flammability Limit
UFT	Upper Flammability Temperature
UL	Underwriters Laboratory
ULP	Unleaded Petroleum
UST	Underground Storage Tank

Executive Summary

Objective

The objective of the current project was to determine the incremental change in risk due to a change in the storage, handling and dispensing of spark ignition engine fuel at a service station. Specifically, the study evaluated the effects associated with the substitution of high ethanol content fuel blends (denoted as E51, and E83, respectively) as well as denatured fuel ethanol (denoted as E98) for gasoline containing 10 vol% ethanol (E10). E10 is the most commonly dispensed fuel at service stations in the United States. To accomplish this objective, a two-step assessment approach was used. An initial qualitative risk review was completed to compare fuel blends and identify accident scenarios that could impact the public at a filling station. A subsequent quantitative risk assessment was then performed of these scenarios including consequence modeling of the hazards of a fuel release and developing the likelihood and risk estimates for comparison.

The main objective of the qualitative risk review was to review the design and operation of a service station, and to identify scenarios for detailed study as part of the quantitative risk assessment. The result of qualitative risk review was the development of seven (7) scenarios that were selected for analysis in the quantitative risk assessment. These scenarios were:

1.) A spill of fuel to the ground during unloading of a tanker truck to an underground storage tank (UST);
2.) Ignition of UST vent stack vapors, flashback and detonation of UST headspace;
3.) Ignition of vapors in UST unloading area, flashback and detonation of UST headspace ;
4.) Direct ignition of UST flammable tank headspace, detonation of UST headspace ;
5.) An uncontrolled spill of fuel to the ground in the dispensing area;
6.) Nozzle fire, flashback and detonation of vehicle fuel tank headspace; and
7.) Detonation of vapors in a vessel associated with California tank pressure management system.

Methodology

The quantitative risk assessment used the PHAST hazard analysis tool to model discharge and dispersion, pool spreading and evaporation, as well as flammable effects of the scenarios identified. For the purposes of the hazard analysis model, fuel properties were selected to represent the worst-credible scenario case. The study was interested in evaluating the potential for fuels to be stored under conditions such that the tank headspace becomes flammable, allowing the tank detonation scenarios detailed above to occur. A fuel tank headspace generally contains too high of a concentration of hydrocarbon vapor to ignite; the headspace is above the upper flammability limit. As the temperature in the tank decreases, the concentration of hydrocarbon vapor in the headspace decreases. The tank headspace will become flammable when the fuel decreases below its upper flammability temperature (UFT). The UFT is determined by the fuel's vapor pressure (a measure of fuel volatility used in fuel blending) [1]. The UFT decreases as fuel vapor pressure increases. The UFT of ethanol-containing spark-ignition engine fuels blended for sale in the US ranges from ~25 degrees Fahrenheit at a vapor pressure of 5.5 psi to -20 degrees Fahrenheit at a vapor pressure of 13 psi.

For the purposes of modeling the release, discharge and dispersion, pool spreading and evaporation, and the flammable effects of the release scenarios, fuels were selected that represented a worst credible scenario basis in regards to these types of hazards. Higher vapor pressure fuels create larger flammable vapor releases and result in larger impacts than lower vapor pressure fuels. Alternatively, fuels with very high vapor pressures have very low UFT values and are therefore less likely to be potentially stored below the UFT. Therefore, the study used fuels at the upper limit of the summer fuel standards and regulations. The vapor pressure was set as follows for the consequence modeling: E10 – 10 psi, E51 – 8.5 psi, E83 – 8.5 psi, and E98 – 2.4 psi. These ethanol fuel blends represent summer fuel blends that comply with EPA summer gasoline requirements for E10 in selected regions (9.0 psi base gasoline + 1.0 psi waiver), and ASTM D5798 Class 1 standards for E51 and E83 fuels. There are no standards that set a vapor pressure specification for E98. The vapor pressure of the E98 fuel selected for consequence modeling in this study is below average industry values. The study assumed E98 to be denatured using a low vapor pressure denaturant; however, current practice is for blenders to denature ethanol using high vapor pressure natural gasoline. A higher vapor pressure denaturant would drive increased vapor generation and larger flammable vapor releases than those calculated in this report.

For scenarios 2, 3, 4 and 6, which involve the detonation of a tank headspace, it was necessary to model the cases at the UFT of the fuels being modeled. Thus, the E10, E51, and E83 blends were modeled at their respective UFT value of 5 degrees Fahrenheit, while the E98 fuel was modeled at its respective UFT value of 95 degrees Fahrenheit. Modeling each fuel at its respective UFT generates a worst credible scenario vapor release that has the potential to lead to a tank headspace detonation. The likelihood of each fuel type being stored at a temperature at or below its respective UFT was incorporated into the likelihood analysis by a team-based risk assessment of each of the four fuel types. For scenarios that did not involve tank headspace detonation, each of the fuels was modeled at the same temperature. The temperature selected for cases 1 and 5, which involved only liquid fuel spills and pool fires, was 95 degrees Fahrenheit.

The quantitative risk assessment used the modeling results to assess the consequences of the scenarios for each fuel in question. Each scenario was modeled to determine the impact of the incident on people in the surrounding area. The physical properties of each fuel type studied affect the size of flammable vapor clouds that may lead to flash fire hazards, as well as the amount of thermal radiation released by the fuel as it burns in a fire.

The quantitative risk assessment developed likelihoods for each scenario based on the potential causes identified in the qualitative risk assessment. The identified causes were used to construct a fault tree for each of the scenarios. The fault trees were used to calculate the likelihoods used in the quantitative risk assessment. The vapor dispersion results from the scenario modeling was also used to account for the probability of ignition for each scenario. The size of the flammable vapor cloud released by each fuel type varies, and fuels that generate larger flammable plumes are more likely to be ignited.

The consequence and likelihood results were combined to determine the risk of each scenario and the cumulative risk of the scenarios for each fuel type. The risk is expressed as a value called to as the societal risk index (SRI). SRI is a commonly used value in risk assessment that represents the number of fatalities expected per year to occur as a result of a hazard scenario or a combination of hazard scenarios. Once the SRI values were calculated for each scenario and each fuel type the values were scaled to the benchmark fuel, E10. We may interpret the results to indicate that the current rate of fatal accidents can be scaled by the appropriate scaled risk result if we substitute the selected fuel for E10 without implementing any additional safeguards.

Results

The results of the study indicate that the risk associated with handling, storing, and dispensing the various ethanol fuel blends was highest for E98. E10 and E83 fuel blends represented nearly identical levels of risk, while the E51 fuel blend posed the lowest overall risk. If the scenarios are considered by type, it is apparent that the E98 and E83 fuels represent the highest risk of tank headspace detonation, while the E10 fuel represents the highest risk from fuel spill scenarios. Risk results are provided in Table 1 for each of the fuels, as well as by scenario type. Risk results are reported relative to E10, therefore, the risk for E10 is set to a value of 1 and the other fuels are scaled accordingly. Based on published literature, unloading gasoline-ethanol blends with ethanol concentrations up to 10 vol% presents the same fire-safety hazards as gasoline.

Note that the cumulative risk results include consideration of E98 being handled and used in the same manner as E10, E51, and E83. E98 is not currently dispensed as a commercial fuel, so the risk of nozzle fire or fuel spill at the dispenser is not present for E98 in the current marketplace. These results include the use of E98 as a fuel available at the dispenser. Service stations operating blender pumps that store E98 should consider these E98 dispensing scenarios may occur as a result of blender malfunctions and may refer to specific scenarios related to the storage of E98 in USTs in the risk results reported for those specific scenarios.

Table 1: Scaled Risk Results by Fuel Type

Fuel	All Scenarios	Tank Headspace Detonations	Fuel Spills
E10*	1	1	1
E51	0.6	0.65	0.6
E83	0.97	25	0.22
E98	12	400	0.20
* The E10 fuel blend is the benchmark for all risk values. All risk values are scaled equally to set the E10 risk to a value of 1.			

The E98 fuel presents the highest overall risk relative to the E10 benchmark. The high risk of the E98 fuel is driven by the increased likelihood of tank headspace detonations. E98 creates flammable tank headspaces up to 95 degrees Fahrenheit, whereas the other fuel blends in the study are required to be nearer to 5 degrees Fahrenheit to create flammable tank headspaces. The higher UFT of E98 results in increased vaporization, leading to larger flammable vapor plumes from flammable tank headspaces that extend farther than E83 and E51 blends. Although the flammable vapor plumes from E98 do not exceed those from the E10 fuel, the reduced likelihood of ignition is offset because the E10 fuel is less likely than E98 to be stored under conditions that create a flammable tank headspace.

The increased risk of the E10 fuel as compared to the E51 and E83 fuels is driven by the high risk of fuel spill scenarios for E10. The increased risk associated with E10 fuel spills, as compared to higher ethanol fuel blends, is the result of several factors that were analyzed as part of the consequence modeling. Firstly, the fire scenarios for E10 present larger radiation zones than other fuel blends due to the fact that E10 has the highest flame emissivity of the fuel blends analyzed. Flame emissivity decreases with increasing ethanol concentration of the fuel blends. A second reason for E10's increased risk results is the fact that the E10 blend has the lowest Lower Flammable Limit (LFL) and the higher vapor pressure. Blending increased quantities of ethanol into gasoline results in depression of the vapor pressure and an increase in the LFL of the fuel. The result is that higher ethanol fuels produce less flammable vapor, and it requires less air to dilute the vapor below its LFL. Therefore, when comparing fuel spills of the fuels, E10 produces the largest amount of flammable vapor. This increases the probability of E10 being ignited in a spill scenario. The tangible end result which directly affects the risk of ignition is that the reduced vapor pressure and LFL of higher ethanol content blends result in a smaller flammable vapor plume than E10.

Although the cumulative risk of the E83 fuel from all scenarios does not exceed the cumulative risk of the benchmark E10, the risk of E83 fuel from tank headspace detonations does exceed the risk of the E10 benchmark. The high risk of the E83 fuel from tank headspace detonations is caused by the increased likelihood of E83 to be stored in the flammable range. The UFT of E83 is much more sensitive to ethanol content as compared to lower ethanol content fuel blends; minor blending errors for E83 fuels can have large effects on the temperature at which the headspace becomes subject to detonation.

Recommendations to mitigate the increased risk of handling E83 and E98 fuel blends in identified scenarios are provided in the Recommendations section near the end of the report. A summary of conclusions made in the study are presented in the Conclusions section at the end of the report.

Introduction

Background

The consumption of high-ethanol content fuels has increased in recent years. The term ethanol flex fuel or E85 has been used to refer to fuels used in flexible-fuel vehicles (FFVs). Ethanol flex fuel contains 16 vol% to 83 vol% ethanol

. Ethanol fuel blends for flexible-fuel automotive spark-ignition engines blended in accordance with ASTM D5798 may have an ethanol concentration ranging from 51 vol% to 83 vol% with the balance being gasoline or hydrocarbon in the gasoline boiling range. According to the US DOE Energy Information Administration, there were 10.7 million FFVs in use in 2012, with 2,300 stations dispensing ethanol flex fuel across the country. More than 340 of the stations had blender pumps that offer various ethanol-gasoline blends [1].

The US Department of Energy supports efforts to increase the use of ethanol-rich transportation fuels such as E85. Furthermore, the mission of the US DOE's Clean Cities program is to advance the energy, economic, and environmental security of the United States by supporting local decisions to adopt practices that reduce the use of petroleum in the transportation sector. However, infrastructure compatibility and safety have historically been one of the most difficult deployment hurdles to address when introducing a new transportation fuel. The proximity of self-serve fuel dispensers and underground storage tanks to the consumer elevates concerns regarding potential unintended consequences. The physical and chemical properties of ethanol-rich fuels are different from those of conventional transportation fuels; therefore it is critical to evaluate the situation to ensure safety.

According to National Fire Protection Association (NFPA) data, there are over 5,000 fires per year at filling stations. These fires have resulted on average in 2 deaths and 48 injuries, on an annual basis. 61% of the fires involved vehicles, and the most common type of material ignited is liquid fuel [2]. The NFPA report does not distinguish between spark-ignition engine fuel types, so conclusions cannot be made from this data regarding the fire risk of various fuel blends. Fuels with properties different from the gasoline blends currently dispensed at most retail stations have the potential to change the frequency of these events. Therefore it is prudent to consider the effects of fuel properties, specifically those of high-ethanol content fuels, on the risk to people at the service station.

To assess the change in risk, a probabilistic risk assessment (PRA) based approach was warranted rather than relying on the limited historical/anecdotal data which does not reflect a market that is handling large volumes of high-ethanol content fuel. The baseline fuel selected for the study was a blend of 10% ethanol and 90% gasoline, commonly referred to as E10. E10 was selected as the benchmark fuel as it is currently the most widely used spark-ignition engine fuel in the market place. Based on published literature and guidance to fuel handlers and service station operators, "unloading gasoline-ethanol blends with ethanol concentrations up to 10 % presents the same fire-safety hazards as gasoline", and "the fire hazard for spilled E10 should be considered the same as for base gasoline" [2], [5]. The risks associated with gasoline are expected to be similar to those of E10, as the flammable properties of the fuel are similar. The most important difference between E10 and gasoline from a fire risk perspective is ethanol's increased electrical conductivity, which reduces the likelihood of static accumulation and discharge that may ignite the fuel.

There are a relatively small number of US service stations currently selling high-ethanol content fuel, but that number stands to increase in the future as a result of increased demand, and government legislation. Considering the forecasted increase in the demand for high-ethanol content fuels it is prudent to consider the change to the risk imposed to service stations as a result of handling, storing, and dispensing these fuels.

Objectives

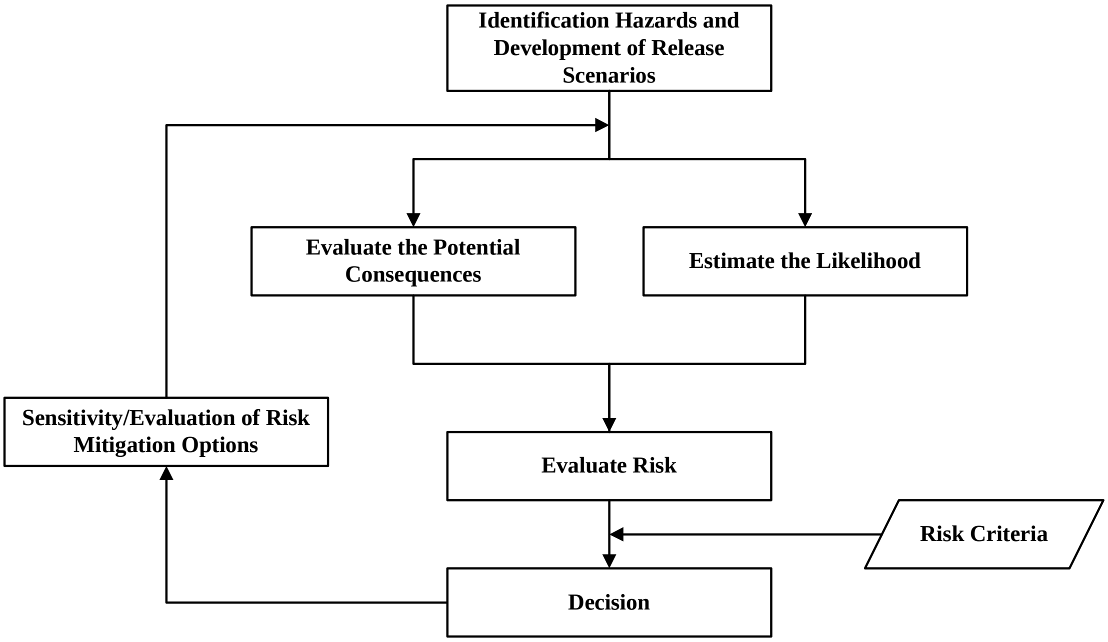
This risk analysis was conducted to fully judge the safety implications, if any, of the introduction of new high ethanol content fuel blends into the marketplace. While it is also necessary to understand potential risks posed to fuel handlers along the distribution chain, including pipeline and terminal operators, these analyses are not included here, but should be considered for future studies.

The objectives of the current project were to determine the incremental change in risk due to a change in spark ignition engine's fuel stored, handled and dispensed at a service station, specifically, ethanol flex fuel blends (e.g. a blended fuel of 51-83 vol% ethanol plus 49-17 vol% gasoline) as well as denatured ethanol. A benchmark was set at the currently accepted public safety level of a station handling, dispensing, storing, and allowing for self-serve dispensing of an E10 blend (10 vol% ethanol blended into a base gasoline).

The vapor pressure (a measure of fuel volatility used in fuel blending) of the fuels was set as follows for the purposes of consequence modeling only: E10 – 10 psi, E51 – 8.5 psi, E83 – 8.5 psi, and E98 – 2.3 psi. These ethanol fuel blends represent summer fuel blends that comply with EPA summer gasoline requirements for E10, and ASTM D5798 Class 1 standards. The vapor pressure of each of the high ethanol content fuel blends was set at the upper limit of the allowable vapor pressure range in order to generate a worst credible scenario in regards to the generation of flammable vapors. More volatile fuels (those with higher vapor pressures) generate more flammable vapor than less volatile fuels. The fuel volatility was used in the consequence modeling to determine the relative size of potential flammable vapor releases from tank headspaces or the evaporation of liquid spills to the ground.

To meet these objectives, AcuTech based its approach on the use of generally accepted risk assessment methodologies, as detailed in guidelines published by the American Institute of Chemical Engineers' Center for Chemical Process Safety. An overview of the risk assessment process is illustrated in
Figure 1.

Figure 1: Risk Assessment Overview [3]



The underlying basis of risk assessment is simple in concept, and provides a structured methodology and guidance to answer questions such as:

- What can go wrong (what are the hazards)?
- How likely is it (what is the frequency of occurrence)?
- What are the consequences (and potential impacts)?
- What is the level of risk?
- Is the level of risk tolerable?
- Are additional safeguards required (to reduce the likelihood or consequence)?
- How does the risk compare to other alternatives?

The term "risk" means different things to different people, and unless it is clearly defined in a particular context, any discussion on this subject will have the potential to be both confusing and misleading. One of the objectives of this project is to define the risk assessment protocol and establish risk criteria to evaluate, for E51, E83 and E98:

- If the incremental level of risk is tolerable, considering the existing safeguards;

- If the incremental risk identified is not tolerable, then what additional safeguards are needed to reduce or manage the risk of the high-ethanol blends?

- How does the risk compare to E10?

Scope

The focus of the current effort is on service station tanks as well as vehicle fuel tanks. The intended audience is the safety community, i.e., NFPA, AHJs (Authorities Having Jurisdiction), Fire Marshalls, UL (Underwriter's Laboratory), safety officers at fuel marketing companies, petroleum equipment installers/maintainers, automotive companies, and other interested parties.

The risk assessment takes into consideration events that fall in these general classes:

- Hardware or human failure that may result in the electrostatic ignition of a flammable tank headspace (Underground Storage Tank (UST), Atmospheric Storage Tank (AST), Light Duty or Medium Duty vehicle tank).
- Human error resulting in release of a flammable tank headspace in the presence of an ignition source.
- Accidental impact on hardware resulting in release of flammable headspace in the presence of an ignition source.
- Catastrophic hardware failure leading to instantaneous release of flammable headspace in the presence of an ignition source.
- Degradation hardware failure resulting in a gradual release of flammable headspace in the presence of an ignition source.
- Other fires (area fires, pool fire, brush fire) which result in release of flammable headspace in the presence of an ignition source.

Items that are not within the current scope, and are not be included in this analysis:

- Terminal storage tanks, tanker trucks and rail cars.

- Materials compatibility, unless directly related to a failure mode that would cause or allow a spark of sufficient energy to enter the headspace above ethanol gasoline blends.

- Toxicity and environmental impacts (groundwater or air quality).

Risk Assessment Approach

Overview

Risk assessments can vary from simple, screening-level analyses intended to provide an estimate of the range of hazards and risk, to very comprehensive, detailed analyses of incident probabilities, hazardous materials release probabilities, the adverse effects resulting from exposure to these hazardous materials, and comparison of the level of risk to various risk criteria.

The basis for the information and data used as an input to this risk assessment is:

- Data generated by the National Renewable Energy Laboratory (NREL) and others.
- Analyses provided by Reddy [4].
- Expertise that resides in the Risk Assessment/Hazard Analysis (RA/HA) team regarding all aspects of fuel delivery and dispensing at public service stations.

For this project, a phased approach to assessing risks was utilized, starting with simple analyses and progressing in complexity. The levels of risk assessment in the study can be defined as follows:

- **Qualitative Risk Assessment** is an assessment based primarily on description using historical experience and engineering judgment, with little quantification of the hazards, consequences, likelihood, or levels of risk. This is a preliminary risk assessment step, and is normally applied before further semi-quantitative or full quantitative assessments are conducted. The results may be used for the prioritization of hazards or risks.
- **Quantitative Risk Assessment** includes numerical estimates of both likelihood and consequence, and a calculation of risk (in terms of impacts per year). Quantitative risk assessments include a full spectrum of release scenarios, and as such the results can be compared directly to published risk criteria.

Definitions

The risk analysis process utilized by AcuTech made use of the following definitions:

- **Risk** – The chance of the impacts to people, property, business, or damage to the environment. It is measured in both likelihood and magnitude of the loss. To evaluate risk, a combination of hazard, event, consequence and likelihood is used.
- **Hazard** – A chemical or physical condition that has the potential for causing adverse impacts.
- **Event** – An unplanned incident or a series of incidents leading to a specific release scenario, and resulting consequence.
- **Consequence** – A measure of the expected outcome of an event within the hazard zone. It is expressed in terms of impact, such as the number of potential casualties, amount of property damage, business interruption or contamination of the environment.
- **Likelihood** – A measure of the expected probability of occurrence of an event. This is expressed as expected events per year.
- **Societal Risk** - The relationship between the likelihood of an event and the number of people affected. Reported as the societal risk index (SRI), the value represents the number of fatalities expected per year to occur as a result of a hazard scenario. These

values are reported relative to the E10 baseline fuel. Therefore, they are reported as scaled risk results.

- **Risk Criteria** – Defined levels of risk that enable a judgment to be made regarding the significance of estimated risk levels. This report sets the current, publicly accepted risk of the service station handling and dispensing E10 as the acceptable risk criteria.

Project Tasks

The project was conducted under the following main task headings:

- Task 1 – Project Planning
- Task 2 – Literature Review
- Task 3 – Qualitative Risk Assessment
- Task 4 – Quantitative Risk Assessment
- Task 5 – Results / Reporting

Task 1 – Project Planning

Initial planning was conducted through a series of meetings and teleconferences between AcuTech, CRC and the CRC Project Panel, as required. The meetings confirmed the scope of work, goals and objectives and schedule for each of the tasks and provided an opportunity for clarifications and input to the risk assessment process.

As part of these initial team meetings the blends to be investigated were discussed and reviewed. Additionally, the range of credible ambient temperatures was finalized with the RA/HA team, ensuring these parameters span the extremes of the most dangerous but plausible, conditions.

Following the planning meetings AcuTech prepared an updated project schedule and work plan.

Task 2 – Literature Review

Before beginning the qualitative and quantitative risk assessments, a literature review was completed. The focus of the literature review was:

1. General Literature Review. Review by AcuTech of literature provided by the CRC Project Panel and any other sources of data regarding headspace flammability for handling flammable liquids germane to the analysis as well as other case studies of explosions of this nature that have occurred, been investigated for root cause, and documented. The literature survey included a review of codes, preventative barriers and incidents in Sweden and Germany that have aggressive requirements in this area, as well as other applicable international regulations.

2. Review of static electricity issues. AcuTech conducted a review and study of static electricity with respect to gasoline-ethanol blends. The review examined whether gasoline-ethanol blends can create and hold sufficient static during product transfer activities which promote static generation. Specific activities may include, but are not limited to: nozzle flow velocities during vehicle refueling, truck/rail/marine loading rates, product transfers into tanks, product transfers/drops into underground storage tanks, vapor velocities out of vessel vents during these events, product velocities during overfill/overflow events, and other activities that could be more hazardous than E10 transfers.

3. Definition of primary fire and explosion hazards. AcuTech identified and detailed fire and explosion hazards at the service station over a range of possible ambient temperatures. In consultation with the CRC Project Panel, the scenarios of greatest concern regarding potential hazard that could lead to potential fatalities and injuries to the public, as well as to workers in the distribution system, were defined as the focus of the remainder of the study. These hazards were identified as part of the literature review and defined in detail in the Qualitative Hazard Analysis conducted in Task 3.

4. Development of tolerance criteria. AcuTech worked with CRC and the RA/HA team to develop a consequence vs. frequency risk matrix for use in evaluating the hazardous scenarios developed in Task 3. The risk assessment matrix utilized was consistent with DOD MIL-STD-882E, Standard Practice for System Safety, Appendix A [6], consisting of:

- Consequences and Impact Levels:
  - Health and Safety Impacts – Ranging from no impact to potential fatality/ multiple fatalities
  - Financial Impacts – Not within the current scope
  - Environmental – Not within the current scope
- Likelihood – Ranging from improbable to frequent

Task 3 – Qualitative Risk Assessment

AcuTech facilitated an initial qualitative risk analysis to identify and evaluate the range of key scenarios of concern for the high ethanol content fuels. The Hazard and Operability (HAZOP) methodology was utilized for the study (see, Qualitative Risk Analysis Section for details of the study and results).

The Qualitative Risk Analysis was conducted over two sessions – October 15, 2013 (at RA/HA Meeting in Chicago) and December 16/17, 2013 (at AcuTech headquarters in Vienna, VA). The study was recorded by AcuTech, using PHA-Pro™ software. PHA-Pro™ is one of the leading Process Hazards Analysis (PHA) software tools in the market.

Scenarios

The HAZOP included discussions of the following types of scenarios:

- Fire during a fuel hose drop hose/truck/UST connect
- Disconnect (static)
- Fire inside UST (static)
- Fire inside UST (electrical short pump/sensor)

- Surface/Area (brush/forest) Fire overwhelms tank vents/tanks
- Spill/pool fire at dispenser flash back to UST/to P/V vents
- Spill/pool fire during fuel drop flash back to UST/to P/V vents
- Lighting strike on UST vents
- Lighting strike on UST with EVR Phase I systems
- Stage 2/nozzle fire flash back to vehicle tank/to UST
- Loss of containment from meter/hose/nozzle spill fire/flashback to UST
- Failure of legacy P/V, vapor fire flash back to UST

The risk matrix developed in Task 2 was used to aid the team in defining "high" risk service station accident scenarios for more detailed analysis. Seven HAZOP scenarios were identified for detailed consequence modeling and likelihood analysis in Task 4.

Task 4 – Quantitative Risk Assessment

In practice the majority of "high" risk issues cannot be resolved using qualitative techniques alone. The next phase of the risk assessment approach applied quantitative risk techniques to better refine the estimates of consequence and likelihood of the scenarios developed in Task 3, as well the benefits on any identified risk reduction measures.

Consistent with the definition of a quantitative risk assessment, the process includes quantifying the consequence (hazard severity and impacts) using consequence modeling software, and quantifying the likelihood using failure rate data, fault tree, and event tree analysis.

Literature Review Results

Fuel Properties

Ethanol is blended with gasoline to produce fuels with an ethanol content ranging from 10 to 98% ethanol by volume. The properties of ethanol-gasoline fuels vary as a result of the ethanol content, as well as the hydrocarbon blending components used. Table 2 provides a comparison of several of the physical properties for neat ethanol and gasoline related to the risk of fire and explosion. These properties represent those of pure ethanol and gasoline respectively, ethanol fuel blends have different properties determined by the amount of ethanol in the blend and the specific properties of the gasoline used for blending.

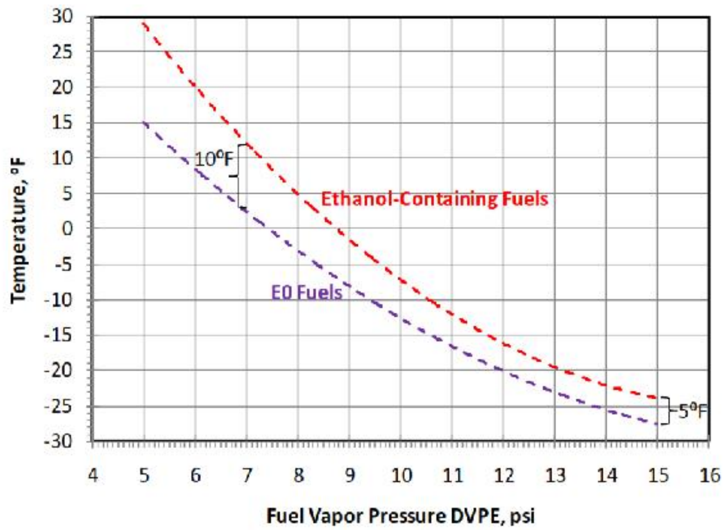
Table 2: Flammable Properties of Neat Ethanol and Gasoline [1]

Property	Ethanol	Gasoline
Lower Heating Value (BTU per gallon)	76,300	116,900
Vapor Pressure (PSI)	2.3	7-16
Flammable Range (%)	3-19	1-8
Auto-Ignition Temperature	850	495
Stoichiometric Air/Fuel Ratio (by weight)	9	14.7

The lower volatility of ethanol, indicated by the lower vapor pressure, causes the flammable temperature range of ethanol to be higher than gasoline. Gasoline stored in a closed container at normal atmospheric temperatures creates an equilibrium vapor headspace that exceeds the flammable range of 1-8% hydrocarbon. The vapor headspace of a tank storing gasoline is not able to ignite and burn, as there is insufficient oxygen to sustain a combustion reaction. Pure ethanol or E98 under the same conditions however may create a flammable headspace, providing the potential for ignition of the headspace of a tank containing ethanol. .

Blending ethanol into gasoline increases the upper flammability temperature limit and creates a fuel with a flammable range that is more likely to extend into the range of ambient temperatures. Figure 2 illustrates the effects of ethanol content on the flammability of a fuel tank headspace.

Figure 2: Effect of Ethanol on Upper Flammability Temperature [4]



As a result of the increased auto-ignition temperature of ethanol, ethanol vapors have a reduced potential for hot-surface ignition; however, this difference does not preclude ignition of ethanol vapors by hot surfaces

Electrostatic Hazards in Service Stations

Introduction

As a part of the Literature Assessment, a review of static electricity issues in service stations was conducted with the objective of gaining a better understanding of the roles of static ignition sources in the fire and explosion risks in service stations. The review focused on static ignition hazards associated with:

- Unloading road tankers into gasoline storage tanks at service stations; and
- Refueling automobiles.

Sources of electrostatic ignition at service stations have ignited many flash fires and explosions and resulted in personal injuries and property damages. The occurrence and energy level of electrostatic ignition sources are affected by many factors, including the characteristics of the liquid fuels, weather conditions, the equipment (road tankers, dispensing systems and automobiles), unloading work procedures, customer activities, and service procedures (storage tanks). While any one of these factors could play a major role in individual situations, the aim of this review was to provide an overall picture of the electrostatic hazards in service stations, particularly the effects of the difference between ethanol-gasoline blend fuels and conventional gasoline fuels on the static ignition risk in road tanker unloading, fuel storage, and vehicle refueling.

This review has identified some important research articles, incident investigation reports, and incident history reports which are listed as references.

This review presents a summary of the general understanding of the static issues in service stations based on the current best knowledge about the electrostatic ignition phenomena as affected by equipment design and operating practices at the time of the incidents. Since the static issues are dependent on the equipment designs and operations, the influential factors on static ignition risks have to be dealt with in risk assessment processes for individual scenarios.

Electrostatic Hazard Characteristics

Conductivity is an important physical property that affects the risk of electrostatic ignition and is often used to classify liquids into nonconductive and conductive liquids. The definitions of conductive and nonconductive liquids may vary from standard to standard, however, a general consensus is that liquid with a conductivity value less than 50 picoSimens per meter (pS/m) can retain significant amount of electrostatic charge even when the liquid is in contact of earthed metallic surfaces.

Nonconductive Liquids

It is generally recognized that liquids with electric conductivities less than 50-100 picosiemens/meter (pS/m) are nonconductive (insulating) liquids, which can accumulate hazardous levels of electrostatic charges in typical industrial processes.

Gasoline without ethanol can have electric conductivity varying from 10 to 3000 pS/m [8]. API Recommended Practice 2003 "Protection Against Ignitions Arising out of Static, Lightning, and Stray Current" [6] states that a liquid with a conductivity less than 50 pS/m is a static charge accumulator. The European Standard [7] also considers liquids having conductivities less than 50 pS/m as nonconductive liquids. NFPA 77 considers liquids possessing a conductivity less than 100 pS/s as nonconductive liquids. [8]

Gasoline without ethanol can have electric conductivity varying from 10 to 3000 pS/m [6] and can be capable of retaining hazardous levels of electrostatic charges. Experiments have shown that the highest charge generation occurs in a conductivity range of 5-50 pS/m [9].

Gasoline Blended with Ethanol

The conductivity of liquid fuels is not a major factor in the accumulation of a charge in fuels when systems are properly grounded. The conductivities of some liquid fuels were measured at 21 °C by Jaakko Paasi et. al (2009) [10]. The conductivity of the ether-petrol (conventional gasoline) used in tests was on the order of several hundred pS/m. On the other hand, the addition of 10 vol% ethanol (an E10) increased the electrical conductivity of the liquid fuel blend significantly. The conductivity of E10 was over 10,000 pS/m and E85 had a conductivity over 10^7 pS/m. These results show that the commercial gasoline-ethanol blends are conductive liquids.

Similar results were obtained by other researchers [11]. Reference [11] states that gasoline blended with at least 10 vol% alcohol (E10) has an electrical conductivity several orders of magnitude higher than traditional fuels and is unlikely to generate hazardous levels of static electricity due to liquid flow.

Electrostatic Ignition Hazards during Unloading Road Tankers into Gasoline Storage Tanks at Service Stations

Fire and explosion incidents when unloading gasoline fuels from road tankers occur from time to time and there have been media reports on such incidents.

Electrostatic Ignition Hazards during Unloading

The risk of electrostatic discharge (sparking) from the liquid (gasoline) is determined not only by the conductivity of the liquid but also the rate of static charge generation on the liquid. The rate of electrostatic charge generation on liquid is dependent on the physical properties (electrical conductivity) and flow conditions (flow rate an pipe/hose diameters). One important safety rule from industrial experience is that if the product of flow velocity and the diameter of the pipe/hose is less than 0.5 m^2/s, the risk of sparking from liquid will be low, although it cannot ensure that static ignition will not occur [8]. During fuel tank truck unloading, the main source of electrostatic charge generation is the gasoline flow through various components in the tank truck unloading system, such as the hoses and piping components. Electrostatic sparks from insulated conductors in fuel unloading system are among the most incendive discharges that can occur.

Since gasoline-ethanol blends (with at least 10% alcohol) have conductivities several orders of magnitude higher than traditional fuels, they are unlikely to generate hazardous levels of static electricity due to liquid flow. As long as the fuel liquid is in contact with ground in the liquid fuel unloading system, it is unlikely to accumulate hazardous levels of static charge on the liquid.

It should be noted that the high conductivity of gasoline-ethanol blends only prevents static ignition sources from the fuel liquids. All other potential ignition sources that can cause ignition of ethanol-free gasoline can also pose electrostatic ignition hazards to gasoline-ethanol blends.

Work Safety - Related Electrostatic Ignition Sources during Road Tanker Unloading

There are many situations in road tanker unloading operations where fires and explosions can be initiated by electrostatic discharges from components other than fuel liquids. The most likely electrostatic ignition source is the one who unloads the road tanker (usually the truck driver). In one tragic case, a fire/explosion was ignited, most likely by a spark from the driver when he was checking the fuel level inside the tanker. The driver suffered severe burns and later died.

Such incidents typically happen when the following situations occur:

1) Leaks from road tankers, hoses, or connections;
2) Overfill of underground storage tanks – as a result of not following operating procedures, lack of sound requirements from companies, lack of training, lack of requirements for both service stations and the truck deliveries; or
3) Criminal acts such as gasoline theft or sabotage.

Flash Fires in Filling Automobiles

The Petroleum Equipment Institute (PEI) has been collecting data on service station fires during vehicle refueling, which are related to electrostatic discharges and has published a summary of incidents from 1993 through March 2010 [14]. A detailed report listing all incident reports received and confirmed by PEI through March, 2010 contains information classified by various categories.

One hundred seventy-six reports (176) were compiled for the report. In all of the incidents, PEI was able to verify that no open flames, running motors, or electrical continuity problems were involved. The accidents occurred with both conventional and vacuum-assist Stage II vapor recovery nozzles. There were no accidents reported to PEI when balance system nozzles were used. Driveway surfaces included concrete, asphalt, stone, crushed rock and dirt. Fires occurred with many different types of nozzles, hoses, breakaways and dispensers. No cell phones were involved. A wide variety of clothes were worn by the refuelers. Rubber-soled shoes were worn by the refuelers in 94% of the accidents where footwear was identified.

The summary shows a pattern that more incidents occurred on cold days when the humidity in air was low. Among the 176 fires, 87 fires occurred when the refueler returned to the vehicle during the refueling process and then touched the nozzle after leaving the vehicle. Thirty-nine reports described fires before the refueling process began, when the refueler touched the gasoline cap or the area close to it after leaving the vehicle. Thirty-two fires did not involve either of these two fact situations. In all but two of these cases the refueler was not the source of the electrical discharge and the source of ignition could not easily be determined.

These data suggest that in most cases the sparks would have been from the refuelers and in some cases the sparks could have been from the nozzles or other parts of the dispensing system or vehicles.

Persson et al. [15] conducted measurements in and around fill pipes using an actual gasoline dispensing unit to determine the fuel concentrations and composition present around the refueling pipe in a vehicle in conjunction with refueling.

In the case of "conventional" tanks, one can verify that the fuel vapor concentration inside the refueling pipe was approximately 10-12% which is probably above the flammability limit. The fuel vapor concentration outside the refueling pipe was, however, within flammability limits (approximately 5-6%) when the gas recovery system was not activated. When the gas recovery system was activated, very low concentrations of fuel vapors were measured at all points outside the refueling pipe. These concentrations were probably below flammable limits.

Test results of tanks that had Onboard Refueling Vapor Recovery (ORVR) showed that the fuel vapor concentration inside the refueling pipe was below the minimum detection level for the analysis instruments. Based on this fact, one can draw the conclusion that the risk for ignition is significantly reduced by the ORVR.

It is of interest to note that the fuel vapors emitted in conjunction with refueling contain mainly petrol fractions despite the high concentration of ethanol in the liquid phase.

As pointed out by Persson et.al [15], the number of tests and types of tanks tested was very limited in this test series considering the large number of car models on the market. As all possible fuel combinations could potentially be present in the fuel tanks during refueling, the gas concentrations and composition could vary significantly. Further, the effect of temperature, wind and the presence of a vapor recovery system, or an ORVR system, may also have a direct effect on the extent of the "cloud" of fuel vapor produced when refueling. It is, however, clear that a flammable mixture could be present around the refueling opening, in particular in the absence of an ORVR (Onboard Refueling Vapor Recovery) system.

Summary of Key Findings Regarding Electrostatic Hazards

1) Unlike conventional gasoline, ethanol gasoline blend fuels (E10 or higher) have high electric conductivities, which makes it unlikely to generate hazardous levels of electrostatic charge by liquid flow. In other words, there is little risk of electrostatic charging with such fuels themselves during unloading, refueling and receiving in storage tanks. However, electrostatic ignition sources other than fuels can still occur in service stations when handling gasoline-ethanol blend fuels.

2) During unloading of ethanol-free gasoline fuels from road tankers, there is a risk of electrostatic ignition by hoses that are made from insulating materials. However, when unloading ethanol blends, it is unlikely to have electrostatic charging on the fuel unless the hoses are charged externally by other mechanisms.

3) Tank truck drivers or people who are involved in unloading operations can become the ignition sources of road tanker fires under abnormal conditions such as:

    – Leaks of fuel liquids;

    – Breakage of hose/pipe connections;

    – Inspection of liquid levels in storage tanks;

    – Inspection of liquid levels in road tankers;

    – Not following work safety procedures.

4) Electrostatic sparks are a major ignition source that has ignited flash fires in service stations during refueling. Among these sources, the refuelers are the dominant ignition sources. However, incident history indicates that in some cases the sparks that initiated the fires could have been from components of the refueling system or vehicles.

5) Measurements results show that the fuel vapors emitted in conjunction with refueling contain mainly conventional gasoline fractions despite the high concentration of ethanol in the liquid phase.

Use of Conservation Vents and Flame Arresters on UST Vents

The American Petroleum Institute (API), in API Standard 2000 [16] states that a flame arrester is not considered necessary for use in conjunction with a pressure/vacuum valve venting to atmosphere, because flame velocities are lower than vapor velocities across the seat of the pressure/vacuum valve. However, testing has proven that flames can flashback across conservation vents [17]. As a result of this, many organizations recommend, and some regulatory authorities require, the use of flame arresters and specifically do not allow the use of conservation vents to prevent flashback. Included among these are:

- The American Institute of Chemical Engineers (AIChE) states specifically, "A conservation valve should not be used as a flame arrester, unless the device is approved according to flame arrester standards." [17]
- The Southwest Research Institute performed a study of relevant literature and found several bodies that advise the use of flame arresters. One of the especially relevant issues pointed out in this survey was that, "Since the minimum experimental safe gap (MESG) decreases as the ethanol concentration is increased, flame arresters designed for gasoline may have gaps too large to stop flame propagation for gasoline-ethanol blends especially with higher concentrations of ethanol." [18]
- The Swedish Petroleum Institute states that, when loading storage tanks, "Flame arresters must…" be used. [19]
- The Swedish Authority for Civil Protection and Preparedness endorses the Swedish Petroleum Institute's recommendation regarding flame arresters: "For those who do not build according to SPI's recommendations, it is important that a professional investigates and assesses the need and placement of such protection." [20]
- The UK Association for Petroleum and Explosives Administration (APEA) has issued guidance that, among other requirements, states, "As there is likelihood that a flammable atmosphere will be present in… [the] storage tank, the following measures are required to prevent a flame (from an external fire) from travelling through pipework and into the tank.
    - A flame arrester should be situated at all open entries to the tank vapour space including the following positions:
        - - The end of or in the vent pipe
        - - The stage 1b vapour recovery connection
        - - The stage 2 vapour recovery connection between the dispenser and the vapour return line. [21]
- The German equivalent of OSHA has implemented requirements that all underground storage tanks containing greater than 60% ethanol must have flame arresters of explosion group IIA. [22]

Other Literature Search Findings

There were several other findings identified during the literature search performed for this report. Much of this information was used in the development of this analysis. Those most relevant/significant findings are summarized below:

- Blending fuel ethanol and base gasoline together can create a range of products with properties different than the original constituents. Before handling, storing, and dispensing gasoline-ethanol blends, consideration should be given to the design and compatibilities of all components coming in contact with the blended liquid and vapors. Blend properties that should be taken into account include, stress corrosion cracking of steel structures, the flammability of vapors, vapor pressure, the hydrophilic nature of ethanol, the differential solvency of ethanol (i.e., the impact on polymeric materials, such as swelling, extraction, permeation, and embrittlement) and the water tolerance of ethanol blends. When a new blend is introduced, evaluate these properties for every step in the supply chain to assure product quality and safe handling and storage. [23]

- Ethanol fuel has corrosion properties that differ from gasoline that must be taken into account when selecting materials. Inter alia aluminum, zinc, and brass are unsuitable materials for ethanol fuel service. Ethanol fuel can also affect certain plastics and rubber materials in a manner different than gasoline. [20]

- When ethanol is added to gasoline, the vapor pressure of the blend is higher than that of the gasoline alone for low ethanol concentrations. An addition of fuel ethanol to base gasoline to make an E10 blend will typically increase the vapor pressure of the blended fuel by approximately 6.89 kPa (1 psi) above that of the gasoline alone. With further addition of ethanol, the vapor pressure of the blend decreases until it reaches the vapor pressure of ethanol at 100 % concentration. [23]

- It should be noted that fighting Ethanol E85 fires with foam requires access to an alcohol-resistant quality. [19]

- In manual level measurement (direction finding), the increased risk of ignition must be considered. There should be instructions on how the measurement is performed in a safe manner and as an extra precaution, use a wooden skewer. From the safety point of view, however, of the options available for level measurement, e.g., with measuring sticks, automatic tank gauging (ATM), the preferable one is direction finding. [20]

- E85 of summer and winter qualities were conditioned in sealed vessels at various temperatures, and the composition and concentration of the fuel vapors were determined. Fuel vapors from conditioned vessels were also used for ignition tests in an explosion chamber (the bomb). The tests show that the fuel vapors mainly consist of petrol fractions despite the high content of ethanol in the liquid phase. The bomb tests indicate a flammability range of the fuel vapors from about -18°C up to about 2°C to 5°C for E85 of summer quality. These tests indicated a flammable range up to -8° to -9°C for winter E85 and up to -20°C for petrol. The lower limit of the flammable range was not investigated for these fuels. [24]

- The consequences of ignition of fuel vapors inside some fuel tanks for cars have also been studied. Electrical sparks were generated inside the tank or at the filling opening. In addition, a spill fire below the tank was used as an ignition source. When the ignition occurred inside the tank, the overpressure caused a rupture and generated a short duration flame outside the tank. [24]
- Tests have also been conducted to study the fuel vapor concentration and composition around the filling pipe during filling of the tank. The measurements indicate that vapors in the flammable range might be present around the filling opening, especially if the vapor recovery system at the fuel pump is not activated. [24]

Incidents

There is a history of various types of fire and explosion incidents involving gasoline occurring at service stations. Ethanol containing fuels are subject to many of the same types of scenarios, but the expected consequence differs, especially if a fuel tank headspace is flammable and ignites.

Nozzle Fires

Nozzle fires are rare occurrences but they do occur during dispensing and fueling. The incident involves the ignition of vapors venting from the vehicle fuel tank filling neck during vehicle refueling. Displacement of the vehicle fuel tank headspace results in flammable vapors venting from the vehicle filling neck, and the creation of a flammable vapor cloud. Gasoline and ethanol containing fuels will both create a flammable vapor cloud when the tank headspace is displaced. In the majority of nozzle fire incidents, the flammable vapor is ignited by the customer, either by static discharge or the presence of a sparking device or open flame; however, other ignition sources in the area may also have the ability to ignite the nozzle fire, so long as the ignition source reaches the flammable vapors.

Nozzle fires are normally marked by deflagration of the flammable vapor cloud and a sustained torch flame at the filler neck as the vapors venting from the fuel tank continue to burn. Flashback and detonation in the fuel tank is not normally possible as the vapor headspace is above the upper flammable limit. In the event that the tank headspace is in the flammable range, flashback through the fill line could result in headspace deflagration and catastrophic failure of the fuel tank.

Nozzles fires may escalate into pool fires if the filling nozzle is removed from the vehicle. This action can result in a spill of fuel to grade, with the fuel being ignited by the nozzle fire.

The hazards of nozzle fire are fire engulfment, and heat flux from fire radiation from the resulting pool fire. Flashback into the vehicle fuel tank will result in flash fire and pool fire radiation hazards, consistent with testing in Sweden [24].

Underground Storage Tank Detonations

Underground storage tanks (USTs) are used to store large volumes of fuel at service stations. The USTs are filled from tanker trucks on a periodic basis. USTs operate at atmospheric pressure with an open vent to the atmosphere.

Historically, UST detonations have been rare occurrences, as the tank headspace in a storage tank is generally above the upper flammability limit at normal atmospheric temperatures. However, UST detonations in storage tanks have occurred in idled USTs where fuel weathered. Lower vapor pressure fuels, or fuels subjected to low ambient temperatures may cause tank headspaces to become flammable and could result in tank headspace detonation if ignited.

Based on incident documentation, UST detonations are marked by a collapse of the concrete pad above the UST, as the surrounding materials falls into the void left by the failure of the UST walls [25].

The hazards of UST detonation are present for people located on top of the UST who may fall into the crater left by the UST and suffer burns and/or impact injuries.

Pool Fires

Pool fires occur when a flammable liquid is spilled to an open area and ignition of the fuel results in a fire burning above the pool. When a flammable liquid is spilled, it spreads to form a pool, and the fuel may be ignited immediately by liquid contact with an ignition source, or ignition of vapors generated by liquid evaporation. The fire will spread to cover the surface area of the spreading pool.

The size of the flame will depend on the spill surface and the thermo-chemical properties of the hazardous material. If the spill is confined, the confined area will determine the pool size which will then dictate the size of the fire. If the spill is unconfined, the pool dimensions will depend on the amount of liquid released (liquid volume), burning rate of the liquid, and the terrain surface characteristics.

The hazards associated with pool fires are fire engulfment, and heat flux from fire radiation.

Qualitative Risk Analysis

Qualitative Risk Analysis (Process Hazard Analysis) Overview

The study team members were guided through a systematic approach using guidelines set forth in Standard Practice for System Safety, MIL-STD-882E, developed by the Department of Defense and a PHA-Pro™ template developed by AcuTech for the review. The review was conducted over two sessions – October 15, 2013 and December 16/17, 2013

The methodology used for the qualitative risk assessment is the Hazard and Operability (HAZOP) technique. HAZOP is a structured means of systematically reviewing a process to identify potential hazards, understand potential consequences and impacts, evaluate current safeguards, estimate the level of risk, and determine appropriate measures to reduce or eliminate the likelihood or severity of the hazards to a tolerable level of risk. HAZOP is recognized as an accepted methodology by industries and regulatory agencies worldwide. This includes both OSHA PSM (29 CFR §1910.119[e]) and EPA RMP (40 CFR Part 68) regulations in the United States, as well as SEVESO II Directive; Control of Major Accident Hazards (COMAH); IEC 61511; ANSI/ISA S84.00.01 internationally. In addition, the American Petroleum Institute (API RP 750 and API RP 14J) and the American Institute of Chemical Engineers (*Hazard Evaluation Procedures*, *2nd Edition*) recognize the value of this methodology in analyzing process hazards.

The HAZOP study proceeds sequentially, studying each section of the process included in the project scope. The process under review is partitioned into "nodes," where there is a distinct intention for process parameters (for example, a specific intended temperature, pressure, or flow rate, or operation type).

The HAZOP technique is based on the premise that hazards and operability problems stem from deviations from design intent. To facilitate the review of each node in a structured manner, guidewords are used to capture the ways in which process parameters can deviate from design intent such as; No, More, Less, Misdirected, Reverse, etc. Other guidewords are defined and used as necessary. The guidewords are systematically combined with the relevant process parameters to yield deviations (e.g., No Flow, High Temperature, Low Pressure, etc.). For each deviation, credible causes are developed to define:

- Consequences
- Safeguards
- Risk Level
- Recommendation to Mitigate Risk, as deemed necessary

HAZOP is intended to be a team review of the process, hazards, consequences of deviation, safeguards, and need for additional risk reduction. Therefore, to conduct the HAZOP proposed in this task, a team of individuals from CRC and the RA/HA team with knowledge of the process and hazards participated.

The PHA team consisted of members of the CRC Project Panel and a study facilitator/scribe from AcuTech Consulting Group. Table 3 provides a roster of the team members present for the team sessions. The PHA was documented using a PHA template created for IHS's PHA-Pro™ software program.

Table 3: Risk Assessment/Hazard Analysis Team Members

Full Name	Company	Oct. 15, 2013	Dec. 16/17, 2013
Colin D Armstrong	AcuTech Consulting Group	X	X
Brent Bailey	Coordinating Research Council	X	
Dennis Boyd	BP America	X	X
Lew Gibbs	Consultant	X	
David Heller	AcuTech Consulting Group		X
Gary Herwick	Transportation Fuels Consulting	X	X
Jerry Horn	Chevron	X	
Dehong Kong	AcuTech Group Inc.	X	
Jim Simnick	BP America	X	
Chris Tennant	Coordinating Research Council	X	X
Marie Valentine	Toyota	X	X
Bill Woebkenberg	Mercedes Benz	X	
Kristi Moriarty	NREL		X
Scott Mason	Phillips 66		X

Results

Based on the results of the qualitative risk assessment, and discussions with the Project Panel representatives the following set of seven scenarios were detailed for further study as part of the QRA. The potential causes of the scenarios are detailed as well.

1. Large spill to grade during unloading (tanker truck hose rupture, or similar event that results in large spill).
   - Causes
     - Vehicle impact
     - Human error
     - Mechanical Failure

2. Ignition of UST vent stack vapors, with flashback through the vent connection and UST detonation
   - Causes
     - Surface fire/brush fire overwhelms tank vents
     - Ignition from lightning
     - Intentional defeat of stage 1 vapor recovery
     - High rate of vapor release during UST filling

3. Ignition of vapors vented at grade in UST area, with flashback and UST detonation
   - Causes
     - Human Error
       - Venting of vapors from UST at grade (loose stage 1 connection or dry brake propped open)
     - Ignition by static
     - Ignition by vehicle

4. Direct Ignition of UST headspace
   - Causes
     - Ignition by electrical malfunction
     - Ignition during manual gauging activities

5. Uncontrolled spill of fuel to grade in the dispensing area
   - Causes
     - Human Error
     - Mechanical Failure

6. Nozzle fire with flashback potentially into the fuel tank headspace if flammable
   - Causes
     - Static Ignition
     - Human Error creating ignition source

7. Detonation of vapors in an aboveground storage tank (AST) tank associated with California tank pressure management systems (consider in conjunction with UST detonation consequences)
   - Causes
     - UST Detonation Scenarios described in items

Quantitative Risk Analysis

Method

Figure 3: Quantitative Risk Assessment Method

In this section, the risk assessment method is applied to understand the overall risks that are associated with the use of E10, E51, E83, and E98 fuels. Refer to Figure 3 for the risk assessment method flow chart.

Consequence Analysis

In the terminology of risk assessment, consequence is a measure of the expected outcome of an event. It is measured or expressed as "hazard distance" or "hazard zone". The impact analysis addresses the potential effects of the hazardous consequences to people in the area of the service station.

The primary model that is used in this analysis is the commercially available PHAST (Process Hazard Analysis Software Tool) software, available from Det Norske Veritas (DNV). The PHAST software package is the oil, gas and chemical industry's leading commercial consequence package. Since its release in 1987, it has had an investment of 300 man-years for modeling, training, support and sales, of which 100 man-years have been directed to modeling development and improvement. PHAST has been well validated and is widely used in the oil and gas and chemical industry. Its models are well interconnected -- the source term model initializes the pool model, which initializes the dispersion model and initializes the flash fire and pool fire models. Therefore with PHAST, there is greater transparency in results than is the case with other packages where the user is required to manipulate the data at each calculation stage.

When modeling the hazards for high ethanol fuels, the zones or distance for different types of consequences (i.e., fires or explosions), it is very important to use a consistent set of criteria for estimating the degree of impact. These "endpoint" criteria refer to the following:

- For determining flammability hazards, several endpoint criteria are used. For flammable liquids that form pool fires or jet fires, a steady heat load or thermal radiation criteria, expressed in kW/m^2 or $BTU/hr\text{-}ft^2$ is used. For determining the flash fire hazard zone, a flammability vapor envelope that is diluted to its lower flammability limit (LFL) is typically used.

Hazard distances are directly influenced by the endpoint criteria used in the consequence analysis, with lower criteria leading to larger affected areas. Therefore it is important to establish a level of consistency in using these criteria.

For the cases of fires, endpoint criteria are a function of the thermal radiation levels, with the levels typically chosen to be consistent with the onset of third degree burns, second degree burns and the threshold for second degree burns. Three thermal radiation levels proposed are selected and are consistent with the data on human exposure to fires [26]:

- Fatality: > 12 kW/m^2
- Serious Injury: > 5 kW/m^2
- Minor Injury: > 2 kW/m^2

For flash fires, a single set of criteria is used, corresponding to the flammable envelope of the vapor cloud. Therefore, the endpoint criterion for fatality from a flash fire is taken to be the Lower Flammability Limit (LFL).

Likelihood Analysis

An important component of risk analysis is the estimation of the likelihood or frequency of each failure case or release scenario. Initiating event failure frequencies for each of the scenarios studied in the QRA are estimated using various sources (the preference will be for utilizing publically available data) including:

- TNO Guidelines for Quantitative Risk Assessment
- Health & Safety Executive (HSE) failure rates and event data for land use planning
- AcuTech's internal database

To supplement the initiating event frequencies, the following techniques will be used, as required:

Fault Tree Analysis

Fault Tree analysis (FTA) is used to develop process-specific events in order to focus on each such incident and break it down into basic equipment failures and human errors. Combining the probabilities and frequencies of the various human errors and equipment failures results in an overall frequency of the event occurring.

Event Tree Analysis

Event tree analysis is used for evaluating the range of possible outcomes that could occur following the release of a hazardous material. Therefore, the event tree analysis is used to determine the likelihood of different mitigation options working or failing, as well as the range of possible hazardous outcomes.

To complete the Event Trees the initial release frequency is defined (based on historical data, FTA, etc.) and entered into the initiating branch. Next probabilities are assigned to the remaining branches of the event tree, which are associated with the probability of the different outcome occurring. The final result is a unique scenario frequency for each potential consequence.

Uncertainty and Sensitivity

The risk assessment techniques described above are used to determine the risk-level associated with accidental releases of hazardous materials. Quantitative results are determined using various likelihood databases, consequence models, and other assumptions. Each of these inputs have limited accuracy, therefore there is uncertainty associated with risk assessment results. As a result, risk estimates should not be treated as exact measurements, but as a best estimate of the actual risk level.

Various sources of uncertainty are found in risk calculations, and these sources can be classified according to the different levels of calculation [27]:

- **Starting Points** – Before a risk assessment is started choices have to be made with regard to starting points. A conservative, worst-case approach requires a different type of model and different set of parameter values/assumptions than a best-estimate calculation.
- **Parameter Values** – As part of a risk assessment, parameters are collected and developed that represent the inputs to the analysis. Sources of uncertainty may include: impacts from exposure to a hazardous material (toxicity, thermal radiation, and blast overpressure), physical data for the chemical process, failure frequency data, etc.).
- **Models** – Uncertainties in models reflect the weaknesses, deficiencies and inadequacies intrinsic to any model, and is a measure of the degree to which a model fails to represent reality.

Clearly, uncertainty can be an issue if the limitations of the inputs are not fully transparent/understood in the decision making process. Therefore as part of any risk assessment:

- All inputs and assumptions should be documented.
- Sensitivity analyses should be conducted to determine the influence of inputs on the risk results.

Quantitative Risk Results

The results of the quantitative analysis will clearly define the level of consequence and likelihood, and the level of risk. In addition to the risk of the initiating event, the quantitative analysis and results will assess the adequacy of any existing or proposed safeguards.

Specifically the following types of results are provided:

- A risk summary table for each scenario, enabling a comparing the risk of the baseline E10 to E51, E83, and E98.
- The relative risk calculation (consequence x frequency) for the impacts to the public will be developed. This risk estimates are reported relative to the benchmark E10 fuel.
- Proposed recommendations to reduce the risk of scenarios that are determined to exceed the risk of the benchmark E10 fuel.

Scenarios

As part of the qualitative risk analysis study, seven scenarios were identified for further study in the quantitative risk analysis. The seven scenarios are provided here along with the potential causes, details of the scenario, and outline of the consequence modeling. The causes and details listed for each scenario were determined from the input of the RA/HA team, and data available from the literature review.

1. Large fuel spill to grade during unloading (tanker truck hose rupture, or similar event that results in large spill).
    - Causes
        - Vehicle impact
        - Human error
        - Mechanical Failure
    - Details
        - Volume – Tanker truck compartments are 3000-4500 gallons. Assuming 2000 gallons in compartment at time of release,
        - Release – 4" drop hose from the bottom of the tanker truck, full diameter
        - No diking/curbing, free pool spreading
        - Tanker truck operates at atmospheric pressure
    - Modeling
        - Release of fuel to ground, pool spreading, pool vaporization, flame radiation impacts

2. Ignition of UST vent stack vapors, with flashback through the vent connection and UST detonation
    - Causes
        - Surface fire/brush fire overwhelms tank vents
        - Ignition from lightning
        - Intentional defeat of stage 1 vapor recovery
        - High rate of vapor release during UST filling
    - Details
        - Volume- Tanks in high blend ethanol use will be between 6,000 and 12,000 gal.
        - Release – Plume from vent stack, UST pressure - 6-12 " water column, 2" vent line
    - Modeling
        - Modeling of plume dispersion at the UST tank vent during unloading event to determine distance to LFL and mass of flammable vapor cloud
        - UST Detonation - Qualitative evaluation of risk to driver/truck in event of unloading at time of UST detonation. No blast overpressure, consequence is limited to the cave-in of the unloading pad over the UST.

3. Ignition of vapors vented at grade in UST area, with flashback and UST detonation
    - Causes
        - Human Error
            - Venting of vapors from UST at grade (loose stage 1 connection or dry-break connection point propped open)
        - Ignition by static
        - Ignition by vehicle
    - Details
        - Volume- Tanks in high blend ethanol use will be between 6,000 and 12,000 gal.
        - Release – Plume from vent stack, UST pressure - 6-12 " water column, 3" hose connection

- Modeling
  - Discharge and plume dispersion modeling to determine distance to LFL for vapor release from UST at grade level
  - UST Detonation - Qualitative evaluation of risk to driver/truck in event of unloading at time of UST det. No blast overpressure, consequence is limited to the cave-in of the unloading pad over the UST.

4. Direct ignition of UST headspace
   - Causes
     - Ignition by electrical malfunction
     - Manual gauging of UST
   - Details
     - Volume- Tanks in hi blend ethanol use will be between 6,000 and 12,000 gal
   - Modeling
     - UST Detonation - Qualitative evaluation of risk to driver/truck in event of unloading at time of UST detonation. No blast overpressure, consequence is limited to the cave-in of the unloading pad over the UST.

5. Uncontrolled spill of fuel to grade in the dispensing area
   - Causes
     - Human Error
     - Mechanical Failure
   - Details
     - Rate – 10 GPM from the dispenser
     - Volume – Dispensers are generally limited to $100 of fuel
     - No diking/curbing, free pool spreading
   - Modeling
     - Release of fuel to ground, pool spreading, pool vaporization, flame radiation impacts

6. Nozzle fire with flashback potentially into the fuel tank headspace if flammable
   - Causes
     - Static Ignition
     - Human Error creating ignition source
   - Details
     - Rate – 10 GPM fill of tank displacing vapors out fill line (ignition of venting vapors)
     - Volume – Average vehicle fuel tank capacity (light duty truck, 20 gallons)
   - Modeling
     - Vehicle fuel tank detonation – Fuel tank catastrophic failure after pressure increase due to headspace deflagration
     - Discharge and plume dispersion modeling to determine distance to LFL for vapors vented from fuel tank fill line during refueling

7. Detonation of vapors in an vessel associated with California tank pressure management systems
   - Causes
     - UST Scenarios
   - Details

- Volume - 400 gal tank
  - o Modeling
    - Mechanical explosion model, blast overpressure impact

Fuel Properties

Four ethanol-fuel blends were identified for study, E10, E51, E83, and E98. Ethanol fuel blends may be blended to varying specifications depending the geographic region and season.

For the purposes of modeling the release, discharge and dispersion, pool spreading and evaporation, and the flammable effects of the release scenarios, fuels were selected that represented a worst credible scenario basis in regards to these types of hazards. Higher vapor pressure fuels create larger flammable vapor releases and result in larger impacts than lower vapor pressure fuels. Alternatively, fuels with very high vapor pressures have very low UFT values and are therefore less likely to be potentially stored below the UFT. Therefore, the study used fuels at the upper limit of the summer fuel standards and regulations. The vapor pressure was set as follows for the consequence modeling: E10 – 10 psi, E51 – 8.5 psi, E83 – 8.5 psi, and E98 – 2.4 psi. These ethanol fuel blends represent summer fuel blends that comply with EPA summer gasoline requirements for E10 in selected regions (9.0 psi base gasoline + 1.0 psi waiver), and ASTM D5798 Class 1 standards for E51 and E83 fuels. There are no standards that set a vapor pressure specification for E98. The vapor pressure of the E98 fuel selected for consequence modeling in this study is below average industry values. The study assumed E98 to be denatured using a low vapor pressure denaturant; however, current practice is for blenders to denature ethanol using high vapor pressure natural gasoline. A higher vapor pressure denaturant would drive increased vapor generation and larger flammable vapor releases than those calculated in this report.

The fuels were developed in the PHAST software to match the vapor pressure specifications of the standards or regulations, and the PHAST software developed all of the applicable physical properties of the blended fuel, including the flammability limits of the vapor. Table 4 provides selected physical properties of the blended fuels used in the PHAST consequence modeling software.

Table 4: Fuel Properties from PHAST

Fuel Type	E10	E51	Flex-Fuel	Denatured Ethanol	Comments
Ethanol Content (Vol %)	10	51	83	98	
Vapor Pressure of the Blended Fuel (psi)	10.0	8.5	8.5	2.4	-DVPE of E10 determined by EPA summer gasoline spec -DVPE of E51 and E83 determined by requirements of ASTMD5798 Class 1 fuel spec -DVPE of E98 determined assuming 5.7 psi CARBOB
UFL	1.2%	2.2%	3.5%	4.1%	

Fuel Type	E10	E51	Flex-Fuel	Denatured Ethanol	Comments
LFL	8.4%	13.0%	16.9%	18.7%	
Vapor Pressure of the Gasoline Blendstock (psi)	9	9	15	5.7	

It should be noted that the PHAST software was not able to accurately model the non-ideal mixing of ethanol and gasoline. Therefore, the vapor pressure of the ethanol component used to create the gasoline/ethanol blend was adjusted to compensate for the non-ideal nature of the mixed fuel's vapor pressure. Directly adjusting the vapor pressure of the ethanol component allowed the program to produce a fuel blend that matched the correct ethanol concentration, correct gasoline composition and the appropriate fuel vapor pressure. The gasoline used to produce the blends was mixed to a vapor pressure specification set to match the appropriate blending component per the nomograph for ethanol and gasoline blending [4].

Consequence Modeling Methodology

Descriptions of the consequence models used in the study are provided in the following sections for each hazard type. Details of the consequence models for each scenario are provided in the QRA Results section.

Pool Fire

Pool fire scenario models are built into the PHAST software. The hazards of pool fire scenarios include thermal radiation, as well as flash fire resulting from ignition of evaporated vapors.

Upon ignition, a spilled flammable liquid will burn in the form of a large turbulent diffusion flame. The size of the flame will depend on the spill surface and the thermo-chemical properties of the hazardous material. If the spill is confined, the confined area will determine the pool size which will then dictate the size of the fire. If the spill is unconfined, the pool dimensions will depend on the amount of liquid released (liquid volume), burning rate of the liquid, and the terrain surface characteristics.

Thermal radiation emanates from the visible portions of the flame. The actual radiation received by a person depends on the distance from the flame surface, as well as other atmospheric conditions, with sheltering reducing the magnitude of the thermal radiation hazard. The endpoint criterion for fatal radiation exposure is 12 kW/m^2.

For the purposes of all pool fire scenarios modeled in the QRA, there was assumed to be no curbing to confine the liquid spill. The spill was allowed to spread until the pool radius was limited by evaporation, or the pool reached the minimum pool thickness set point of 0.4 inches. The minimum pool thickness is based on the EPA reference for offsite consequence analysis [28].

Additionally, it should be noted that all pool fire consequences are developed assuming a worst-case scenario that the pool is given the ability to spread completely to its maximum radius before ignition. Ignition of the pool at the time of release would result in less severe consequences, as the radius of the pool would be limited by the consumption of fuel in the combustion.

The impact of pool fires on the surrounding population is calculated based on the area surrounding the release that is exposed to radiation levels greater than 12 kW/m^2.

Vapor Generation, Discharge and Dispersion

PHAST software was used to model the generation, discharge, and dispersion of fuel vapors for several of the identified scenarios in the QRA.

The discharge and dispersion of UST headspace vapors was modeled using the PHAST atmospheric storage tank venting model. The model is designed to simulate the venting of headspace vapors from an atmospheric storage tank during the filling process. The model assumes the vapor vented from the tank to be an equilibrium concentration of air and fuel. The discharge rate of vapor is set directly by defining the filling rate of the tank. PHAST is able to model the discharge conditions of the vapor release, which is governed by the release conditions, as well as the plume dispersion, which is governed by the fuel vapor properties and the atmospheric conditions defined in the model. The dispersion is modeled using PHAST's Unified Dispersion Model (UDM) which is a well-documented and trusted source of accurate dispersion results. The results of the model provide all size parameters of the 3-dimensional flammable vapor cloud, including boundaries of the plumes UFL and LFL.

PHAST also simulates the vapor generation from a liquid spill of fuel to grade, referred to as pool vaporization. If an ignition source is not present, the spilled liquid is allowed to evaporate as the pool spreads. The pool vaporization is modeled within PHAST using the PVAP model, which is integrated with the PHAST pool spreading model and the UDM. The result is that the model is able to output the rate of pool vaporization and the size and dimensions of a resulting flammable vapor cloud which may be generated by the pool. Ignition of the flammable vapor cloud results in a flash fire that also ignites the liquid pool, resulting in a pool fire.

Vehicle Fuel Tank

The ignition of a flammable tank headspace in a vehicle fuel tank will result in catastrophic failure of the fuel tank. The combustion of flammable vapors in a confined vessel is able to generate an internal pressure up to 130 pounds per square inch [29]. Vehicle fuel tanks are not rated to contain these high internal pressures, and will be subject to sudden catastrophic failure if subjected to these conditions.

The PHAST model was used to simulate the catastrophic failure of a vehicle fuel tank. The model is able to simulate the release of liquid and vapor under pressure during a catastrophic failure. The release of materials results in several hazards. Firstly, the ejected liquid forms droplets which vaporize as they travel through the air, creating a flammable vapor cloud. This vapor cloud can result in flash fire hazards, and in the case that the failure is the result of tank headspace combustion, it must be assumed that the vapor cloud is immediately ignited at the time of release. Secondly, the remaining liquid which does not vaporize is able to generate a liquid pool that leads to a pool fire. These hazards are consistent with testing performed in Sweden [24].

PHAST is not able to account for the impacts of the surrounding vehicle components on the catastrophic failure of the tank; the results of the model represent a tank that is not surrounded by other equipment which impedes the release of the liquid droplets from the pool and vapor cloud. However, it is valuable to understand the impacts of an unconfined failure, and the model results do provide insight into the nature of the failure and the hazard.

UST Detonation

The detonation of the headspace of a UST is a rare occurrence, but industry has documented occurrences of USTs at service stations detonating. There are no models to effectively simulate the detonation of a UST, but the documented events provide a clear description of the hazards of such an event [25].

Documented cases of UST detonation show that it results in the “cave-in” of the pad above the UST, as the UST is compromised and the fill below the concrete enters the remaining void. It will be assumed for the purposes of the study that the detonation will result in the fatality of any person who is on the 20 foot by 30 foot pad above the UST at the time of detonation.

Weather Conditions

All models were run assuming a worst-case scenario weather condition, using a 1.5 m/s wind speed and a Pasquill Stability Class of F. The ambient temperature of the scenarios was varied depending on the nature of the event. Scenarios that required ignition of flammable tank headspaces were modeled at a temperature intended to represent conditions necessary for the tank headspace to be in the flammable range. For the E10, E51, and E83 fuels, an ambient temperature of 5 degrees Fahrenheit was used; this temperature is based on the low ambient temperatures required to create flammable tank headspaces with these fuel blends [4]. For E98, an ambient temperature of 95 degrees Fahrenheit was used; this temperature corresponds to the UFT of E98. Pool fire scenarios were modeled at a temperature of 95 degrees Fahrenheit for all fuels to represent a worst-case scenario in terms of vapor generation from liquid spills. The likelihood of each fuel being stored in the range of ambient temperatures where tank headspaces are flammable was assessed as part of the likelihood analysis.

Impacts to Populations

For the purposes of assessing the impacts to populations, the following assumptions were made,

- There is assumed to be one person present at the point of release in the following scenarios
    - One Truck Driver - UST filling from tanker truck (fuel spill to grade, ignition of vapors from UST vent, ignition of vapors vented at grade)
    - One employee – Gauging activities that result in ignition of the UST headspace
    - One patron - Vehicle refueling(nozzle fire and fuel spill to grade)
- The area around the point of release is assumed to be occupied by the public outdoors at a population density of 1.13E-4 persons per square foot. This is equivalent to 2 people present within a 75 foot radius of the release location. This value does not include the person at the location of release in the event the release scenario as described above.

Fault Tree Analysis

Methodology

Fault tree analysis is used to predict the likelihood of consequence events that may be the result of many different initiating events and/or contributing factors. For the purpose of analyzing the likelihood of the scenarios in this study, fault trees were developed for each scenario. The fault trees were built to represent the hazard scenarios and initiating events identified in the qualitative risk assessment. The fault tree analysis was performed using the commercially-available "IHS FTA-Pro" software program.

In order to determine the quantitative likelihood of each scenario, it was necessary to provide frequencies and/or probabilities of failure on demand of all initiating events and contributing factors. Because there is not a well-documented database of failure rates of hazard scenarios for service stations to reference, it is necessary for these values to be estimated based on empirical data and industry knowledge. Table 5 provides the qualitative-quantitative evaluation method used to assign frequencies to all initiating events and contributing factors. The quantitative values provided are aligned with the quantitative values in MIL-STD 882E [6].

Table 5: Qualitative-Quantitative Evaluation Method

Qualitative Values From MIL-STD 882E		Quantitative Occurrence Values	
Level	**Fleet or Inventory**	**Description**	**Incidents/Year**
A	Continuously experience	Happens routinely in industry	1×10^{-1}
B	Will Occur Frequently	Occurs in industry on a regular basis, possible to occur on-site	1×10^{-2}
C	Will Occur Several Times	Occurs in industry periodically, isolated events	1×10^{-3}
D	Unlikely, but can be reasonably expected to occur	Rare occurrence(s) in industry	1×10^{-5}
E	Unlikely to occur, but possible	No documented occurrences in industry but possible to occur	1×10^{-6}

When discussing risk and the likelihood of events occurring, it is especially important to understand the basis of the risk estimation. All risk results developed in this report use a single service station as the basis of all event likelihoods and risk values. An event that occurs periodically in industry will only occur rarely or may never occur at a specific site. Risks are managed at a site level and risk criteria are developed for use evaluating risks of one specific operation, so it is standard practice to evaluate risks for operations individually. In corporations with one or multiple sites, it is important to understand the risk of hazardous consequence scenarios at a corporate level, but this report does not address those issues.

Ignition Probabilities

Additionally, it was necessary for the fault tree of some scenarios to be modified based on the results of consequence modeling results. Specifically, the probability of ignition of a flammable release is a function of the release size. Larger releases, which extend over a larger area of land are more likely to reach a source of ignition than smaller releases. Therefore, a modification factor was added to the ignition branch of each fault tree to account for the size of the flammable release. The largest release of the model was assigned a factor of 1, while the other release scenarios were assigned a value set by the ratio of that scenario's distance to flammable endpoint divided by the largest scenario's distance. The ignition probability modification factor was limited to a minimum value of 0.01 to prevent a scenario's likelihood from being reduced to 0 in the event of a very small and/or negligible flammable vapor plume. This is meant to reflect the fact that a flammable tank headspace may be ignited directly at the source of the release without a flammable vapor plume extending into the atmosphere.

Likelihood of Flammable Tank Headspaces

In order for an event to result in detonation of a UST or vehicle fuel tank, the stored fuel must be within the flammable range. To fully assess the risk of scenarios with the potential for ignition of a tank headspace, the likelihood of a fuel being stored in the flammable range must be considered. Fuels blended to the EPA and ASTM fuel standards referenced in Table 4 do not generate flammable tank headspaces at the normal ambient temperatures encountered during the season for which they are blended. However, there is the potential for a fuel to generate a flammable tank headspace if it is blended incorrectly, or used outside of the normal ambient conditions for which it was blended.

To assess the likelihood of tank headspaces being flammable for the various fuel types used in the study, a fault tree analysis was performed using input from the CRC Project Panel. The analysis was conducted in a two hour meeting facilitated by AcuTech. The team members that participated in the assessment are listed in Table 6.

Table 6: Tank Headspace Flammability Assessment - Team Members

Full Name	Company
Colin D Armstrong	AcuTech Consulting Group
Gary Herwick	Transportation Fuels Consulting
Jerry Horn	Chevron
Jim Simnick	BP America
Chris Tennant	Coordinating Research Council
Scott Mason	Phillips 66
Kristi Moriarty	NREL

To assess the likelihood of the tank headspace being flammable for various fuel types, the team developed credible scenarios that would lead to the various ethanol fuel blends (E10, E51, E83, and E98) being stored under conditions that result in a flammable tank headspace. Due to the fact that the flammable range of E98 spans across normal ambient conditions for fuel storage throughout the year, no modification factor was developed for E98. It is assumed that E98 tank headspaces are always in the flammable range. The team discussed the likelihood of each of the causes for the three ethanol fuel blends, E10, E51, and E83, using the definitions of likelihood and frequency provided in Table 5. The causes identified by the team, as well as the assigned likelihoods for each fuel type are provided in Table 7.

Table 7: Tank Headspace Flammability Causes

	E10	**E51**	**E83**
Blending Error	1×10^{-5}	1×10^{-5}	1×10^{-1}
Fuel Stored for Extended Period at Station	1×10^{-5}	1×10^{-3}	1×10^{-3}
Ambient Temperatures Below Normal	1×10^{-3}	1×10^{-3}	1×10^{-3}
Low VP fuel blended in Spring for VOC Control Season	1×10^{-3}	0	0

It should be noted that the likelihood of E83 being blended incorrectly, resulting in the fuel's upper flammability temperature reaching normal ambient temperatures was assessed by the team to be more likely than for E10, or E51. In order to blend E85 to a vapor pressure of 8.5 psi (upper limit of ASTM D5798 Class 1), a 15 psi gasoline blendstock is required. The 15 psi gasoline blendstock is a blending component that is not generally available during summer gasoline season. The result is that most E85 fuel blends that have been sampled are low vapor pressure, ranging from 4.5 to 6 psi [31]. Fuels with a vapor pressure of 5 psi have a UFT of ~42 degrees Fahrenheit. These lower vapor pressure blends are more likely to be stored at temperatures below the UFT.

The result of the flammability assessment was the calculation of likelihood of the UST and vehicle fuel tank headspaces being flammable for each fuel type. The likelihood of a flammable tank headspace being present at a service station for each of the fuel types is provided in Table 8.

Table 8: Likelihood of Tank Headspace Flammability by Fuel

Fuel	**Likelihood**
E10	2.019×10^{-3}
E51	2.009×10^{-3}
E83	1.02×10^{-1}
E98	1

It should be noted that standards and general industry practices for the blending high ethanol content fuels (E51 and E83 in this study) have changed in recent years. Up-to-date data for the vapor pressure of high ethanol content fuel blends was not available at the time of study. The tank headspace flammability assessment results and ultimately the risk results of this study would be affected by more accurate data regarding current industry blending practices and a more detailed analysis of tank headspace flammability in the market. The potential for fuels to be stored under conditions that result in the formation of flammable tank headspaces is a complex issue that warrants additional analysis in future work.

Likelihood Results

In order to present all results relative to the benchmark E10 fuel, the likelihoods for each fuel type were scaled based on the likelihood of the E10 fuel. Therefore, the E10 fuel benchmark presents a likelihood value of 1, while the other fuels' risks are represented by a likelihood value scaled to that value. For example, a high ethanol content fuel scenario that is ten times as likely to occur as the E10 scenario would be shown with a likelihood of 10, while a scenario that is half as likely to occur would be represented by a likelihood value of 0.5. The likelihood values are used to create the scaled societal risk index values which are a representation of relative risk: consequence, and likelihood.

The assigned initiating event frequencies and probabilities of failure on demand, as well as the modification factors for ignition are all provided in the QRA results section. The fault trees for each scenario as well as the fault tree developed in the tank headspace flammability assessment are provided in Appendix A.

Results

QRA Scenario Results

Scenario 1: Spill of fuel to Grade during Unloading of Tanker Truck to UST

Consequence Modeling Details

The scenario model was designed to simulate an uncontrolled loss of containment of liquid fuel from the tanker truck or unloading hose. The consequence model was set up as a release of liquid fuel from a 3" hose at ground level. The driving force for fuel discharge was set to be the liquid head in a 6 ft. diameter, 20 ft. long horizontal cylinder, containing 2000 gallons at the time of the release. The release rate was set to be time-varying to account for the loss of liquid head as the volume in the tank decreased. The pool fire scenario was not dependent on tank headspace flammability, so the results are presented based on a 95 degree Fahrenheit ambient temperature. This temperature represents the worst-case scenario pool fire consequence.

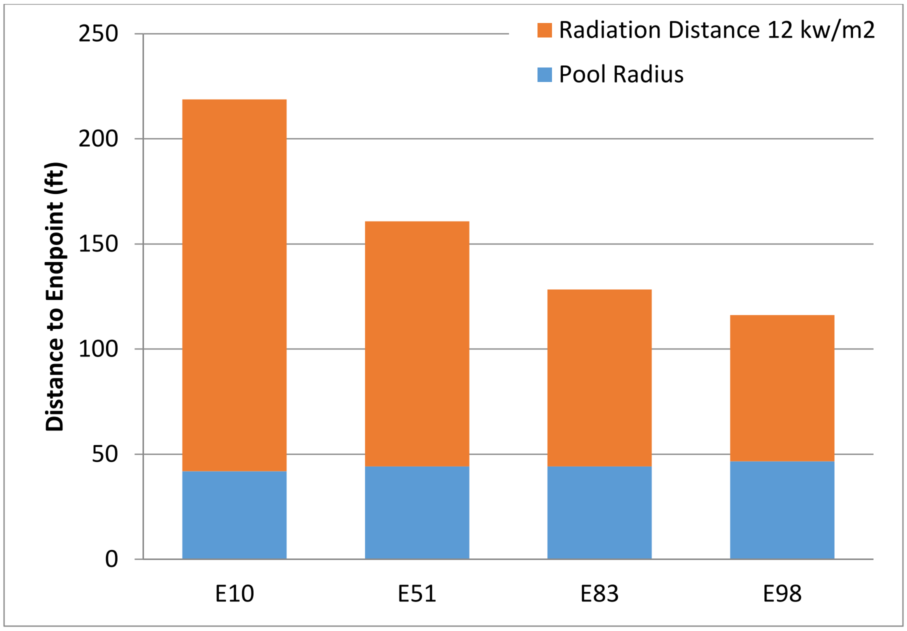
The results of the consequence model indicated hazards were present for pool fire, and flash fire from the ignition of vapors evaporated from the liquid pool.

The consequence modeling results indicated that all fuels presented similar pool spreading characteristics, the maximum pool radius was 42 to 47 feet for all fuels. However, the results showed that the radiation from pool fires varied significantly depending on the fuel type. The E10 provided the longest distance to the 12 kW/m^2 endpoint at 219 feet. The radiation exposure distances decreased with increasing ethanol content to a minimum distance of 116 feet for the E98 fuel. The flash fire results for the fuels also decreased with the ethanol content from a maximum distance of 192 feet for the E10 fuel, to a minimum distance of only 1 foot with the E98 fuel. The increased flash fire hazard of the E10 fuel can be attributed to the increased vapor pressure which results in a larger flammable vapor cloud. The governing hazard was the pool fire radiation, which exceeded the flash fire envelope fatal endpoint distance for all fuels. The consequence modeling results are summarized in Table 9 and Figure 4.

Table 9: Consequence Modeling Results - Scenario #1: Truck Unloading Spill

Tanker Spill			
	Pool Radius	**Radiation Distance**	**Flash Fire Envelope**
Fuel	**Ft**	**Ft**	**Ft**
E10	42	219	193
E51	44	161	111
E83	44	128	70
E98	47	116	1

Figure 4: Pool Fire Results - Scenario #1: Truck Unloading Spill



Likelihood Results

The likelihood of the release and ignition of the pool fire was assessed using fault tree analysis based on the input received from the qualitative risk analysis. The potential direct causes and contributing factors for the fuel spill and sources of ignition that were identified for the scenario are provided in Table 10, and the fault tree is provided in Appendix A - Figure 1.

Table 10: Initiating and Contributing Events - Scenario #1: Truck Unloading Spill

Cause	Description	Frequency Assigned (yr^{-1})
Vehicle Collision	Vehicle impacts the tanker truck or hose	10^{-5}
Misconnection or Skipped step	Driver error that results in spill of fuel to grade.	10^{-3}
Overfill	Gauging Error, inadequate ullage for tanker truck unloading	10^{-1}
Vapor Recovery Cap Propped Open	Stage 1 vapor recovery connection propped open.	10^{-3}
Hose Rupture	Mechanical Failure of unloading hose	10^{-5}
Coupling Failure	Coupling failure resulting in hose disconnect	10^{-3}
External	Violation of restricted area by the public, vehicle present, smoking, or other ignition source present	10^{-2}
Driver accumulates static charge	Driver accumulates static while working in the area	10^{-1}
Driver discharges static near fuel	Static discharge occurs when driver contacts grounded equipment	10^{-2}

Cause	Description	Frequency Assigned (yr^{-1})
Truck Engine Running	Truck engine running provides ignition sources from high temperature and potentially sparking	10^{-5}
Static accumulation and discharge from fuel unloading	Unloading equipment may generate static from the flow of fuel. Note E10 fuels are highly conductive.	10^{-6}
Size of Flammable Zone	A factor to account for the effect of the flammable area on the potential for ignition.	E10 , E51 , E83 , E98 1 , 0.57 , 0.36 , 0.24

The estimated event frequencies calculated from the FTA for each fuel type were scaled to the benchmark E10 fuel. The scaled likelihoods are provided in Table 11.

Table 11: Scaled Likelihood Results – Scenario #1: Truck Unloading Spill

Fuel	Frequency (scaled)
E10	1
E51	0.57
E83	0.36
E98	0.24

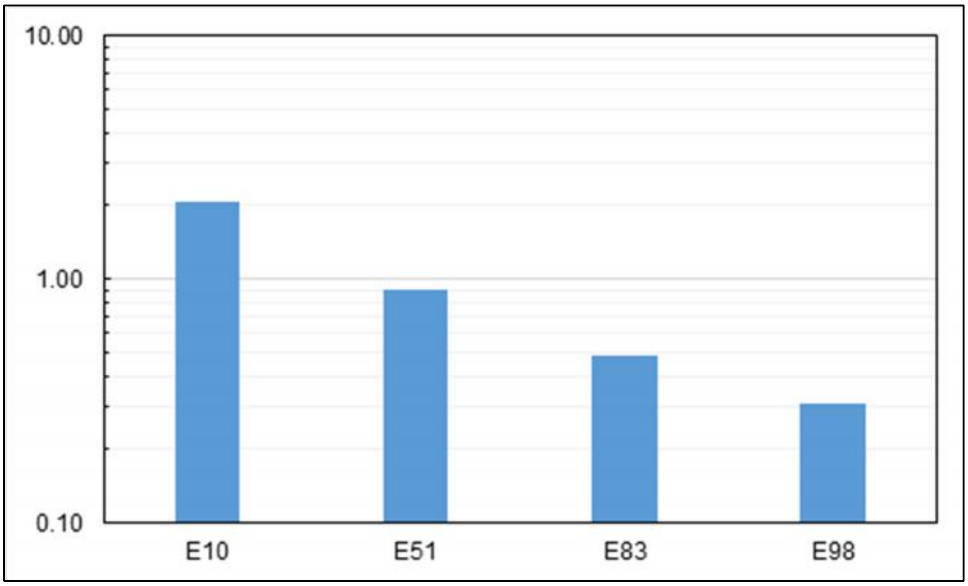
Risk Results

The results of the modeling and likelihood analysis indicate the consequence and probability of the potential fuel spill from the tanker truck during unloading are greatest for the baseline E10 fuel. Reported as the societal risk index (SRI), the value represents the number of fatalities expected per year to occur as a result of a hazard scenario. The higher ethanol fuel blends presented reduced risks of impact from radiation due to lower flame radiation emissivity, and the potential for ignition of the higher ethanol fuels was reduced due to smaller flammable vapor clouds produced by the evaporating liquid pools. The radiation from the pool fire was the governing impact, as it posed the longest distance to fatal endpoint criteria for all fuels. The risk results for the scenario are presented in Table 12 and Figure 5.

Table 12: Scaled Risk Results - Scenario #1: Truck Unloading Spill

Fuel	Fatalities (public)	Fatalities (employee)	Fatalities (Total)	SRI (public)	SRI (employee)	SRI (Total)
E10	1.1	1.0	2.1	1.07	1.00	2.07
E51	0.6	1.0	1.6	0.33	0.57	0.90
E83	0.4	1.0	1.4	0.13	0.36	0.49
E98	0.3	1.0	1.3	0.07	0.24	0.31

Figure 5: Scaled Risk Results - Scenario #1: Truck Unloading Spill



Scenario 2: Ignition of UST Vent Stack Vapors, Flashback and UST Detonation

Consequence Modeling Details

A scenario model was designed to simulate a release of the tank vapor space to the atmosphere from the UST vent stack during the filling of the UST. The model assumes the vapor vented from the tank to be an equilibrium concentration of air and fuel. The model was set up as a release of tank vapors from a 3"-diameter stack at 12 ft. of elevation. The release from the vent stack was angled down, 85 degrees from horizontal, to simulate the release direction of a vent stack with a rain cap. The driving force for discharge was set to be equal to the normal filling rate of a UST from a tanker truck, 300 gallons per minute. This rate represents the highest rate of venting from the UST. The release rate was set to be continuous to allow the plume to reach a steady-state result. The E10, E51, and E83 models were run at 5 degrees Fahrenheit to represent atmospheric conditions that would allow the tank headspace to be in the flammable region. The E98 model was run at 95 degrees Fahrenheit for the same reason. The upper flammability temperature of E98 fuel is significantly higher than lower ethanol content fuels.

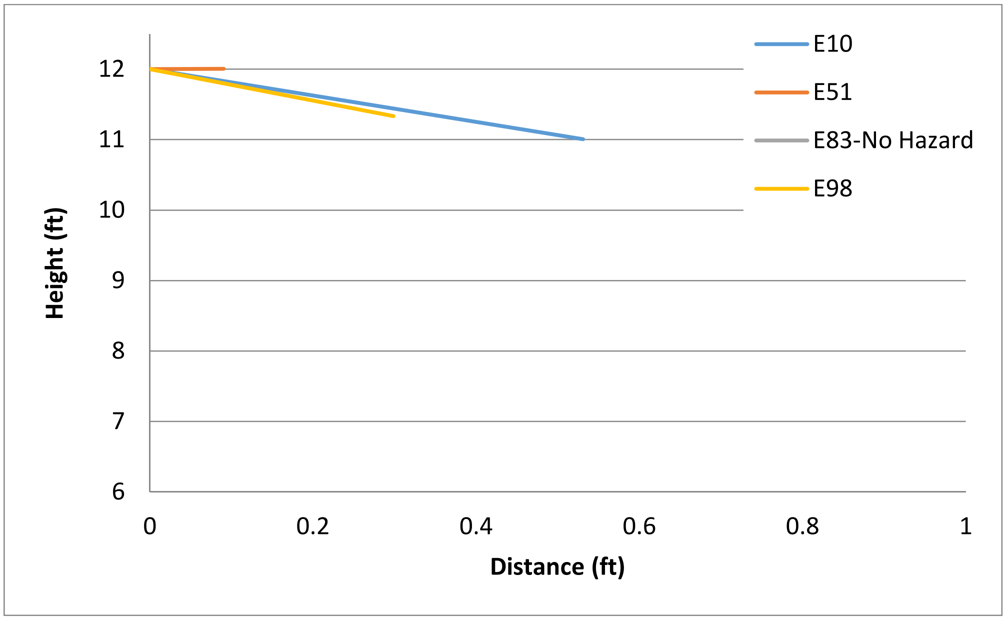
The model results provided information regarding the size of flammable vapor releases from the UST vent. Ignition of the flammable plume from the UST vent would allow the flame to flashback into the vent stack, and ultimately detonate a flammable UST headspace. The size of the flammable plume is used to determine the probability of ignition for the scenario.

For the E10, E51, and E83 fuels, the modeling results indicated that the length of the flammable plume released from the UST vent decreased as the ethanol content of the fuel increased. Moreover, the flammable plumes for those cases extended only a short distance from the vent stack, and the E83 fuel produced no flammable plume. The E10 fuel provided the longest flammable plume, which extended a distance of only 1 foot from the UST vent stack. The E51 fuel provided a plume that extended only 1 inch from the vent stack. The E98 fuel produced a small flammable plume that extended less than one foot from the UST vent stack. None of the plumes extended below an elevation of 11 feet from grade. The likelihood of ignition sources from the public in the area of the vent is therefore very low, as compared to the area at grade level. The nature of the plume dispersion results is a function of several factors. The LFL of high ethanol fuels is higher than low-ethanol content fuels, therefore the dilution and dispersion of the release more quickly reduces the fuel concentration below the LFL. Note that the E98 fuel seems to disagree with these results, however the E98 model was run at a much higher atmospheric temperature due to the very high upper flammability temperature of E98. The results of the UST vapor space discharge and dispersion model are provided in Table 13 and Figure 6.

Table 13: Model Results - Scenario #2: UST Vent Stack vapors

UST Vent Stack				
	Distance (feet)		Height (feet)	
Fuel	UFL	LFL	UFL	LFL
E10	No Hazard	0.53	No Hazard	11.01
E51	No Hazard	0.09	No Hazard	12.00
E83	No Hazard	No Hazard	No Hazard	No Hazard
E98	No Hazard	0.30	No Hazard	11.33

Figure 6: Model Results - Scenario #2: UST Vent Stack Vapors



Likelihood Results

The likelihood of the release and ignition of the vapor was assessed using fault tree analysis based on the input received from the qualitative risk analysis. The potential direct causes and contributing factors for the release and sources of ignition that were identified for the scenario are provided in Table 14, and the fault tree is provided in Appendix A - Figure 2.

Table 14: Initiating and Contributing Events - Scenario #2: UST Vent Stack Vapors

Cause	Description	Frequency Assigned (yr^{-1})
UST Filling, No stage 1 Vapor Recovery	Failure of dispensing hose during use.	10^{-1}
External Fire	Open flam or spark present in the area of the flammable spill.	10^{-3}
Public Source of Ignition	Vehicle running in the area of the flammable spill.	10^{-3}
Size of Flammable Zone	A factor to account for the effect of the flammable area on the potential for ignition.	E10 , E51 , E83 , E98 1 , 0.08 , 0.01 , 0.65

The estimated event frequencies calculated from the FTA for each fuel type were scaled to the benchmark E10 fuel. The scaled likelihoods are provided in Table 15.

Table 15: Scaled Likelihood Results – Scenario #2: UST Vent Stack Vapors

Fuel	Frequency (scaled)
E10	1
E51	0.08
E83	0.5
E98	322

Risk Results

The impact of the ignition of the UST vent stack is the detonation of the UST. UST detonations cannot be effectively modeled, but qualitative assessment of documented UST detonations provides an indication of the expected impact. The UST detonation results in the “cave-in” of the pad above the UST; this is assumed to result in the fatality of a person on the pad. When unloading into the UST, it is assumed that only the driver is present on the pad above the UST.

The results of the consequence modeling and likelihood analysis indicate the consequence of the UST vent stack ignition and UST detonation is constant for all fuel types; therefore the relative risk is driven by the likelihood of the event. The likelihood analysis indicates that the probability of the event is highest for E98, followed by E10, E83, and E51 respectively. Thus the risk of the UST vent stack ignition and UST detonation for each of the fuels follows the same order: E98, E10, E83, and E51.

The high likelihood of ignition and UST detonation for the E98 fuel is driven by multiple factors. First, the E98 fuel has the highest likelihood of being stored in the range of temperatures expected to produce a flammable tank headspace due to the high upper flammability temperature. Second the E98 fuel also presents a flammable vapor plume nearly as large as that of the E10 fuel which has a much lower probability of being in the correct temperature range to have a flammable tank headspace.

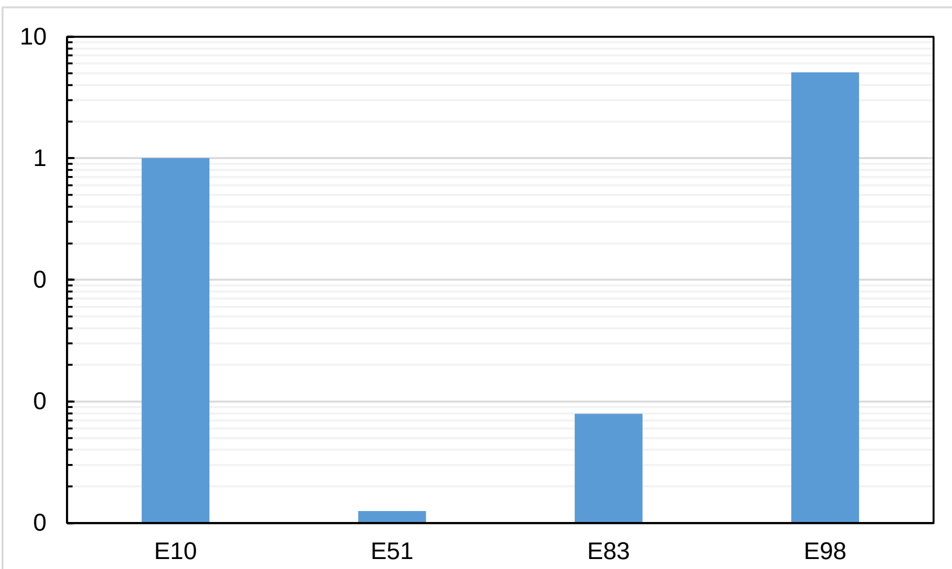
Risk results for the scenario are presented in Table 16 and Figure 7.

Table 16: Scaled Risk Results - Scenario #2: UST Vent Stack Vapors

Fuel	Fatalities (public)	Fatalities (employee)	Fatalities (Total)	SRI (public)	SRI (employee)	SRI (Total)
E10	0	1	1	0	1	1
E51	0	1	1	0	0.08	0.08
E83	0	1	1	0	0.50	0.50
E98	0	1	1	0	322	322

The risk results indicate that the E98 fuel poses the highest risk, followed in order by the E10, E83, and E51 fuel blends. The E98 fuel exceeds the risk of the benchmark E10 fuel, while the E83 and E51 fuels fall below the benchmark risk level of E10. The risks are illustrated in the Figure 7.

Figure 7: Scaled Risk Results - Scenario #2: UST Vent Stack Vapors



Scenario 3: Ignition of Vapors in UST Unloading Area, Flashback and UST Detonation

Consequence Modeling Details

A scenario model was designed to simulate a release of the tank vapor space to the atmosphere from the UST vapor recovery connection during the filling of the UST. The model assumes the vapor vented from the tank to be an equilibrium concentration of air and fuel. The model was set up as a release of tank vapors from a 3" opening at grade. The release was oriented vertically, to simulate the release direction of an opening at grade with no connections. The driving force for discharge was set to be equal to the normal filling rate of a UST from a tanker truck, 300 gallons per minute. This rate represents the highest rate of venting from the UST. The release rate was set to be continuous to allow the plume to reach a steady-state result. The E10, E51, and E83 models were run at 5 degrees Fahrenheit to represent atmospheric conditions that would allow the tank headspace to be in the flammable region. The upper flammability temperature of E98 fuel is significantly higher than lower ethanol content fuels, so the E98 model was run at 95 degrees Fahrenheit.

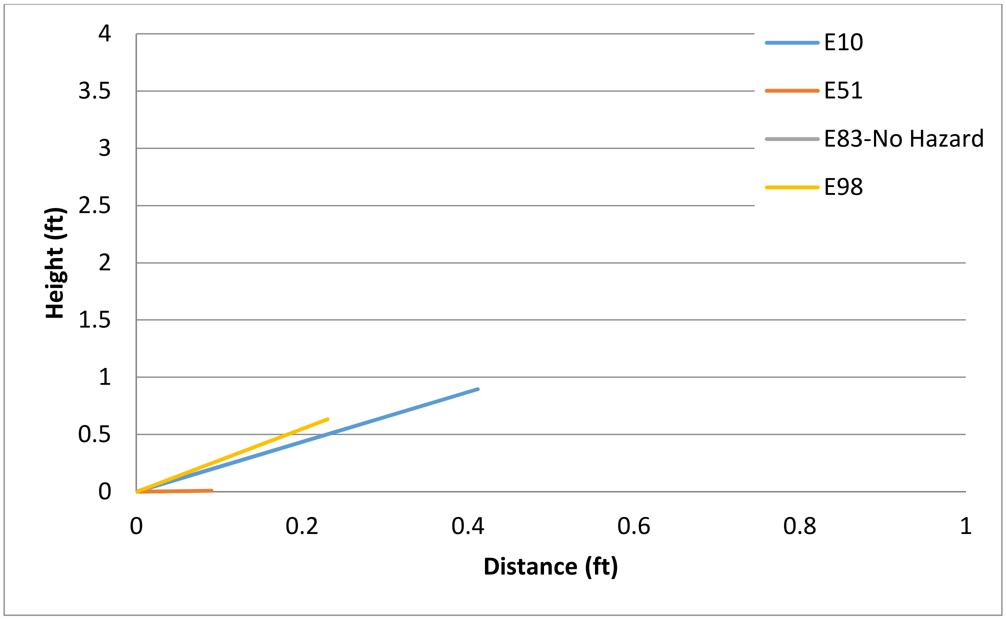
The model results provided information regarding the size of flammable vapor releases from the UST vapor connection. Ignition of the flammable plume from the UST vapor connection would allow the flame to flashback into the UST headspace and detonate a flammable UST headspace. The size of the flammable plume is used to determine the probability of ignition for the scenario.

For the E10, E51, and E83 fuels, the modeling results indicated that the length of the flammable plume released from the UST vent decreased as the ethanol content of the fuel increased. Moreover, the flammable plumes for those cases extended only a short distance from the vent stack, and the E83 fuel produced no flammable plume. The E10 fuel provided the longest flammable plume, which extended a distance of only 1 foot from the UST vent stack. The E51 fuel provided a plume that extended only 1 inch from the vent stack. The E98 fuel produced a small flammable plume that extended less than one foot from the UST vent stack. The nature of the plume dispersion results is a function of several factors. The LFL of high ethanol fuels is higher than low-ethanol content fuels, therefore the dilution and dispersion of the release more quickly reduces the fuel concentration below the LFL. Note that the E98 fuel seems to disagree with these results, however the E98 model was run at a much higher atmospheric temperature due to the very high upper flammability temperature of E98. The results of the UST vapor space discharge and dispersion model are provided in Table 17 and Figure 8.

Table 17: Model Results - Scenario #3: UST Vent at Grade

UST Ground Vent				
Fuel	**Distance (feet)**		**Height (feet)**	
	UFL	**LFL**	**UFL**	**LFL**
E10	No Hazard	0.41	No Hazard	0.90
E51	No Hazard	0.09	No Hazard	0.01
E83	No Hazard	No Hazard	No Hazard	No Hazard
E98	No Hazard	0.23	No Hazard	0.63

Figure 8: Model Results - Scenario #3: UST Vent at Grade



Likelihood Results

The likelihood of the release and ignition of the vapor was assessed using fault tree analysis based on the input received from the qualitative risk analysis. The potential direct causes and contributing factors for the release and sources of ignition that were identified for the scenario are provided in Table 18, and the fault tree is provided in Appendix A - Figure 2.

Table 18: Initiating and Contributing Events - Scenario #3: UST Vent at Grade

Cause	**Description**	**Frequency Assigned (yr^{-1})**
Defeat of Stage 1 Vapor Recovery	Stage 1 vapor recovery connection open but not connected	10^{-3}
Failure of Stage 1 Hose or connection	Mechanical failure of vapor recovery hose, or use of failed hose.	10^{-5}
External	Violation of restricted area by the public, vehicle present, smoking, or other ignition source present	10^{-2}
Driver accumulates static charge	Driver accumulates static while working in the area	10^{-1}
Driver discharges static near fuel	Static discharge occurs when driver contacts grounded equipment	10^{-2}
Truck Engine Running	Truck engine running provides ignition sources from high temperature and potentially sparking	10^{-5}
Static accumulation and discharge from fuel unloading	Unloading equipment may generate static from the flow of fuel. Note ethanol-containing fuels are highly conductive.	10^{-6}

Cause	Description	Frequency Assigned (yr^{-1})
Size of Flammable Zone	A factor to account for the effect of the flammable area on the potential for ignition.	E10 , E51 , E83 , E98 1 , 0.09 , 0.01 , 0.68

The estimated event frequencies were calculated from the FTA for each fuel type and scaled to the benchmark E10 fuel. The scaled likelihood results are provided in Table 19.

Table 19: Scaled Likelihood Results – Scenario #3: UST Vent at Grade

Fuel	Frequency (scaled)
E10	1
E51	0.09
E83	0.5
E98	337

Risk Results

The results of the modeling and likelihood analysis indicate the probability of the potential ignition of the vapors vented from the UST vapor vent at grade are highest for the E98 fuel, while the small size of the plumes for the E51 and E83 fuels reduce the probability of ignition and ultimately the scenario frequency significantly. Discharge and dispersion models show that all of the fuel blends produce small flammable vapor plumes even at very high rates of vapor venting.

The impact of the ignition of the UST vapor vent at grade is the detonation of the UST headspace. UST detonations cannot be effectively modeled, but qualitative assessment of documented UST detonations provides an indication of the expected impact. The UST detonation results in the “cave-in” of the pad above the UST; this is assumed to result in the fatality of a person on the pad. When unloading into the UST, it is assumed that only the driver is present on the pad above the UST.

As with the ignition of vent stack vapors, the high risk of ignition and UST detonation for the E98 fuel is driven by multiple factors. First, the E98 fuel has the highest likelihood of being stored in the range of temperatures expected to produce a flammable tank headspace due to the high upper flammability temperature. Second the E98 fuel also presents a flammable vapor plume nearly as large as that of the E10 fuel which has a much lower probability of being in the correct temperature range to have a flammable tank headspace.

Risk results for the scenario are presented in Table 20 and Figure 9.

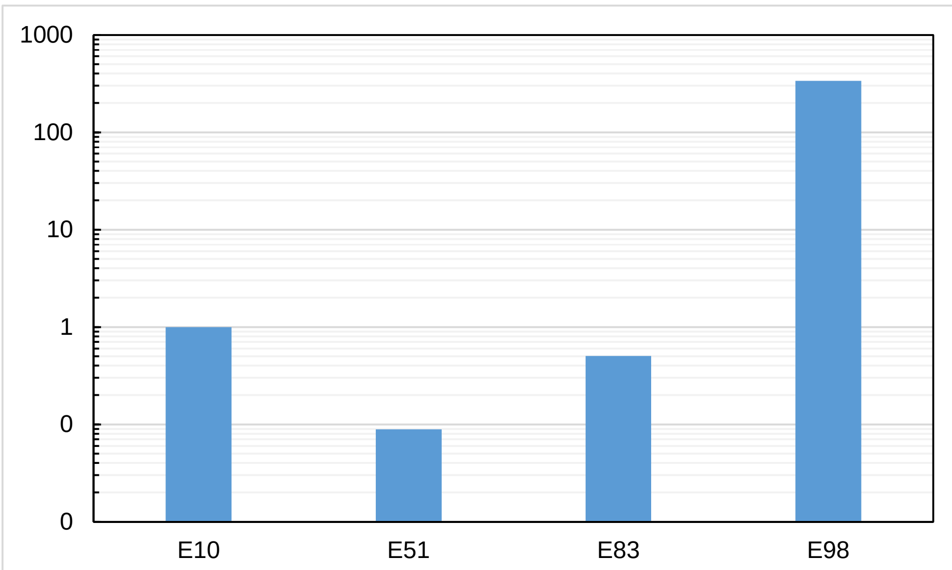
Table 20: Scaled Risk Results – Scenario #3: UST Vent at Grade

Fuel	Fatalities (public)	Fatalities (employee)	Fatalities (Total)	SRI (public)	SRI (employee)	SRI (Total)
E10	0	1	1	0	1	1

E51	0	1	1	0	0.09	0.09
E83	0	1	1	0	0.50	0.50
E98	0	1	1	0	337	337

The risk results indicate that the E98 fuel exceeds the risk of the E10 benchmark for the scenario. The risk of E51 and E83 fuels are less than the risk of E10 due to the smaller vapor plumes. Recommendations for mitigating the increased risk associated the E98 fuel are provided in the recommendations section of the report. There is a very low risk of igniting a vapor plume for the E83 fuel, as the consequence modeling results showed that no flammable plume is produced for E83; however, the fuel is more likely to be stored below the upper flammability temperature and thus the risk exceeds that of E83. The risks are illustrated in Figure 9.

Figure 9: Scaled Risk Results – Scenario #3: UST Vent at Grade



Scenario 4: Direct Ignition of UST Flammable Tank Headspace, UST Detonation

Consequence Modeling Details

Direct ignition of the flammable tank headspace results in the detonation of the UST, assuming that the tank operating temperature is below the stored fuel's UFT. The consequence of UST detonation is qualitatively assessed to result in the local potential for fatality as a result of the tank pad caving-in.

For the purpose of consequence assessment, the causes of UST headspace ignition were divided into two groups: causes that occur when an employee is on the tank pad (manual gauging), and causes that are independent of an employee's presence. An operator or other person present on the pad (assumed as 20 x 30 feet) at the time of the UST detonation is presumed to be fatally injured by the event.

Likelihood Results

Direct ignition of the flammable tank headspace can occur when a fuel is stored below its UFT, and an ignition source is present in the tank headspace, or a connected piece of equipment. Since all fuels are assumed to utilize the same equipment, the likelihood relative to the E10 benchmark is entirely dependent on each fuel's likelihood of having a flammable tank headspace. The potential direct causes and contributing factors for the ignition of the tank headspace that were identified for the scenario are provided in Table 21, and the fault tree is provided in Appendix A - Figure 2.

Table 21: Initiating and Contributing Events - Scenario #4: Direct UST Ignition

Cause	Description	Frequency Assigned (yr^{-1})
Failure of the UST Pump	Failure resulting in electrical spark. Pump is Class 1 Div. 1 rated.	10^{-5}
Low Level, Pump Running, Overheating	Pump temperature exceeds AIT, 689F	10^{-5}
Failure of Electronic Gauging Device	Failure resulting in electrical spark. Gauge is Class 1 Div. 1 rated.	10^{-5}
Gauging stick	Spark generation due to discharge of static from gauging stick	10^{-5}
Gauging Port Cover	Spark generation by removing metal cover	10^{-3}
Lightning	Lightning impact to UST vent stack. Sufficient to ignite vapors inside of vent stack.	10^{-3}

The estimated event frequencies for the scenarios are provided in Table 22.

Table 22: Scaled Likelihood Results - Scenario #4: Direct UST Ignition

Fuel	Frequency (scaled)
E10	1
E51	1
E83	50
E98	495

Risk Results

The results indicate that the likelihood of UST headspace ignition occurring as part of gauging activities is highest for E98. The risk of E98 and E83 fuels exceeded the E10 benchmark, while the E51 fuel had a risk equal to that of E10.

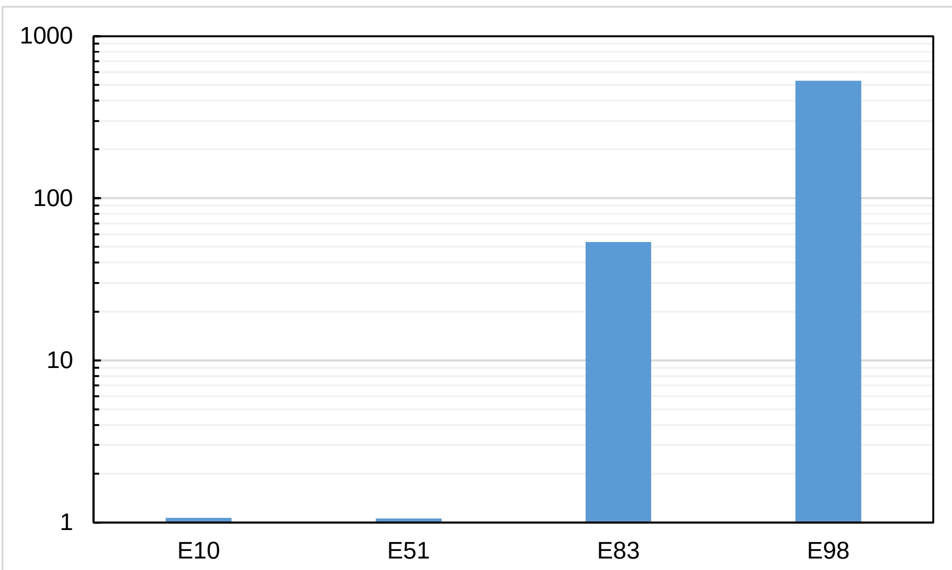
The factor that drives the increased risk of UST ignition and detonation for the E83 and E98 cases is the increased likelihood of those fuels being stored below the UFT (see tank headspace flammability assessment section). The likelihood of E98 being below the UFT is high as a result of the high UFT, while the likelihood of E83 being below the UFT is driven by the likelihood of blending errors that result in reduced fuel vapor pressure and increased UFT accordingly.

Risk results for the scenarios are provided in Table 23 and Figure 10.

Table 23: Scaled Risk Results - Scenario #4: Direct UST Ignition

Fuel	Fatalities (public)	Fatalities (employee)	Fatalities (Total)	SRI (public)	SRI (employee)	SRI (Total)
E10	0.07	1	1	0.07	1	1
E51	0.07	1	1	0.07	1	1
E83	0.07	1	1	3	50	54
E98	0.07	1	1	34	495	529

Figure 10: Scaled Risk Results - Scenario #4: Direct UST Ignition



Scenario 5: Uncontrolled Spill of Fuel to Grade in the Dispensing Area

Consequence Modeling Details

The scenario model was designed to simulate an uncontrolled loss of containment of liquid fuel from the fueling hose of the dispenser. The consequence model was set up as a release of liquid fuel from a 1” hose at ground level. The release rate of the fuel was set to be 10 gallons per minute, limited to a total release volume of 35 gallons. The pool fire scenario was not dependent on tank headspace flammability, so the results are presented based on a 95 degree Fahrenheit ambient temperature. This temperature represents the worst-case scenario pool fire consequence.

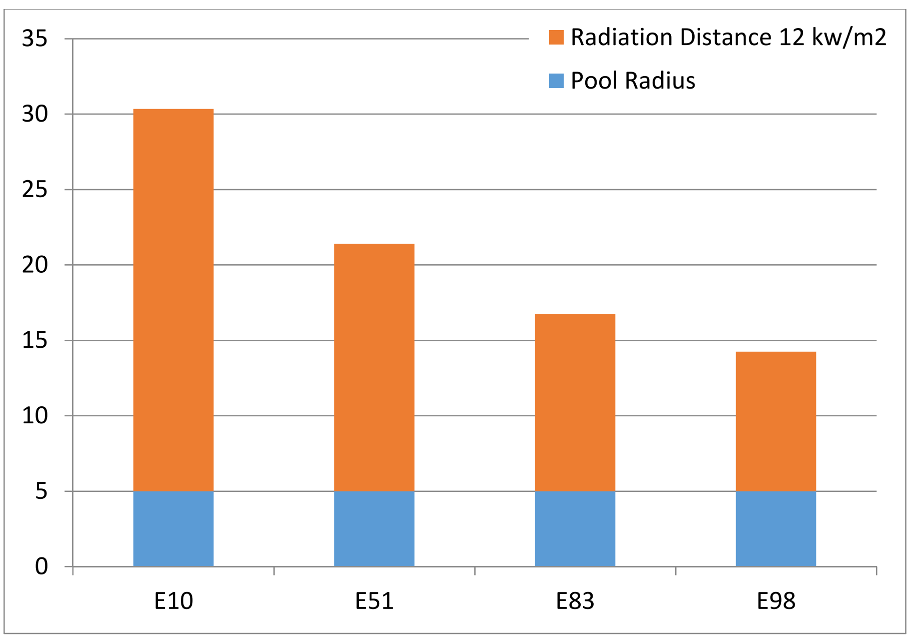
The results of the consequence model indicated hazards were present for pool fire, and flash fire from the ignition of vapors evaporated from the liquid pool.

The consequence modeling results indicated that all fuels presented similar pool spreading characteristics, the maximum pool radius was 6 feet for all fuels. However, the results showed that the radiation from pool fires varied significantly depending on the fuel type. The E10 provided the longest distance to the 12 kW/m^2 endpoint at 38 feet. The radiation exposure distances decreased with increasing ethanol content to a minimum distance of 18 feet for the E98 fuel. The flash fire results for the fuels also decreased with the ethanol content from a maximum distance of 35 feet for the E10 fuel, to a minimum distance of only 1 foot with the E98 fuel. The increased flash fire hazard of the E10 fuel can be attributed to the increased vapor pressure which results in a larger flammable vapor cloud. The governing hazard was the pool fire radiation, which exceeded the flash fire envelope fatal endpoint distance for all fuels. The consequence modeling results are summarized in Table 24 and Figure 11.

Table 24: Consequence Modeling Results - Scenario #5: Dispensing Area Spill

Dispensing Area Spill			
Fuel	**Pool Radius**	**Radiation Distance**	**Flash Fire Envelope**
	Ft	**12 kW/m^2**	**Ft**
E10	6	38	35
E51	6	26	22
E83	6	20	6
E98	6	18	3

Figure 11: Pool Fire Results - Scenario #5: Dispensing Area Spill



Likelihood Results

The likelihood of the release and ignition of the pool fire was assessed using fault tree analysis based on the input received from the qualitative risk analysis. The potential direct causes and contributing factors for the fuel spill and sources of ignition that were identified for the scenario are provided in Table 25, and the fault tree is provided in Appendix A - Figure 3.

Table 25: Initiating and Contributing Events - Scenario #5: Dispensing Area Spill

Cause	Description	Frequency Assigned (yr^{-1})
Dispensing Hose Failure	Failure of dispensing hose during use.	10^{-5}
Human error - dispensing	Nozzle not properly engaged or removed without shutoff.	10^{-2}
Filling nozzle auto shut-off failure	Auto-shutoff nozzle fails to stop fuel flow when tank is full.	10^{-3}
Shear Valve Fails to shut-off flow	Shear valve at dispenser connection fails upon vehicle impact to dispenser	10^{-2}
Vehicle Impact to Dispenser	Vehicle impacts dispenser, causing fuel supply line from UST to fail. Vehicle impact assumed to provide ignition source for release.	10^{-3}
Customer with open flame or sparking device	Open flam or spark present in the area of the flammable spill.	10^{-2}
Vehicle Running	Vehicle running in the area of the flammable spill.	10^{-2}
Size of Flammable Zone	A factor to account for the effect of the flammable area on the potential for ignition.	E10 , E51 , E83 , E98 1 , 0.63 , 0.18 , 0.18

The estimated event frequencies calculated from the FTA for each fuel type were scaled to the benchmark E10 fuel. The scaled likelihoods are provided in Table 26.

Table 26: Scaled Likelihood Results – Scenario #5: Dispensing Area Spill

Fuel	Frequency (scaled)
E10	1
E51	0.65
E83	0.22
E98	0.22

Risk Results

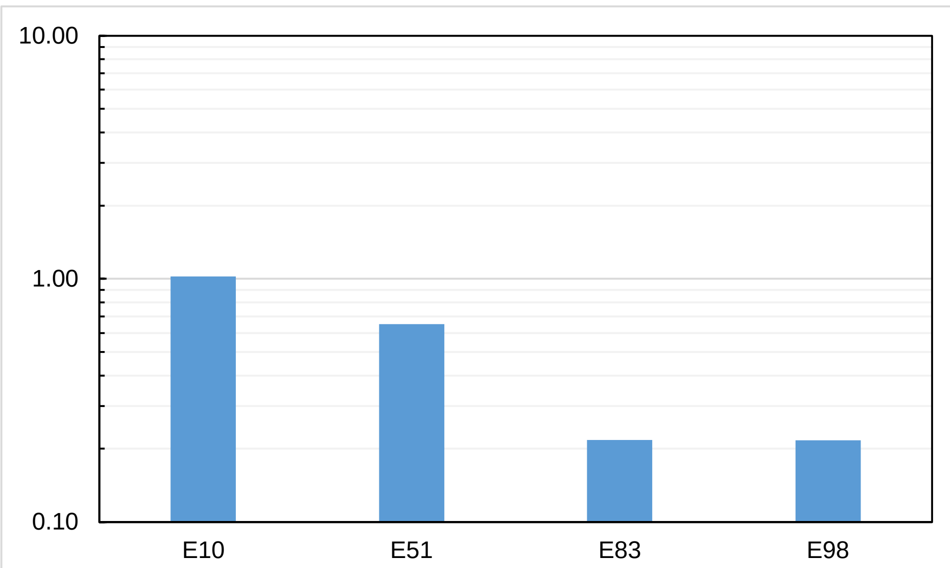
The results of the modeling and likelihood analysis indicate the consequence and probability of the potential fuel spill in the dispensing area during fueling are greatest for the baseline E10 fuel. The higher ethanol fuel blends presented reduced risks of impact from radiation due to lower flame radiation emissivity. While the potential for ignition of the higher ethanol fuels was reduced due to smaller flammable vapor clouds produced by the evaporating liquid pools. The radiation from the pool fire was the governing impact, as it posed the longest distance to fatal endpoint criteria for all fuels. The risk results for the scenario are presented in Table 27.

Table 27: Scaled Risk Results - Scenario #5: Dispensing Area Spill

Fuel	Fatalities (public)	Fatalities (employee)	Fatalities (Total)	SRI (public)	SRI (employee)	SRI (Total)
E10	1.02	0	1.02	1.02	0	1.02
E51	1.01	0	1.01	0.65	0	0.65
E83	1.01	0	1.01	0.22	0	0.22
E98	1.00	0	1.00	0.22	0	0.22

The results indicate that risk associated with the potential spill in the dispensing was highest for the benchmark E10 fuel. The risks are illustrated in Figure 12.

Figure 12: Scaled Risk Results - Scenario #5: Dispensing Area Spill



Scenario 6: Nozzle Fire, Flashback and Fuel Tank Failure

Consequence Modeling Details

The consequence model for the Nozzle fire scenario includes two models: a vapor vent model to assess the probability of ignition of the fuel vapors vented from the tank, and a catastrophic tank failure model to simulate the failure of a fuel tank subjected to headspace deflagration.

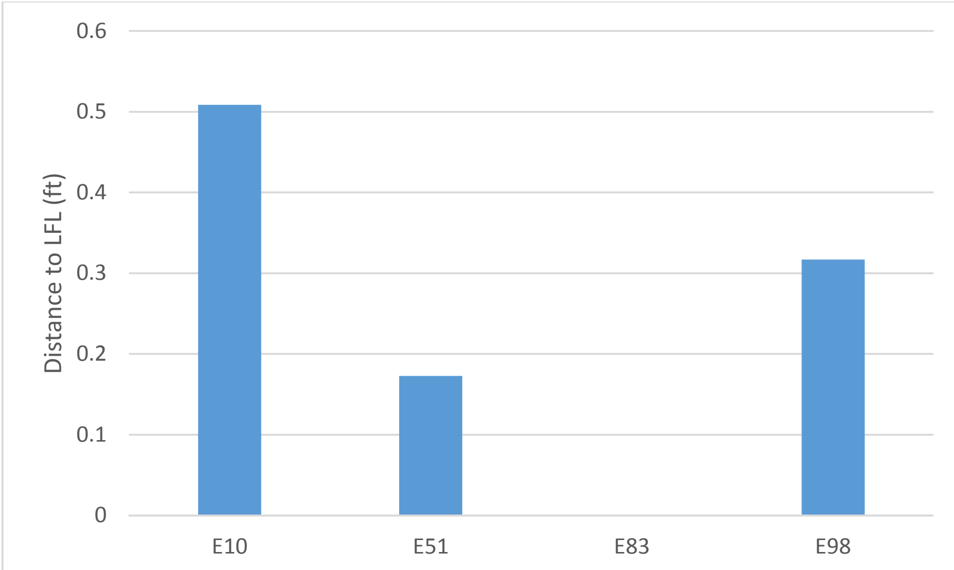
A scenario model was designed to simulate a release of the fuel tank vapor space to the atmosphere from the filling neck during the filling of the fuel tank. The model assumes the vapor vented from the tank to be an equilibrium concentration of air and fuel. The model was set up as a release of tank vapors from a 1” opening at 3 feet of elevation. The release was oriented horizontally, to simulate the release direction of vapor from the side of the vehicle. The driving force for discharge was set to be equal to the normal filling rate of a vehicle fuel tank from a dispenser, 10 gallons per minute. The release rate was set to be continuous to allow the plume to reach a steady-state result. The E10, E51, and E83 models were run at 5 degrees Fahrenheit to represent atmospheric conditions that would allow the tank headspace to be in the flammable region. The upper flammability temperature of E98 fuel is significantly higher than lower ethanol content fuels, so the E98 model was run at 95 degrees Fahrenheit to represent atmospheric conditions that allow a flammable tank headspace. It should be noted that this scenario considers E98 to be dispensed by the consumer into a vehicle fuel tank. In the current market, there are no service stations dispense E98 to vehicles. This scenario involving the dispensing of E98 to a vehicle fuel tank examines a potential scenario that may occur as a result of blender pump malfunction or changes in vehicle design. This vapor release and dispersion model was used to assess the likelihood of nozzle fire ignition for the various fuel types.

To assess the consequence of the nozzle fire and flashback into the vehicle fuel tank, a scenario model was developed to simulate the catastrophic failure of the vehicle fuel tank. The model used the PHAST pressurized vessel catastrophic failure model. The model assumed the tank contained 20 gal of liquid fuel and that the tank reached a pressure of 100 psig at the time of failure. The elevation of the tank was assumed to be 1 foot above grade.

The results of the vehicle fuel tank catastrophic failure model provided consequence results for pool fire and flash fire hazards.

For the E10, E51, and E83 fuels, the modeling results indicated that the length of the flammable plume released from the filling neck decreased as the ethanol content of the fuel increased; E10 provided the greatest distance to LFL, while the E83 fuel produced no flammable plume. The E10 fuel provided the longest flammable plume, which extended a distance of 6 inches from the filling neck. The E51 fuel provided a plume that extended only 2 inches from the filling neck. The E98 fuel produced a flammable plume that extended 4 inches from the filling neck. The nature of the plume dispersion results is a function of several factors. The LFL of high ethanol fuels is higher than low-ethanol content fuels, therefore the dilution and dispersion of the release more quickly reduces the fuel concentration below the LFL. Note that the E98 fuel seems to disagree with these results, however the E98 model was run at a much higher atmospheric temperature due to the very high upper flammability temperature of E98. The results of the vehicle fuel tank vapor space discharge and dispersion model are provided in Figure 13.

Figure 13: Distance to LFL - Scenario #6: Nozzle Fire and Flashback to Fuel Tank

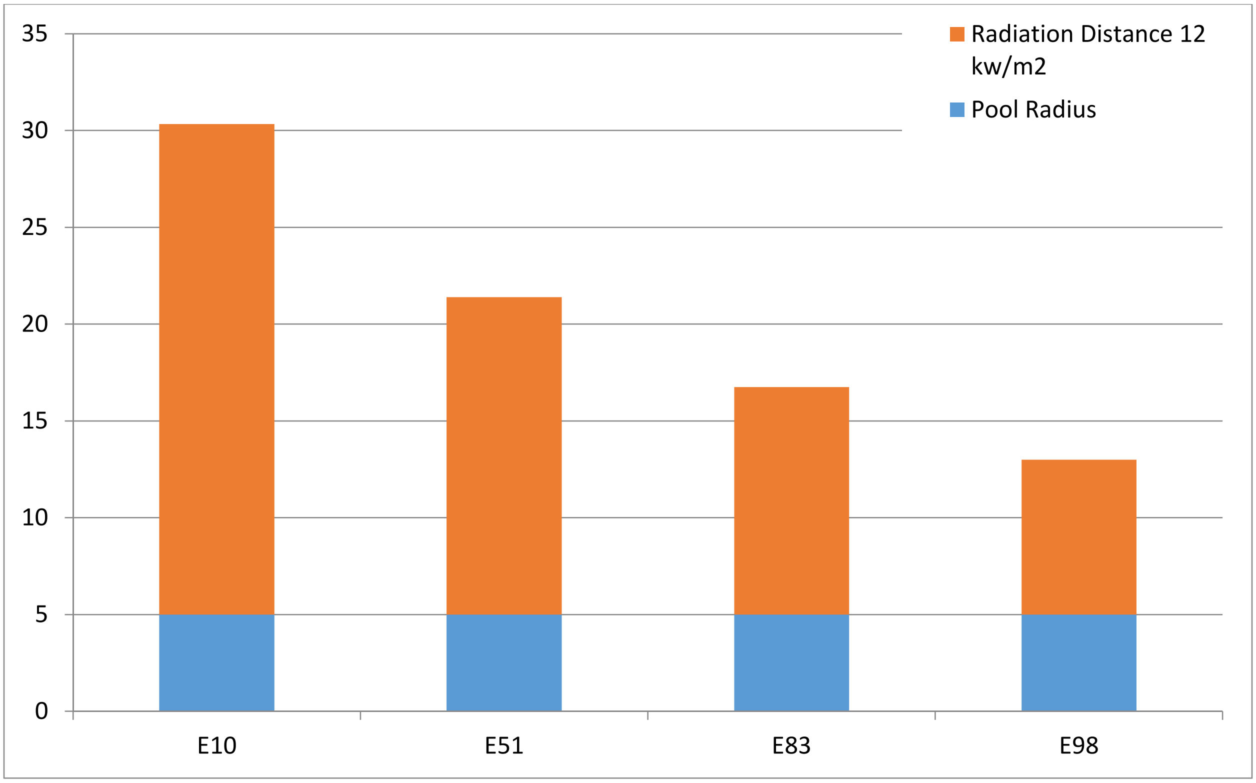


The results of the vehicle fuel tank catastrophic failure models indicate that pool fire scenario creates a hazardous impact area that extends farther than the flash fire hazard for all fuels. The E10 fuel provides the farthest distance to the lethal endpoint for radiation, at 30 feet. Consequence results are presented in Table 28 and Figure 14.

Table 28: Consequence Modeling Results – Scenario #6: Nozzle Fire and Flashback

Fuel Tank Failure			
	Pool Radius	**Radiation Distance**	**Flash Fire Envelope**
Fuel	**Ft**	**12 kW/m²**	**Ft**
E10	5	30	24
E51	5	21	11
E83	5	17	11
E98	5	13	12

Figure 14: Pool Fire Results – Scenario #6: Nozzle Fire and Flashback



Likelihood Results

The likelihood of the ignition of the nozzle fire was assessed using fault tree analysis based on the input received from the qualitative risk analysis. The potential direct causes and contributing factors for the sources of ignition that were identified for the scenario are provided in Table 29. The fault tree is provided in Appendix A - Figure 4.

Table 29: Initiating and Contributing Events - Scenario #6: Nozzle Fire and Flashback

Cause	Description	Frequency Assigned (yr^{-1})
Static	Driver discharges static at filling nozzle	10^{-3}
Other Ignition Source	Driver operating fueling nozzle with ignition source (smoking, lighter, or other)	10^{-3}
Size of Flammable Zone	A factor to account for the effect of the flammable area on the potential for ignition.	E10 , E51 , E83 , E98 1 , 0.34 , 0 , 0.62

The estimated event frequencies calculated from the FTA for each fuel type were scaled to the benchmark E10 fuel. The scaled likelihoods are provided in Table 30.

Table 30: Scaled Likelihood Results – Scenario #6: Nozzle Fire and Flashback

Fuel	Frequency (scaled)
E10	1
E51	0.34
E83	0.51
E98	308

Risk Results

The risk of nozzle fire and flashback to the vehicle fuel tank is highest for the E98 fuel blend. E98 is not currently used as a commercial fuel at service stations in the US, but was examined in this scenario to quantify the risk of E98 handled in the same manner as current commercial fuel blends. The E10 fuel poses the largest consequence, but the E98 fuel has the highest frequency of occurrence because of its high probability of being dispensed below the UFT. The increased radiation results for E10 are a function of the fuels increased flame emissivity. E51 presented a significantly lower risk due to the reduced likelihood of ignition given the very small vapor plume. The consequence model for E83 showed that no flammable vapor cloud was released, resulting in a reduced risk of nozzle fire ignition at the conditions modeled. The E98 fuel provided a larger plume than other high-ethanol content fuels due to the increased UFT of E98. At 95 degrees Fahrenheit, the E98 plume still did not extend past the E10 plume at 5 degrees Fahrenheit.

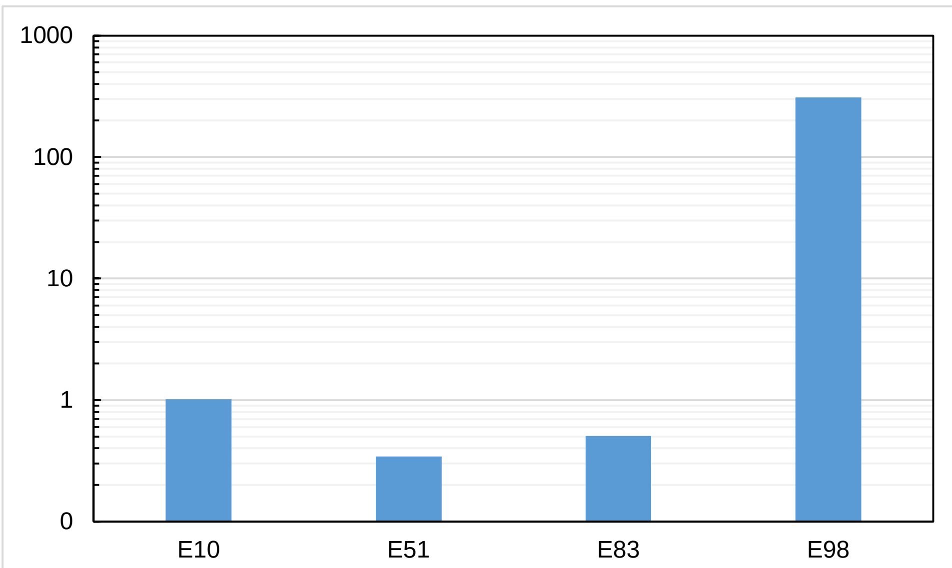
It was assumed that a single patron was present at the source of the nozzle fire at the time of ignition. The surrounding area impacted by the fuel tank failure was assumed to be populated at the standard population density used for all scenarios. Risk Results are provided in Table 31.

Table 31: Scaled Risk Results - Scenario #6: Nozzle Fire and Flashback

Fuel	Fatalities (public)	Fatalities (employee)	Fatalities (Total)	SRI (public)	SRI (employee)	SRI (Total)
E10	1	0	1	1	0	1
E51	1	0	1	0.34	0	0.34
E83	1	0	1	0.51	0	0.51
E98	1	0	1	309	0	309

The results show that the risks of nozzle fire and flashback are highest for the E98 fuel blend, while the E51 and E83 fuel blends fall below the risk of the E10 benchmark. The consequence of the nozzle fire is consistent for all cases. The frequency of occurrence is highest for E98, followed in order by E10, E83, and E51. The risks are illustrated in Figure 15.

Figure 15: Scaled Risk Results - Scenario #6: Nozzle Fire and Flashback



Scenario 7: Detonation of Vapors in a Vessel Associated with CA Tank Pressure Management Systems

Risk Results

The qualitative risk assessment team had a concern that vessels used for tank pressure management in the state of California might detonate in the event of UST detonation. A vessel detonation such as this may result in a blast wave that causes damage to buildings and people in the area.

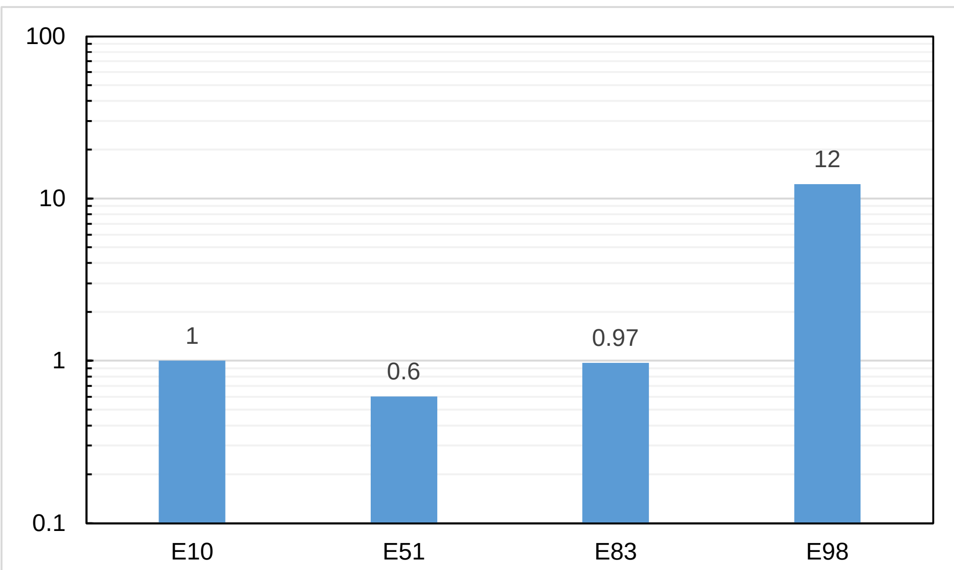
Research into the design of the commercially available tank pressure management systems used to comply with California regulations that require control of emissions from USTs indicated only one that used a vessel to absorb the tank vapor expansion. Documentation of the design of the system indicated that it was constructed of a pressure vessel designed with a maximum allowable working pressure (MAWP) of 137 psig [32]. The maximum pressure generated by the internal combustion of a hydrocarbon/air mixture is 130 psi [29]. Pressure vessels are designed to withstand normal operation at pressures up to the MAWP, and abnormal operations that exceed the MAWP are not expected to result in failure of the vessel unless the internal pressure exceeds 1.5-2 times the MAWP.

The result of this analysis indicates that it is not credible for the ignition of vapors in the UST and/or the tank pressure management vessel to result in the failure of the vessel.

Integrated Risk Results

The results of the study indicate that the highest risks of injury are presented by the E98 fuel blend. The cumulative SRI of all scenarios, scaled to the benchmark E10, is shown in Figure 16. The figure illustrates that the E98 fuel presents the highest overall risk of injury to employees and the public from all of the scenarios considered. Note that the cumulative risk results include consideration of E98 being handled and used in the same way as E10, E51, and E83. E98 is not currently dispensed as a commercial fuel, so the risk of nozzle fire or fuel spill at the dispenser is not present for E98 in the current marketplace. These results include the risks of using of E98 as a fuel available at the dispenser. Service stations operating blender pumps that store E98 should consider these E98 dispensing scenarios may occur as a result of blender malfunctions and may refer to specific scenarios related to the storage of E98 in USTs in the risk results reported for those specific scenarios.

Figure 16: Cumulative Scaled Risk Results by Fuel Type



The hazard scenarios used in the study can be considered to be of two distinct types: scenarios resulting in tank headspace detonation, and fuel spill scenarios that result in flash fire and pool fire hazards. To further analyze the relative risk of the fuel types for various scenarios, it is useful to consider the risk results based on the type of scenario. Cumulative risk results based on scenario type are provided in Figure 17 and Figure 18. Table 32 provides a summary of all cumulative risk data reported.

Figure 17: Cumulative Scaled Risk Results - Tank Headspace Detonation Scenarios

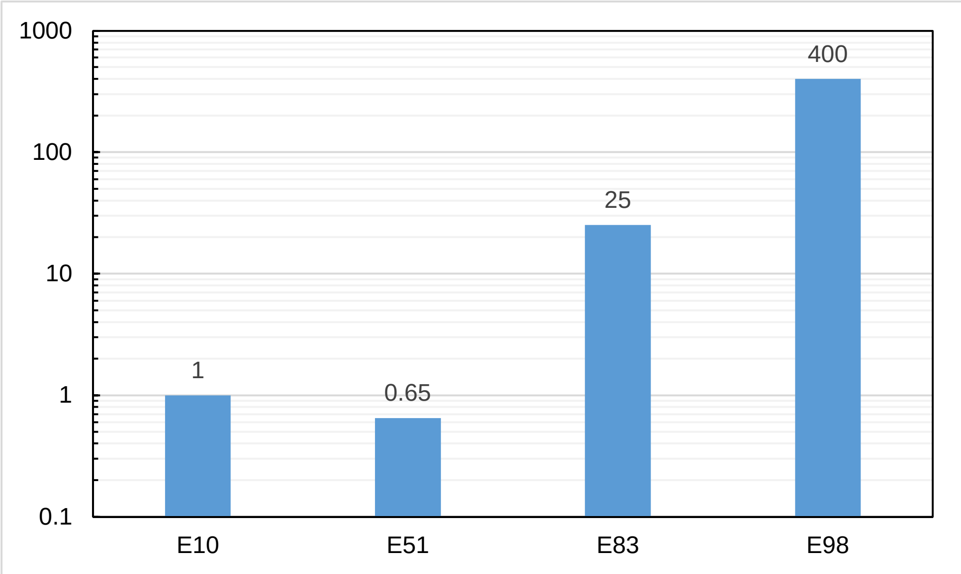


Figure 18: Cumulative Scaled Risk Results - Fuel Spill Scenarios

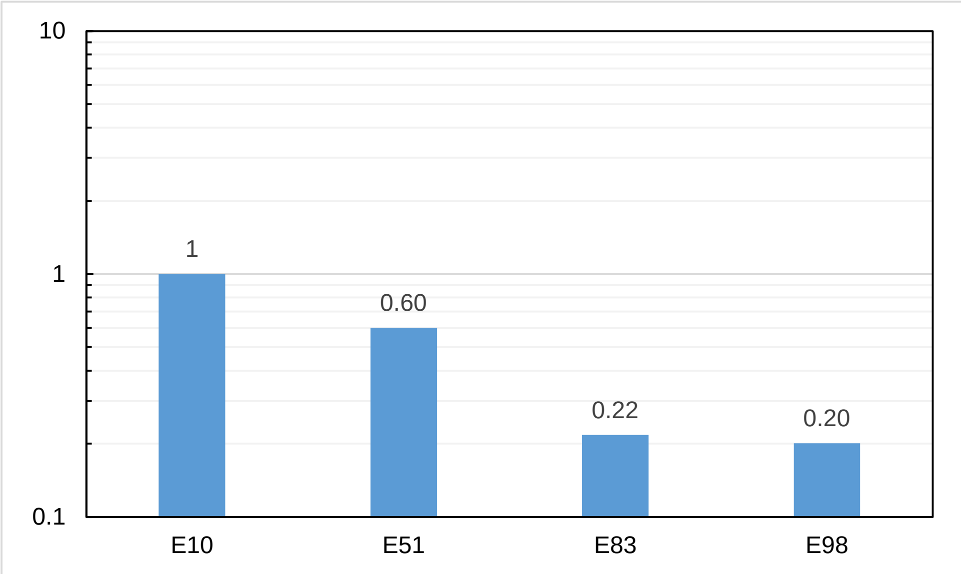


Table 32: Cumulative Scaled Risk Results

Fuel	All Scenarios	Tank Headspace Detonations	Fuel Spills
E10	1	1	1
E51	0.6	0.65	0.6
E83	0.97	25	0.22
E98	12	400	0.20

The E98 fuel presents the highest overall risk relative to the E10 benchmark. The high risk of the E98 fuel is driven by the likelihood of tank headspace detonations. E98 creates flammable tank headspaces up to 95 degrees Fahrenheit, whereas the other fuel blends in the study are required to be nearer to 5 degrees Fahrenheit to create flammable tank headspaces. The higher temperatures used in E98 models result in increased vaporization of the E98 fuels, leading to vapor plumes that extend farther than E83 and E51 blends. Despite the increased temperature of E98 releases from flammable tank headspaces, the E98 plumes do not exceed those of E10. Although the E98 vapor plumes do not exceed those from the E10 fuel, the reduced likelihood of ignition is offset by the fact that the E10 fuel is less likely than E98 to be stored under conditions that create a flammable tank headspace.

The high overall risk of the E10 fuel as compared to the E51 and E83 fuels is driven by the high risk of fuel spill scenarios for E10. The increased risk associated with E10 fuel spills, as compared to higher ethanol fuel blends, is the result of several factors that were analyzed as part of the consequence modeling. Firstly, the fire scenarios for E10 present larger radiation zones than other fuel blends due to the fact that E10 has the highest flame emissivity of the fuel blends analyzed. Flame emissivity decreases with increasing ethanol concentration of the fuel blends. A second reason for E10's increased risk results is the fact that the E10 blend has the lowest LFL and highest vapor pressure. Blending increased quantities of ethanol into gasoline results in depression of the vapor pressure and an increase in the LFL of the fuel. The result is that higher ethanol fuels produce less flammable vapor, and it requires less air to dilute the vapor below its LFL. Therefore, when comparing fuel spills of the fuels at the same temperatures, E10 produces the largest amount of flammable vapor. This increases the probability of E10 being ignited in a spill scenario. The tangible end result which directly affects the risk of ignition is that the reduced vapor pressure and LFL of higher ethanol content blends result in a shorter distance to LFL and a smaller flammable vapor plume than low ethanol content fuels like E10. It must be noted that this effect is offset for E98 in tank headspace detonation scenarios because of the high UFT of E98.

Although the cumulative risk of the E83 fuel from all scenarios does not exceed the cumulative risk of the benchmark E10, the risk of E83 fuel from tank headspace detonations does exceed the risk of the E10 benchmark. The high risk of the E83 fuel from tank headspace detonations is caused by the increased likelihood of E83 to be stored in the flammable range. The likelihood was determined as part of the tank headspace flammability assessment. The UFT of E83 is much more sensitive to ethanol content as compared to lower ethanol content fuel blend; blending errors for E83 fuels can have large effects on the temperature at which the headspace becomes subject to detonation.

Recommendations

The following recommendations are provided to mitigate the risk of scenarios which exceed the risk of the benchmark E10 fuel.

Table 33: Recommendations to Reduce the Risk of Scenarios Exceeding Benchmark

Scenario	Fuels Exceeding Benchmark Risk	Recommendation
Nozzle Fire and Flashback	E98	Vehicle Manufacturers: Consider performing testing on vehicles designed for denatured ethanol fuel to assess the potential for flashback of nozzle fires into the fuel tank. Consider installing flame arresters (as suggested by GM [33]) in the filling necks of vehicles subjected to increased risk of nozzle fire and flashback.
		Service Stations: Consider implementing Stage 2 vapor recovery to reduce the amount of flammable vapor released at the filling neck during vehicle refueling.
Direct Ignition of UST	E83 E98	Service Stations: Consider implementing protective measures to prevent spark generation during manual gauging operations. Potential sources of sparks include static discharge from employee, sparks generated by equipment (port cover, gauging stick). Consider evaluating the material of construction of the port cover and connection, as well as the gauging stick to reduce the likelihood of sparks being generated by the cover or gauging stick impacting its surroundings.
		Service Stations: Consider utilizing automatic gauging devices to reduce the frequency of manual gauging activities.
		Service Stations: Consider installing flame arrestor on the stage 1 vapor recovery connections as is required by UK APEA [21].
UST Vent Ignition and Flashback	E98	Service Stations: Consider installing flame arrestors in the UST vent stacks to prevent flashback into/through the vent line.
		Service Stations: Consider using Stage 1 vapor recovery to reduce the amount of flammable vapor vented from the UST vent stack during filling
Ignition of UST Vapors at Grade and Flashback	E98	Service Stations: Consider installing flame arrestors on the stage 1 vapor recovery connections as is required by UK APEA [21].

*Note that E98 is not currently dispensed as a vehicle fuel, however the scope of this study included analysis of E98 in place of the current baseline E10 fuel.

Conclusions

- **Of the four fuels studied (E10, E51, E83, and E98), E98 presents the highest cumulative risk at the service station.** The high cumulative risk is driven by the fact that the E98 tank headspace is flammable at nearly all ambient temperatures, and therefore tank headspace detonations are more likely to occur.
- **Considering the potential for tank headspace detonation, E98 and E83 fuels present a greater risk of tank headspace detonation than E10.** The reduced vapor pressure of commercially available E83 fuels results in an increased likelihood of the fuel being stored at temperatures below the UFT, while the high UFT of E98 results in the tank headspace being flammable at nearly all ambient conditions.
  - The following recommendations may be considered to mitigate the risk of detonation of underground storage tank headspaces:
    - Consider installing flame arrestors in the vent stacks of USTs storing E98 to prevent flashback into/through the vent line to the tank headspace.
    - Consider using Stage 1 vapor recovery when unloading E98 to reduce the amount of flammable vapor vented from the UST vent stack during filling
    - Consider installing flame arrestor on the stage 1 vapor recovery connections of tanks storing E98 and E83. Similar to the requirements of UK APEA [21].
    - Consider implementing protective measures to prevent spark generation during manual gauging operations of E98 and E83 USTs. Potential sources of sparks include static discharge from employee, sparks generated by equipment (port cover, gauging stick). Consider evaluating the material of construction of the port cover and connection, as well as the gauging stick to reduce the likelihood of sparks being generated by the cover or gauging stick impacting its surroundings.
    - Consider utilizing automatic gauging devices in E98 and E83 USTs to reduce the frequency of manual gauging activities if possible.
- **E10 presents the highest risk from fuel spills.** The fire scenarios for E10 present larger radiation zones than other fuel blends due to the fact that E10 has the highest flame emissivity, the highest vapor pressure, and the lowest lower flammability limit of the fuel blends analyzed. The result of these properties is that E10 fuel spills generated larger flammable vapor clouds and larger fire impacts.
- **Determining the likelihood of various fuel blends to be stored at a service station at temperatures below their UFT is a complex evaluation that warrants additional analysis in future studies.** Such a study must account for many factors, including: the physical properties of the blended fuel, the fuel specifications used, ambient temperature variations, the potential for fuels to be blended incorrectly, terminal blending controls, and fuel delivery frequency among others. These variables vary by geographic region and by service station, compounding the complexity of the evaluation. The tank headspace flammability assessment results and ultimately the risk results of this study would be affected by more accurate data regarding current industry blending practices and a more detailed analysis of tank headspace flammability in the market.

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Appendix A
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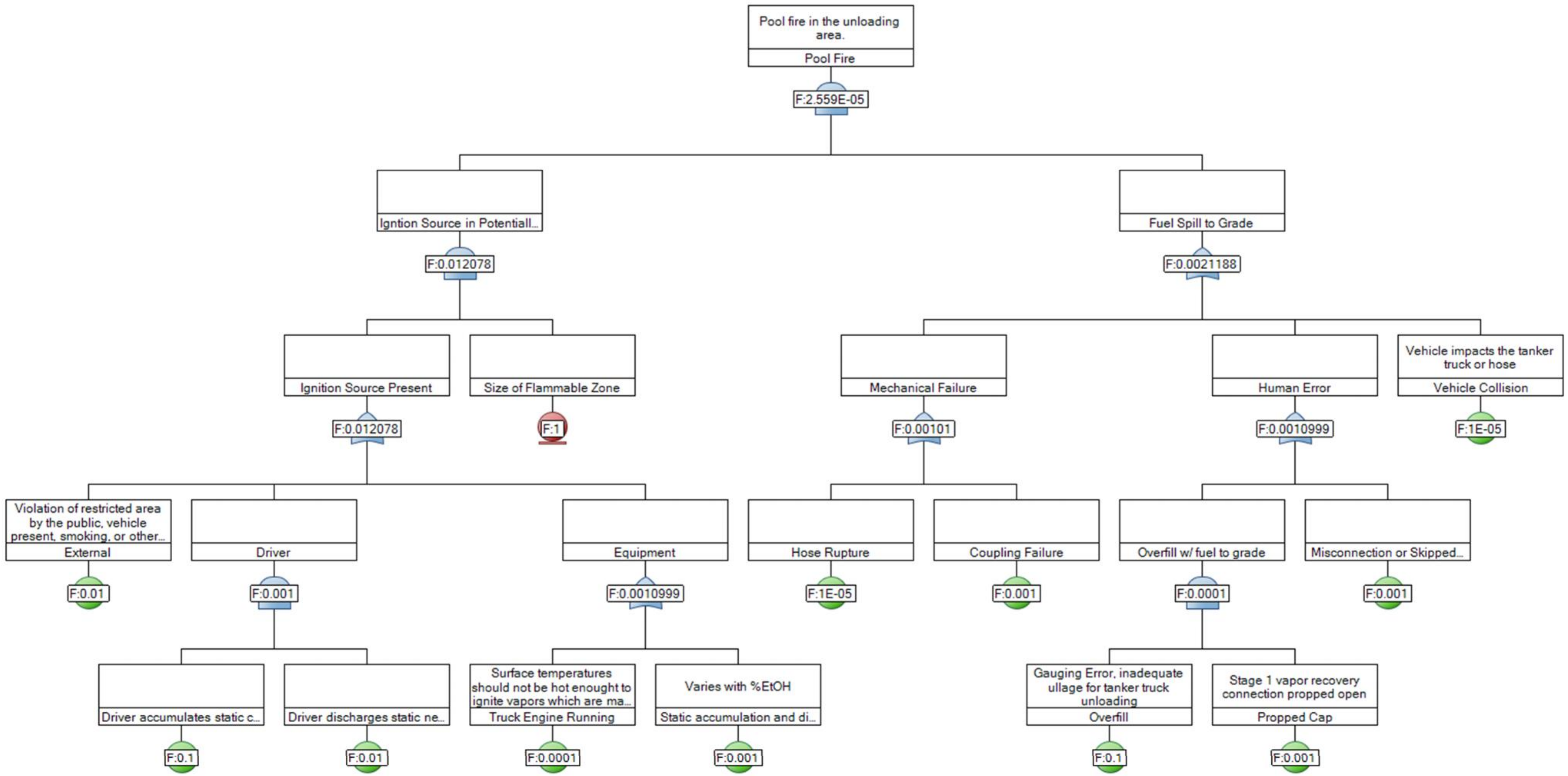
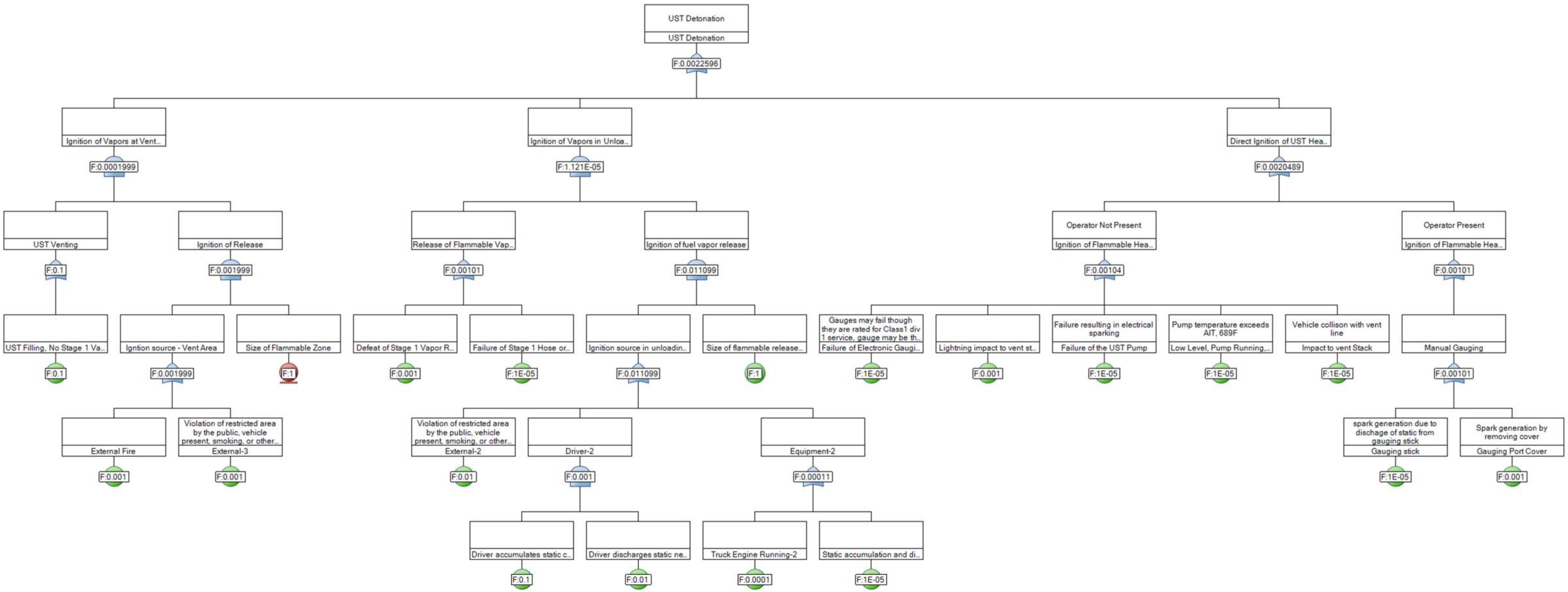
Fault Trees

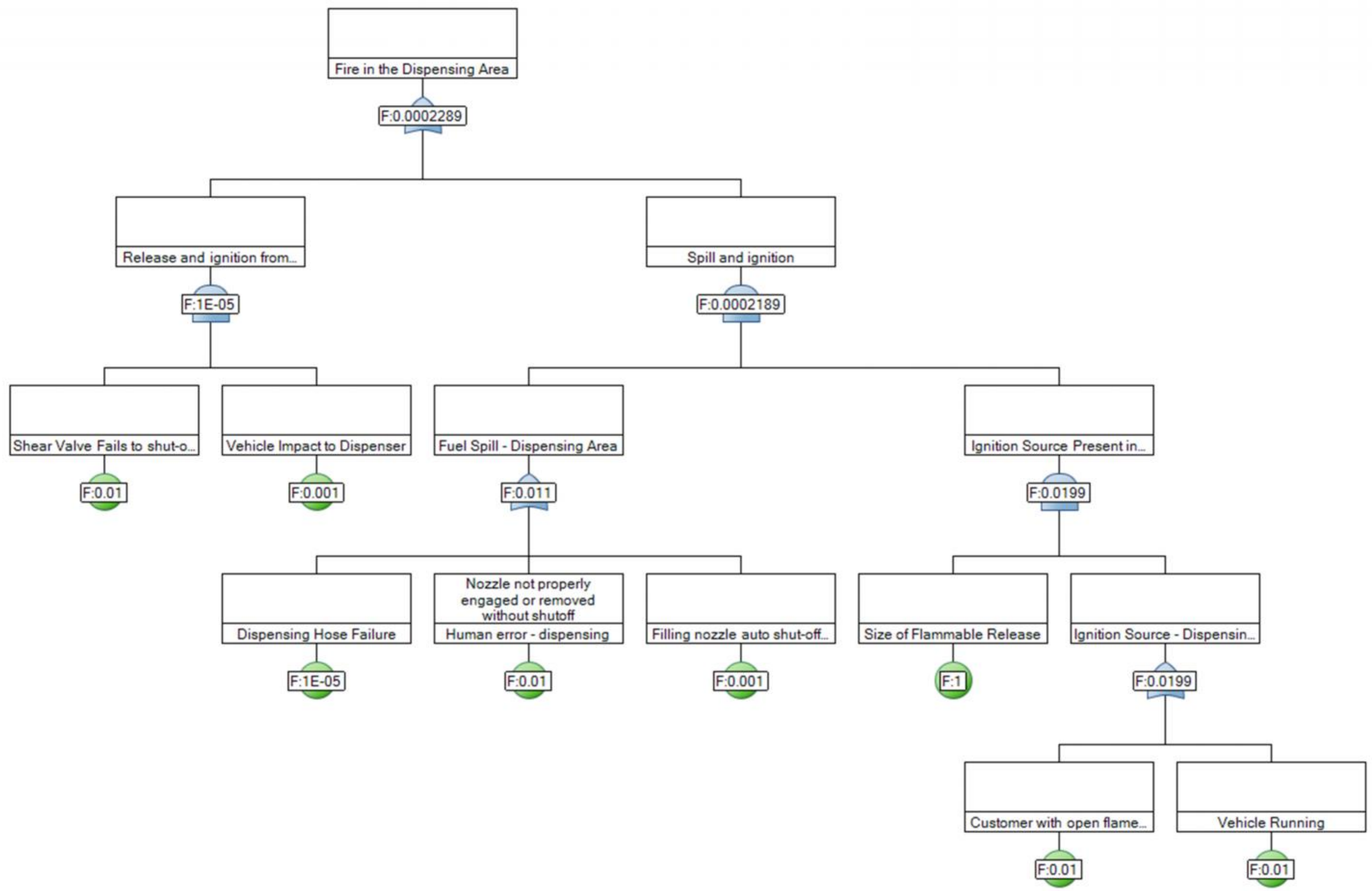
Appendix A - Figure 1: Fault Tree - Scenario #1



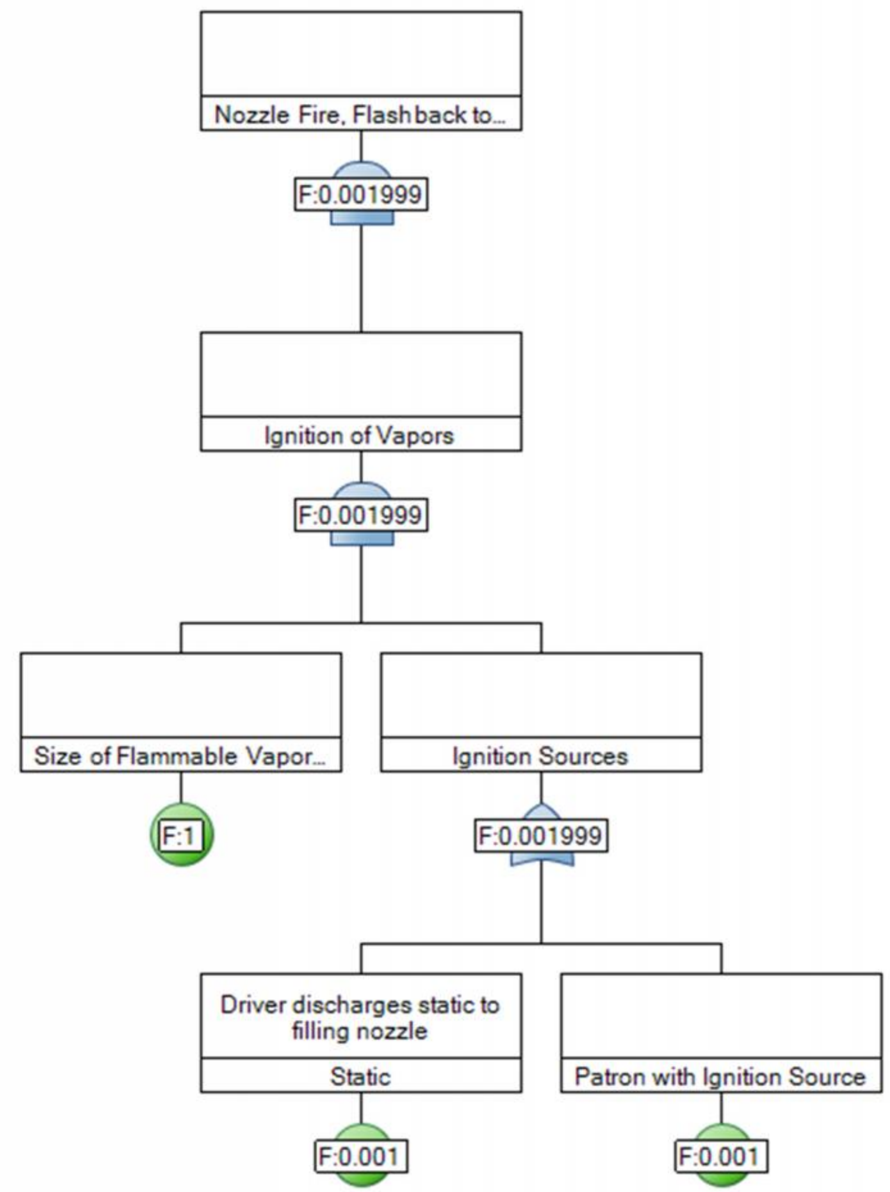
Appendix A - Figure 2: Fault Tree – Scenarios #2, 3 and 4



Appendix A - Figure 3: Fault Tree - Scenario #5



Appendix A - Figure 4: Fault Tree - Scenario #6



Appendix A - Figure 5: Fault Tree - Tank Headspace Flammability Assessment