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Magnitude of Hazards Associated with the Rail Transport of Crude Oil and LPG

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Abstract

Over the past several years, the volume of crude oil being transported by rail has dramatically increased. With this increase, the number of train accidents involving crude oil rail cars has also increased. A common perception of the public is that the risk associated with "crude-by-rail" has increased. This may be true due to an increase in rail car shipments but has the magnitude of hazards associated with crude by rail transport changed? Arguments have been made that the compositions of specific crudes make them more hazardous than conventional crude. Is there a basis for this claim?

As the volume of crude transported by rail has increased, so has the volume of liquefied petroleum gases (LPGs) transported by rail, albeit with different types of rail cars than those used for crude oil.

This paper will investigate the magnitude of hazards associated with rail transport of a range of crude oils and LPGs. The release mechanisms will be affected by the type of rail car employed (DOT-112, DOT-111, and the modified DOT-111 called the 1232) and the fluid condition upon release. The result of the overall analysis will be a side-by-side comparison of hazard magnitude as a function of the transported fluid and the rail car employed.

Introduction

Much of the discussion concerning the risk associated with the rail transport of crude oils has centered around the frequency of accidents and not the consequence(s) associated with the accidents. Since the risk (R) associated with rail transportation of crude oil is the product of frequency (f) and consequence (C) [$R = f \cdot C$] a better understanding of the consequences associated with releases of crude oil during rail transport is warranted. This paper provides insight into the extent of potential hazards associated with four types of crude oil, three types of liquefied petroleum gases (LPGs), and ethanol. The hazards associated with LPGs and ethanol are included in the evaluation in order to put the hazards derived from the crude oils in perspective.

The analysis is targeted at comparing the extent of potential impacts associated with these fluids commonly transported by rail. In order to provide as close to an apples-to-apples comparison as possible, a common set of atmospheric conditions, inventory amounts, and release hole sizes were used. In the evaluation, the following parameters were kept constant.

- Atmospheric Conditions
  - Wind speed = 10 miles per hour
  - Atmospheric stability = Pasquill-Gifford class D
  - Relative humidity = 70%
  - Air temperature = 70°F
  - Substrate temperature = 70°F
  - Surface roughness = 1.57 inches [0.04 meters]
- Inventory Amounts
  - Water capacity of rail cars (DOT-112 and DOT-111) = 33,600 gallons
  - Nominal capacity (full) = 30,000 gallons
- Release Hole Sizes
  - 2-inch diameter hole in liquid phase, orientation = horizontal with the wind
    - Hole assumed to be at midpoint of liquid level
  - 2-inch diameter hole in vapor phase, orientation = vertical
  - Catastrophic failure of rail car with immediate ignition

While this set of conditions may not correspond exactly with the products evaluated in their associated rail cars, they are close enough to allow the hazard impacts to be compared. It should be noted that none of the fluids were defined to have any acutely toxic components (e.g., hydrogen sulfide). Thus, no toxic vapor dispersion calculations were performed.

Rail Cars

The rail car used to transport LPGs is defined as a DOT-112 rail car, commonly referred to as a pressure car. The maximum water capacity of this rail car is 33,600 gallons. Figure 1 shows a DOT-112 rail car and identifies some of its features. The DOT-111 rail car is used to transport crude oils, ethanol, and other materials. Figure 2 shows a DOT-111 rail car and some of its features. For this analysis, the water capacity of the DOT-111 rail car was assumed to be 33,600 gallons. For evaluating the hazards associated with a release of fluid, the DOT-111 and DOT-111 (1232) rail cars are considered the same. For the purposes of this analysis, the rail cars only differ by their pressure rating.

Fluid Data

While the capacities of the two rail car types were held constant, the fluid properties of the materials transported were not. Table 1 presents basic information on the eight materials evaluated in this study. It should be noted that the generic LPG listed in the table is a 50/50 mix (by moles) of propane and *n*-butane. The fluid characteristics of the four example crude oils were taken from the Sandia report titled *Literature Survey of Crude Oil Properties Relevant to Handling and Fire Safety in Transport* [1]. It should be noted that slight changes in the composition of the crude oil would not significantly change the results. This will be partially addressed by evaluating two Bakken compositions. One composition, labeled Bakken, has a Reid vapor pressure of 7.83 psia, while the other Bakken composition, labeled Bakken-S, has a Reid vapor pressure of 11.3 psia.

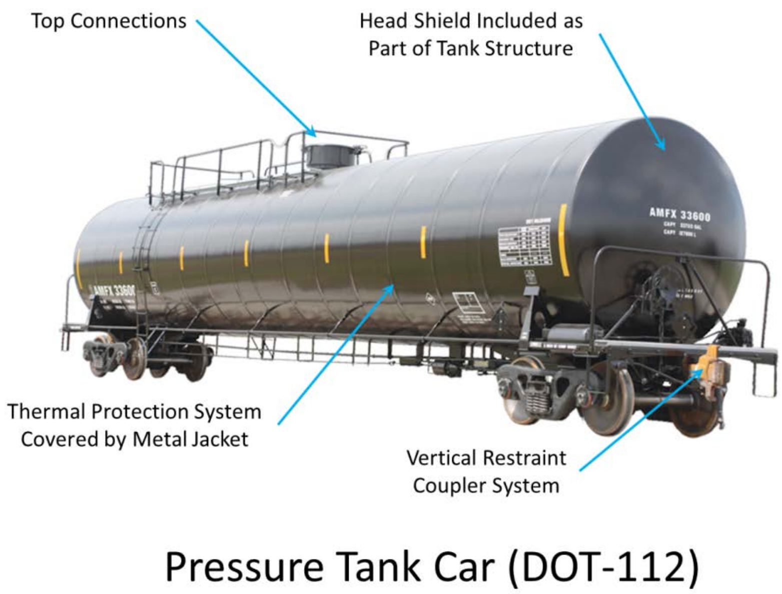

Figure 1. DOT-112 (Used for LPG)

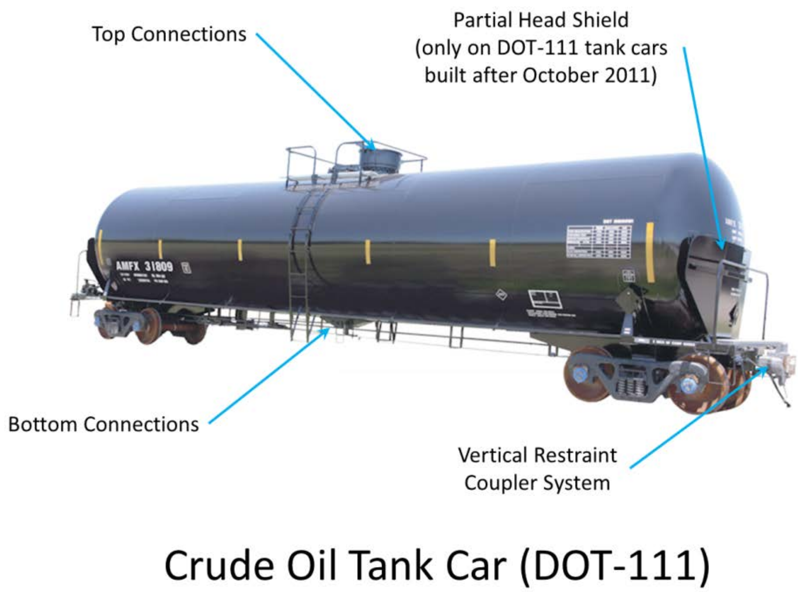

Figure 2. DOT-111 (Used for Crude Oil and Ethanol)

Table 1. Rail Car and Product Parameters

Parameters	**Propane**	**LPG (50/50 C3/*n*-C4)**	***n*-Butane**	**Bakken**	**Bakken-S**	**Denver Basin**	**Eagle Ford**	**Ethanol**
Rail Car Type	DOT-112	DOT-112	DOT-112	DOT-111	DOT-111	DOT-111	DOT-111	DOT-111
Rail Car water capacity (gallons)	33,600	33,600	33,600	33,600	33,600	33,600	33,600	33,600
Rail Car percent liquid full	89	89	89	89	89	89	89	89
Reid Vapor Pressure (psia)	NA[1]	NA[2]	NA[3]	7.83	11.3	7.82	7.95	2.31
Mole Fraction of Light Ends (< C5)	1.0	1.0	1.0	~0.063	~0.076	~0.063	~0.063	NA

NA[1] = vapor pressure of Propane at 100°F is 189 psia

NA[2] = vapor pressure of 50/50 mix (by moles) of Propane and *n*-Butane at 100°F is 82.5 psia

NA[3] = vapor pressure of n-Butane at 100°F is 52 psia

NA = not applicable

Hazards Evaluated

The eight materials evaluated in this study are all flammable fluids. The LPGs are transported in rail cars that maintain the fluid in liquid form due to the fluid vapor pressure. The crude oils and ethanol are transported in what can be described as near-ambient conditions. A release of LPG, crude oil, or ethanol can result in one or more of the following hazards.

- Dispersion of a flammable gas plume, possibly followed by ignition and resultant flash fire. The maximum extent of a flash fire is defined by the distance to the lower flammable limit (LFL).
- Ignition of the vapor or vapor/liquid mix (aerosol), resulting in a torch fire (jet fire). The maximum extent of the radiant hazard is defined by the 1,600 Btu/hr-ft^2 radiant flux level.
- Ignition of the vapor evolving off a liquid pool following a release, resulting in a pool fire. The maximum extent of the radiant hazard is defined by the 1,600 Btu/hr-ft^2 radiant flux level.
- Catastrophic failure of the rail car, followed by immediate ignition of the aerosol mass forming a fireball. The maximum extent of the radiant hazard from the fireball is defined by the 1% mortality level associated with an integrated radiant dose (defined by a probit).
- Overpressure generated by the ignition of the flammable mass generated. A common measure of the extent of overpressure impacts is to define the distance to 1 psig.

While these hazard endpoints do not represent a consistent set (some identify mortality while others identify injury), they are useful when comparing a specific hazard among a range of fluids.

Consequence Modeling

The hazard zones resulting from the liquefied gas, crude oil, and ethanol releases were evaluated to determine the extent and location of flammable hazards. When performing site-specific consequence analysis studies, the ability to accurately model the release, dilution, and dispersion of gases and aerosols is important if an accurate assessment of potential exposure is to be attained. For this reason, Quest uses a modeling package, CANARY by Quest®, that contains a set of complex models that calculate release conditions, initial dilution of the vapor (dependent upon the release characteristics), and the subsequent dispersion of the vapor introduced into the atmosphere. The models contain algorithms that account for thermodynamics, mixture behavior, transient release rates, gas cloud density relative to air, initial velocity of the released gas, and heat transfer effects from the surrounding atmosphere and the substrate. The release and dispersion models contained in the QuestFOCUS package (the predecessor to CANARY by Quest®) were reviewed in a United States Environmental Protection Agency (EPA) sponsored study [2] and an American Petroleum Institute (API) study [3]. In both studies, the QuestFOCUS software was evaluated on technical merit (appropriateness of models for specific applications) and on model predictions for specific releases. One conclusion drawn by both studies was that the dispersion software tended to overpredict the extent of the gas cloud travel, thus resulting in too large a cloud when compared to the test data (i.e., a conservative approach).

A study prepared for the Minerals Management Service [4] reviewed models for use in modeling routine and accidental releases of flammable and toxic gases. CANARY by Quest® received the highest possible ranking in the science and credibility areas. In addition, the report recommends CANARY by Quest® for use when evaluating toxic and flammable gas releases. The specific models (e.g., SLAB) contained in the CANARY by Quest® software package have also been extensively reviewed.

CANARY also contains models for pool fire and torch fire radiation. These models account for impoundment configuration, material composition, target height relative to the flame, target distance from the flame, atmospheric attenuation (includes humidity), wind speed, and atmospheric temperature. Both are based on information in the public domain (published literature) and have been validated with experimental data.

For vapor cloud explosion calculations, Quest uses a model that is a variation of the Baker-Strehlow-Tang (BST) method. The Quest model for estimation of flame speeds (QMEFS) [5] is based on experimental data involving vapor cloud explosions, and is related to the amount of confinement and/or obstruction present in the volume occupied by the vapor cloud.

Consequences Associated with a Release During Ambient Conditions

The first set of consequence calculations were performed as if the accident occurred (e.g., a derailment), and assumed 2-inch diameter hole was generated, and the pressure and temperature in the rail car was not elevated due to an external fire. In this manner, the hazards associated with the eight fluids can be evaluated based on their thermophysical properties during transport.

It is instructive to review the release rate of the various fluids under these conditions. As an example, Figure 3 presents the mass release rate of propane out of a 2-inch hole in the liquid space of a DOT-112 rail car. Since the pressure in the rail car is approximately 126 psia (the vapor pressure of propane at 70°F), there is pressure to force the propane out of the hole. Upon exiting the hole, the propane flashes and forms an aerosol cloud. Figure 3 shows how the various propane phases (vapor = flashed and evaporated, aerosol liquid = liquid droplets that stay suspended in air, liquid to ground = liquid that reaches the ground) are released from the 2-inch hole as a function of time.

Figures 4 and 5 show the release behavior of the 50/50 LPG mixture and the pure *n*-butane respectively. As would be expected, the mass release rate drops as the pressure in the rail car drops (76 psia for the 50/50 LPG mix and 32 psia for the *n*-butane).

Releases of the four crude oils and ethanol would show a different behavior. Since there is no pressure to force the liquid out the hole and there is not an additional hole to allow air to enter, the liquid can only drop out intermittently. After each small volume of liquid is released, air is drawn back into the rail car. This method combined with the low pressure of the rail car does not generate any significant aerosol or vapor formation. Thus, almost all of the crude oil and ethanol releases end up as pools of liquid on the ground.

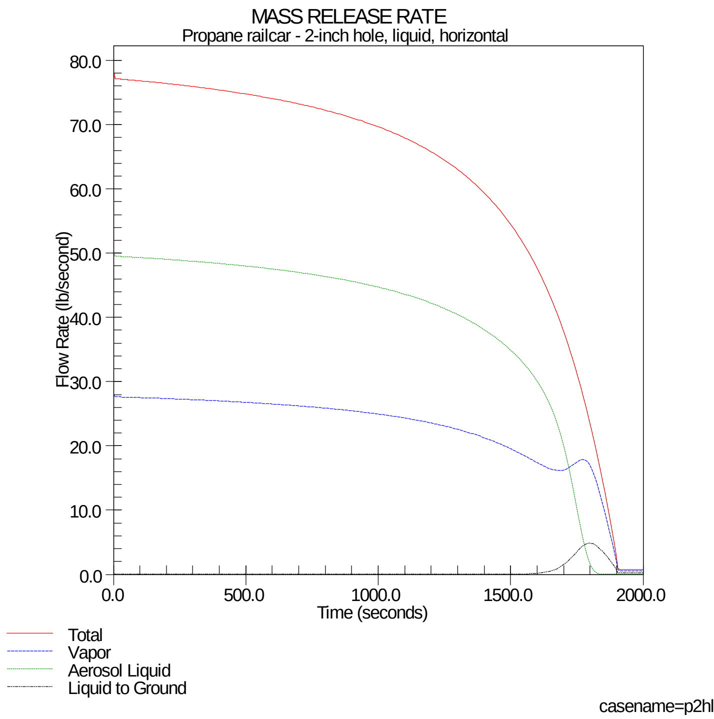

Figure 3. Liquid Propane Release – Ambient Conditions

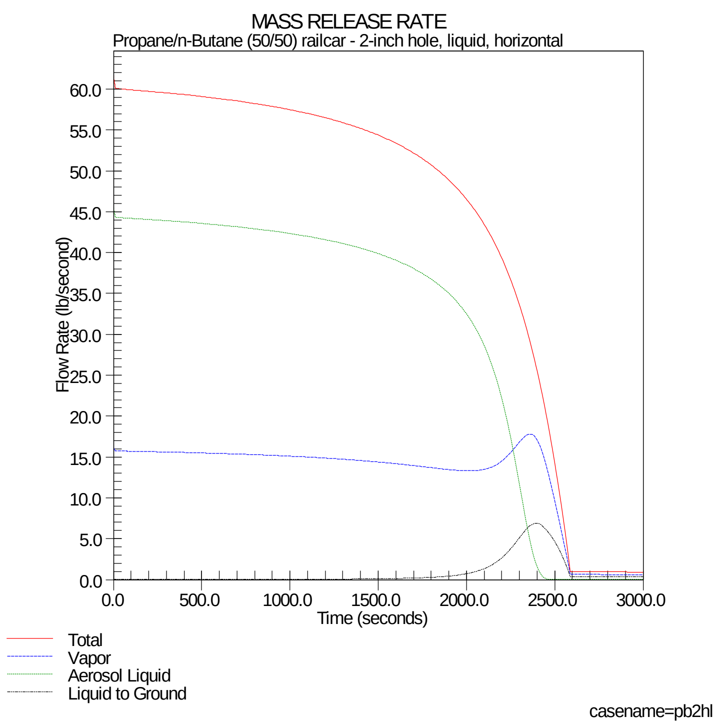

Figure 4. Liquid Propane/*n*-Butane (50/50) Release – Ambient Conditions

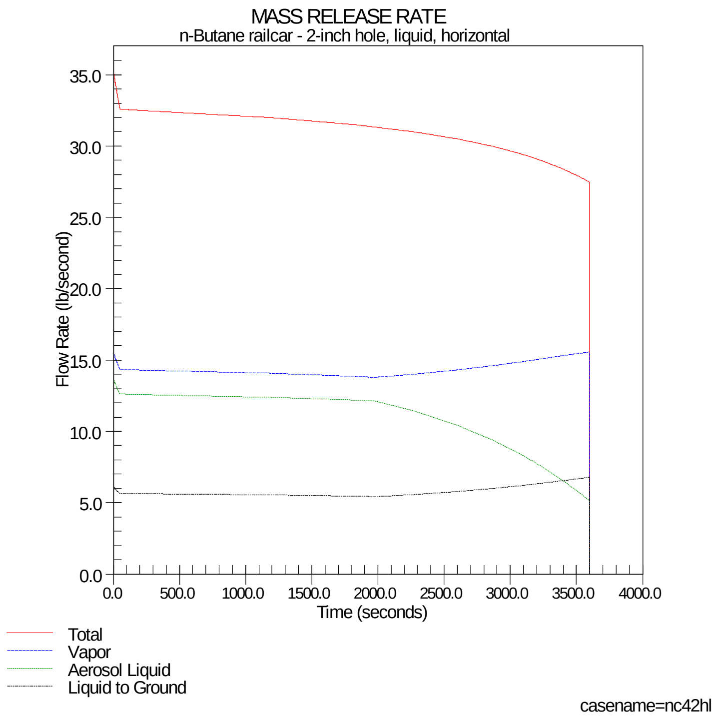

Figure 5. Liquid *n*-Butane Release – Ambient Conditions

Extent of Flash Fires Following a Release from the Liquid Space – Ambient Conditions

Using the CANARY software, the vapor clouds generated following a liquid release from a 2-inch diameter hole in the rail car, oriented horizontally were evaluated. As described above, the liquefied gases demonstrate a different release behavior than the crude oils and ethanol. This is shown in Table 2 where the source of the vapor cloud generating the largest flash fire distance is defined. Table 2 also defines the distance to the LFL for each of the fluid releases under the ambient (Tair = Tfluid = 70°F) conditions. As can be seen from Table 2, the liquefied gases have the potential to generate significantly larger flash fire zones than any of the crude oils or ethanol.

Table 2. Distance (ft) to LFL Following
Horizontal Liquid Release During Ambient Conditions with Source Identified

Propane	**LPG (50/50 C3/*n*-C4)**	***n*-Butane**	**Bakken**	**Bakken-S**	**Denver Basin**	**Eagle Ford**	**Ethanol**
505	450	75	30	30	15	50	10
MJ	MJ	MJ	Pool	Pool	Pool	Pool	Pool

MJ = Momentum Jet Source
Pool = Liquid Pool Source

Extent of Radiant Impacts Following a Release from the Liquid Space – Ambient Conditions

If the fluid released from the 2-inch hole were to ignite, two potential radiant hazards could exist. If enough vapor were generated to sustain a torch fire, a slowly receding torch flame would exist. The extent of the radiant impacts are presented in Table 3. Note that under the ambient conditions, the crude oils and ethanol are not volatile enough to generate a continuous flammable vapor stream leaving the 2-inch hole.

Table 3. Distance (ft) at Ground Level to 1,600 Btu/hr-ft^2 from Torch Fire Following Horizontal Liquid Release During Ambient Conditions

Propane	**LPG (50/50 C3/*n*-C4)**	***n*-Butane**	**Bakken**	**Bakken-S**	**Denver Basin**	**Eagle Ford**	**Ethanol**
215	185	125	NV	NV	NV	NV	NV

NV = Not Volatile Enough to Generate a Torch Fire

If the fluid leaving the 2-inch hole reaches grade and ignition occurs, a pool fire can ensue. For the crude oils and ethanol this is the primary hazard associated with their release. This is shown in Table 4. The results for the four crude oils are similar as their burning characteristics are similar. Ethanol's burning characteristics are slightly different, resulting in a different radiant impact distance. Note that the release of propane and the 50/50 LPG mix do not result in any significant liquid to ground (see Figures 3 and 4), thus pool fires are not possible. The *n*-butane release does result in liquid to the ground (see Figure 5), thus a pool fire is possible.

Table 4. Distance (ft) to 1,600 Btu/hr-ft^2 from Pool Fire Following Horizontal Liquid Release During Ambient Conditions

Propane	**LPG (50/50 C3/*n*-C4)**	***n*-Butane**	**Bakken**	**Bakken-S**	**Denver Basin**	**Eagle Ford**	**Ethanol**
DNE	DNE	100	55	55	55	55	65

DNE = Does Not Exist

Vertical Releases Following a Release from the Vapor Space – Ambient Conditions

All vertical releases were assumed to originate from the vapor space of the rail cars. Thus, only vapor releases were considered as none of the materials evaluated could produce liquid via retrograde condensation. Figures 6, 7, and 8 show the dispersion behavior of the liquefied gases following a vertical vapor release. As can be seen by reviewing the figures, the higher pressure system (propane) produces a longer flammable cloud. However, none of the clouds drift back to grade with a flammable concentration.

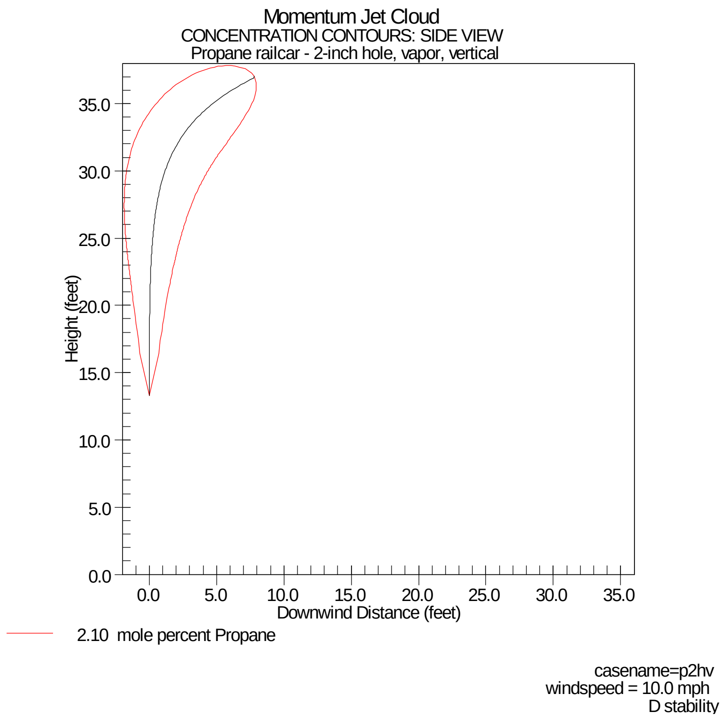

Figure 6. Propane Vapor Vertical Release

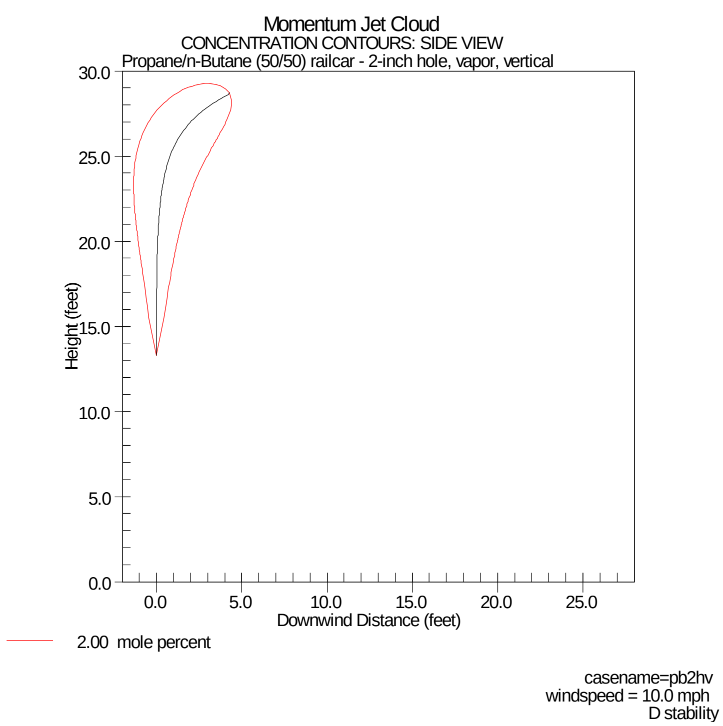

Figure 7. Propane/*n*-Butane (50/50) Vapor Vertical Release

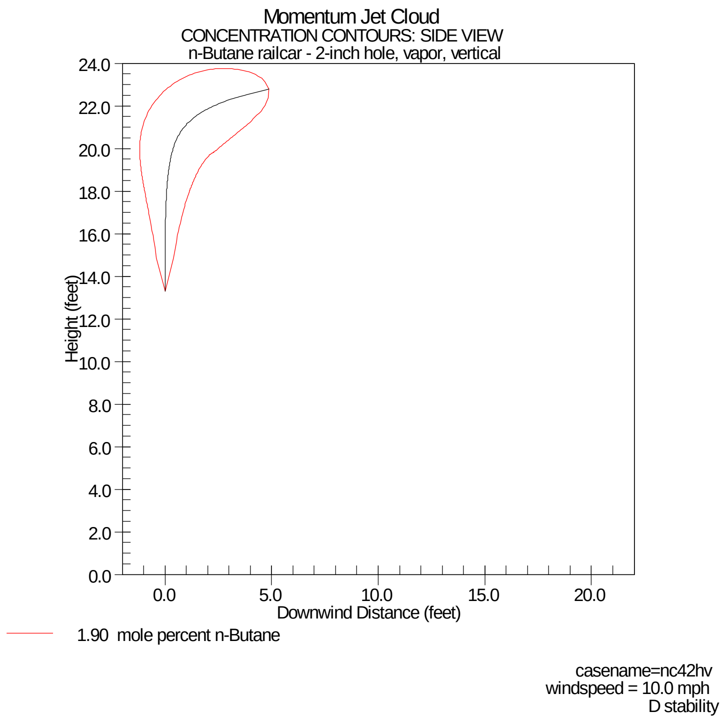

Figure 8. *n*-Butane Vapor Vertical Release

Since the four crude oils and ethanol releases do not have any internal tank pressure to "push" the vapors upward out of the 2-inch hole, no significant flammable vapor cloud is formed. A summary of the grade level flammable zone impacts is presented in Table 5.

Table 5. Distance (ft) to Ground Level LFL Following Vertical Vapor Release During Ambient Conditions

Propane	**LPG (50/50 C3/*n*-C4)**	***n*-Butane**	**Bakken**	**Bakken-S**	**Denver Basin**	**Eagle Ford**	**Ethanol**
DNE	DNE	DNE	DNE	DNE	DNE	DNE	DNE

DNE = Does Not Exist

Extent of Radiant Impacts Following a Release from the Vapor Space – Ambient Conditions

If the flammable vapor released vertically from a 2-inch hole in the vapor space of a rail car were to ignite, there could be ground level radiant impacts due to the vertical torch fire. As described earlier, only the vapor releases from the vapor space of a liquefied gas rail car produce any significant flammable vapor. If any of the vertical vapor releases were to ignite, only those associated with the liquefied gas rail cars produce a ground level radiant impact above 1,600 Btu/hr-ft^2. This information is summarized in Table 6.

Table 6. Distance (ft) at Ground Level to 1,600 $Btu/hr\text{-}ft^2$ From Torch Fire Following Vertical Vapor Release During Ambient Conditions

Propane	LPG (50/50 C3/*n*-C4)	*n*-Butane	Bakken	Bakken-S	Denver Basin	Eagle Ford	Ethanol
55	35	35	DNE	DNE	DNE	DNE	DNE

DNE = Does Not Exist

Consequences Associated with a Release During Fire Conditions

The term "Fire Conditions" is used in the following manner. During or immediately after a rail accident (e.g., derailment) a local fire ensues that increases both the temperature and internal pressure in the rail cars affected by the fire. In order to keep the apples-to-apples comparison in place, the following conditions were reached for each fluid.

- Assume the 2-inch hole in the rail car does not occur until the internal pressure in the rail car reaches ~80 psia.
- For the multicomponent crude oils, *assume* the temperature of the oil is ~380°F when the release starts.
- For the *n*-butane and ethanol (pure components), let the temperature of the fluid equal the equilibrium temperature at 80 psia.
- For the propane and the 50/50 propane/*n*-butane mix, the 80 psia pressure is below the vapor pressure of propane at ambient conditions and near the vapor pressure of the 50/50 LPG mix of 76 psia. Thus, the release behavior for these materials under fire conditions is nearly the same as the release behavior under ambient conditions.

Raising the internal temperature and pressure in the rail cars allows each of the materials to produce a flashing liquid stream out of the 2-inch hole in the liquid space. The release rates of *n*-butane, the four crude oils, and ethanol are presented in Figures 9, 10, 11, 12, 13, and 14. The release curves for the four crude oils (Figures 10, 11, 12, and 13) show a slow decline in release rate as the vaporizing light ends in the oil try to maintain the pressure above the liquid. Of the four crude oils, only the Bakken-S (RVP = 11.3 psia) shows the potential for aerosol formation and only at a low rate.

Extent of Flash Fires Following a Release from the Liquid Space – Fire Conditions

While it is difficult to identify a situation where there is a nearby continuous fire and a dispersing flammable gas cloud that does not ignite, the calculations were completed in order to compare the flash fire zones. With the generation of vapor during the release process, all six of the materials generate a momentum jet cloud that dominates the dispersion calculations to the LFL concentration of the material. These results are presented in Table 7. The results for the propane and 50/50 propane/*n*-butane mix are not applicable since 80 psia is below or near the vapor pressure of these fluids at ambient conditions (70°F).

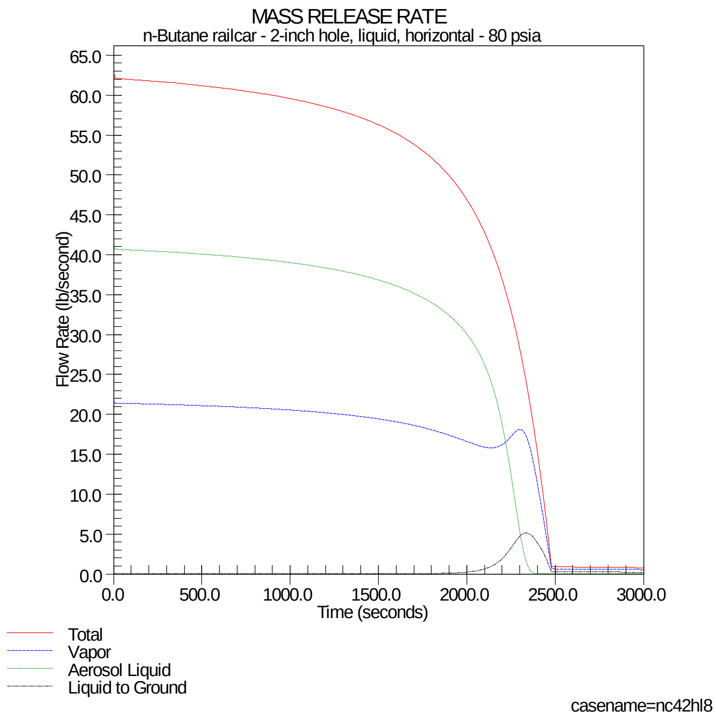

Figure 9. Liquid *n*-Butane Release – Fire Conditions

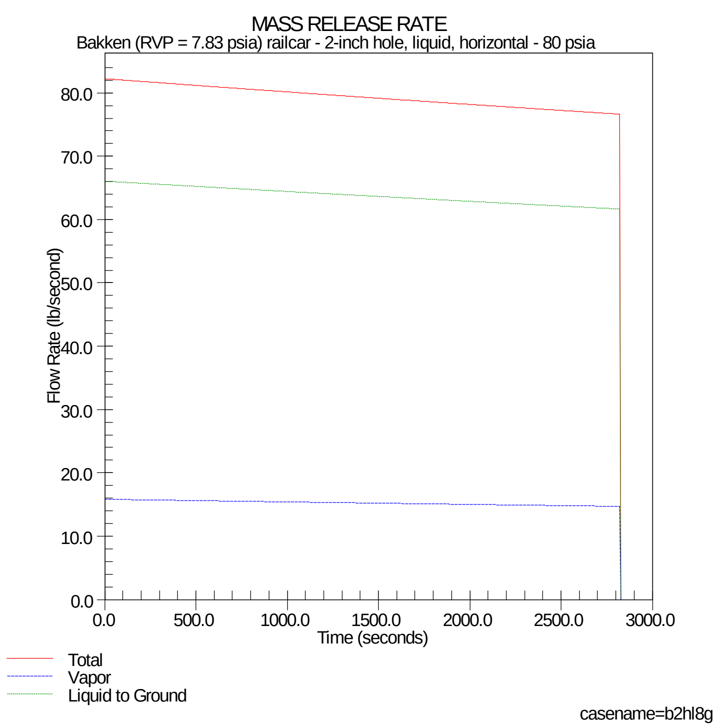

Figure 10. Bakken (RVP = 7.83 psia) Release – Fire Conditions

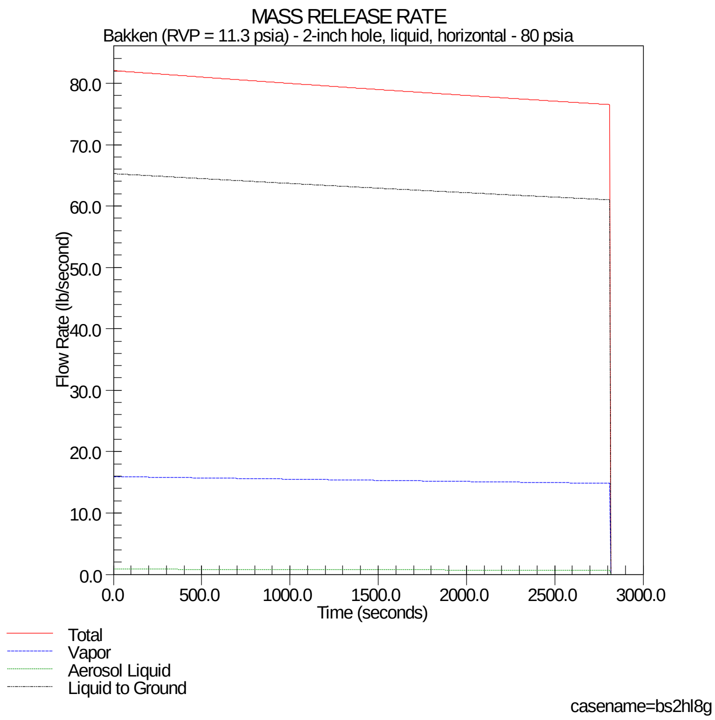

Figure 11. Bakken-S (RVP = 11.3 psia) Release – Fire Conditions

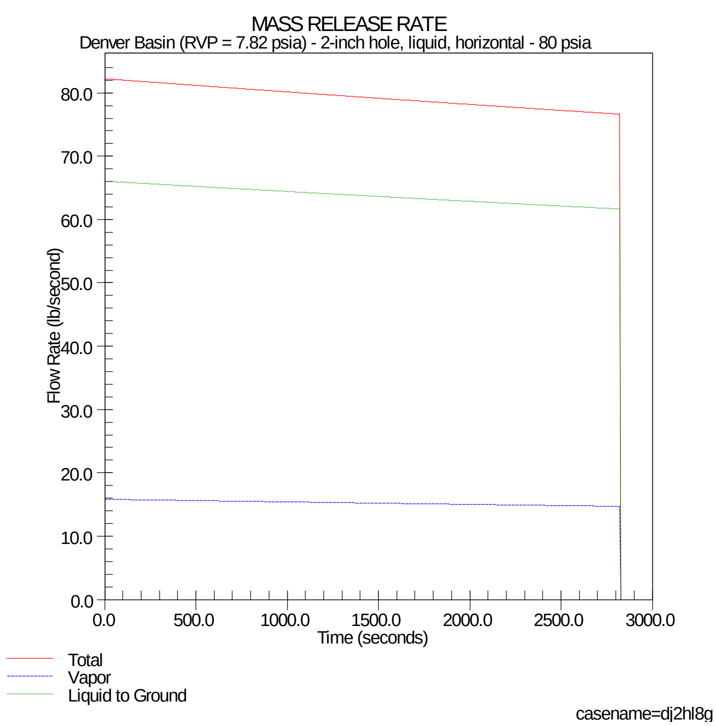

Figure 12. Denver Basin (RVP = 7.82 psia) Release – Fire Conditions

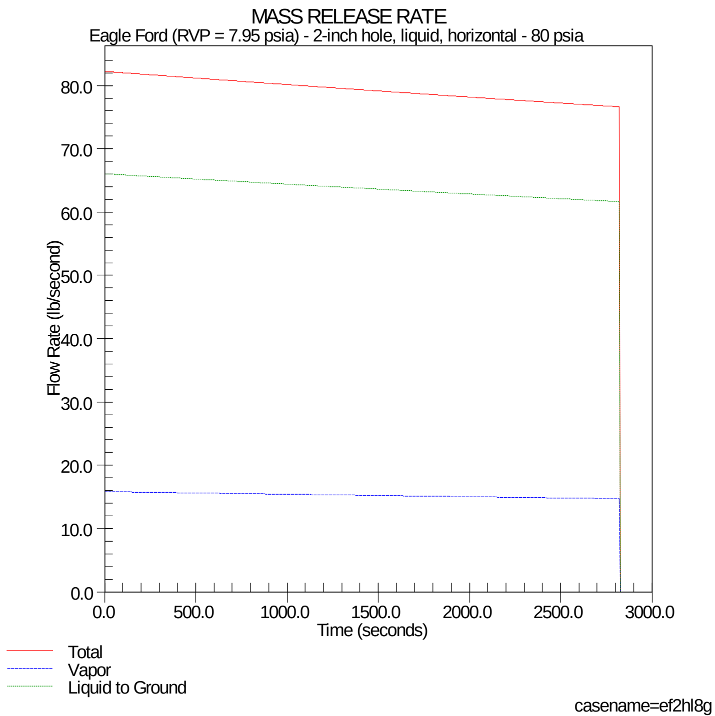

Figure 13. Eagle Ford (RVP = 7.95 psia) Release – Fire Conditions

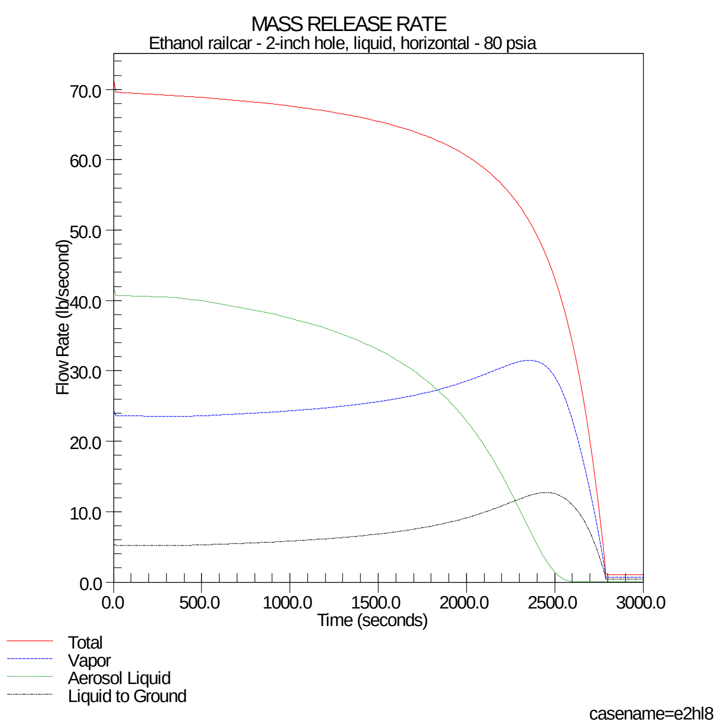

Figure 14. Ethanol Release – Fire Conditions

Table 7. Distance (ft) to LFL Following
Horizontal Liquid Release During Fire Conditions (80 psia) with Source Identified

Propane	**LPG (50/50 C3/*n*-C4)**	***n*-Butane**	**Bakken**	**Bakken-S**	**Denver Basin**	**Eagle Ford**	**Ethanol**
NA	NA	375	135	250	135	135	240
---	---	MJ	MJ	MJ	MJ	MJ	MJ

NA = Not Applicable (similar to ambient condition release)
MJ = Momentum Jet Source

Extent of Radiant Impacts Following a Release from the Liquid Space – Fire Conditions

If the fluid released from the 2-inch hole were to ignite, two potential radiant hazards could exist. If enough vapor were generated to sustain a torch fire, a slowly receding torch flame would exist. These impacts are presented in Table 8. Note that even under the elevated temperatures and pressures defined by the fire conditions, the crude oils are not volatile enough to generate a continuous flammable vapor stream leaving the 2-inch hole. The ethanol release does produce enough flammable vapor to support a torch fire. The propane and 50/50 propane/*n*-butane releases produce similar impacts to the ambient condition releases.

Table 8. Distance (ft) to Ground Level 1,600 Btu/hr-ft^2 From Torch Fire Following
Horizontal Liquid Release During Fire Conditions (80 psia)

Propane	**LPG (50/50 C3/*n*-C4)**	***n*-Butane**	**Bakken**	**Bakken-S**	**Denver Basin**	**Eagle Ford**	**Ethanol**
NA	NA	195	NV	NV	NV	NV	150

NA = Not Applicable (similar to ambient condition release)
NV = Not Volatile Enough to Generate Torch Fire

If the liquid leaving the 2-inch hole reaches grade and ignition occurs, a pool fire can ensue. For the crude oils this remains the primary hazard associated with their release. This is shown in Table 9. The results for the four crude oils are similar just as their burning characteristics are similar. Ethanol's ability to form a torch fire results in the torch fire impacts being larger than the pool fire impacts, The *n*-butane release under the elevated temperature and pressure conditions does not result in liquid to the ground (see Figure 9), thus a pool fire is not possible.

This torch fire and pool fire behavior can be demonstrated following a review of Figures 15 and 16. Figure 15 shows an ignited ethanol release following a rail accident and ignition of ethanol vapor in New Brighton, PA. While more than one rail car released ethanol during the accident, the primary hazard associated with the accident was a continuous fire.

Table 9. Distance (ft) to 1,600 Btu/hr-ft^2 From Pool Fire Following Horizontal Liquid Release During Fire Conditions (80 psia)

Propane	**LPG (50/50 C3/*n*-C4)**	***n*-Butane**	**Bakken**	**Bakken-S**	**Denver Basin**	**Eagle Ford**	**Ethanol**
DNE	DNE	DNE	75	75	75	75	55

DNE = Does Not Exist

Figure 16 shows a pool fire following a release of Bakken crude in a rail accident that occurred in Lynchburg, VA. Here the pool fire, enveloped in thick black smoke typical of a crude fire, is the primary hazard.

Fireballs

In order to generate a fireball involving a rail car (DOT-112 or DOT-111), a catastrophic failure of the rail car must occur. The mechanism by which the failure may develop could be different for pressure cars (DOT-112) and crude cars (DOT-111). The failure mechanism may vary from accident to accident as well as the design of the rail car. However, the overall time line of the failure follows the path presented in Figure 17. Figure 17 assumes that the pressure relief valve (PRV) is in working order. If the PRV is damaged in the accident and not fully operable, the blue line demonstrating the operation of the PRV would be different from the figure, but the overall time line would be similar.

The behavior demonstrated in Figure 17 is most often associated with Boiling Liquid Expanding Vapor Explosions (BLEVEs). BLEVEs are commonly associated with pressure cars (DOT-112) or other pressure vessels. The size and duration of a fireball following a catastrophic failure of a DOT-112 rail car has been modeled by relating the size and duration to the mass of fuel involved. This approach has worked well and is documented in the literature [6, 7, 8, 9].

An example of a BLEVE of a propane rail car is presented in Figure 18. The BLEVE model contained in CANARY matches the fireball size and duration well.

The same type of approach for modeling the size and duration of a fireball associated with a pressure vessel (e.g., DOT-112) can be used to model the size and duration of a fireball generated by a vessel with a lower pressure rating (e.g. DOT-111). There have been catastrophic failures of some DOT-111 rail cars transporting crude oil and ethanol. Two are presented in Figures 19 and 20. Figure 19 shows the fireball formed following the catastrophic failure of a rail car carrying Bakken crude, while Figure 20 shows the fireball formed following the catastrophic failure of an ethanol rail car.

Figure 15. New Brighton, PA (ethanol)

Figure 16. Lynchburg, VA (Bakken)

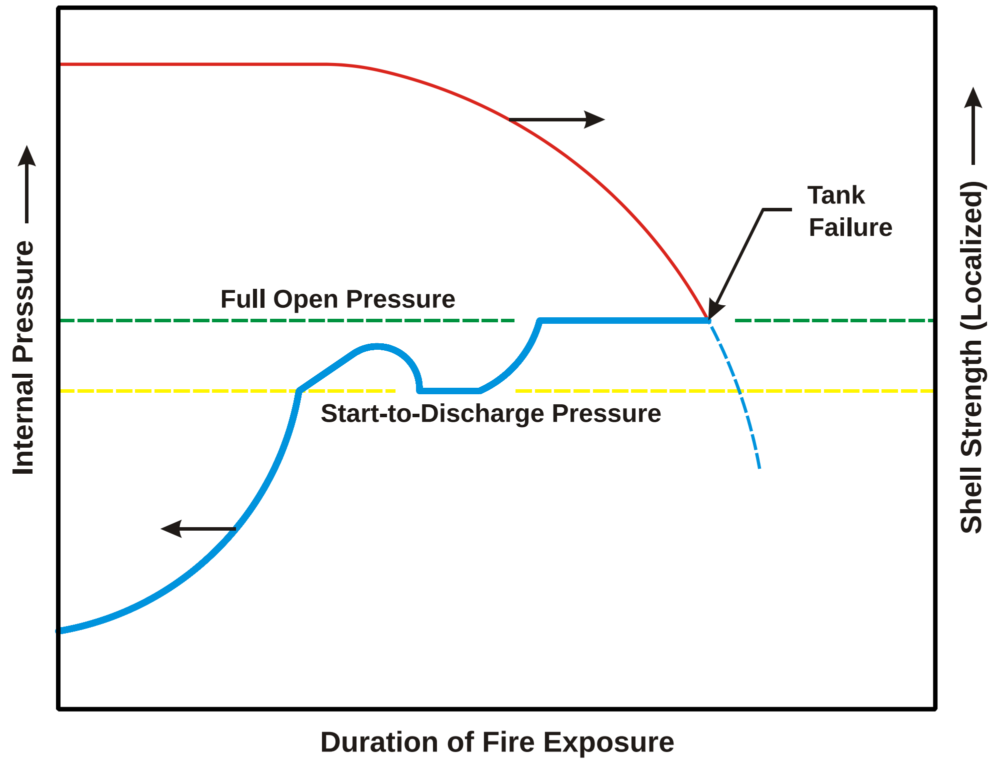

Figure 17. Time Line for a Fire-Induced Catastrophic Vessel Failure

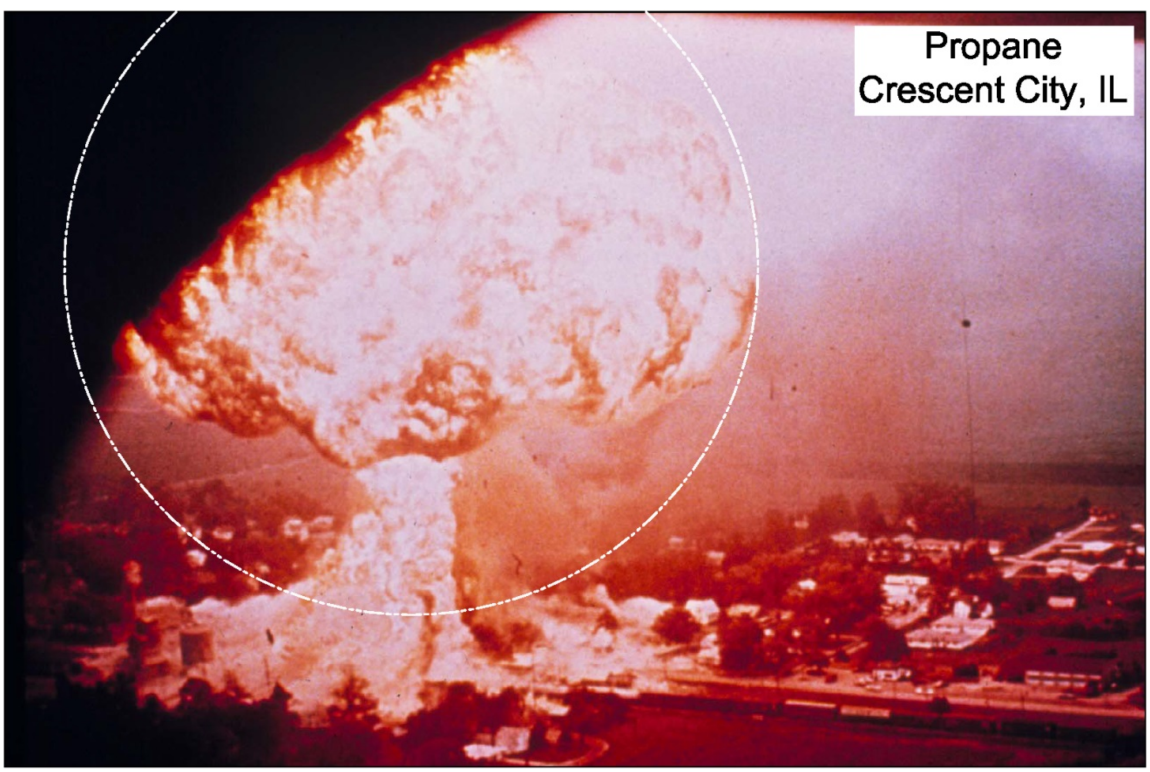

Figure 18. Crescent City, IL (Propane) – Fireball

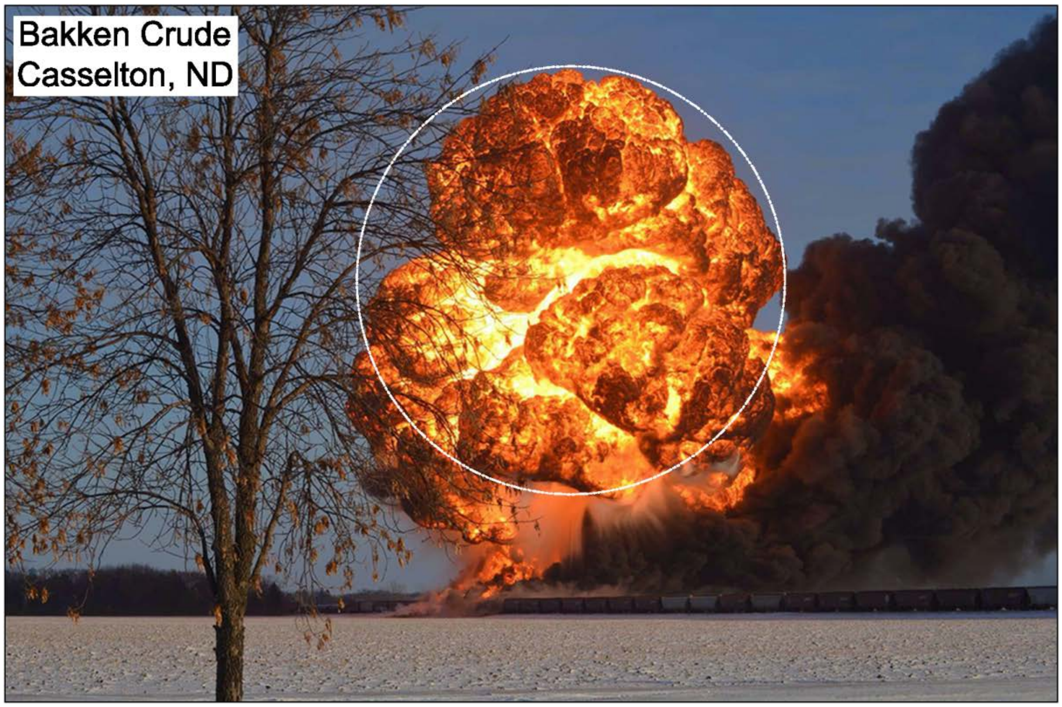

Figure 19. Casselton, ND (Bakken) – Fireball

Figure 20. Plenva, MT (ethanol) – Fireball

To model these fireballs, using the available modeling methodology, several assumptions have to be made. The most important of these is, “At what pressure does the catastrophic failure occur?” For the purposes of this analysis, the failure pressure is defined as follows.

P(failure) = 120% of relief valve set pressure (gauge)

For the DOT-112 rail cars, the relief valve set pressure is assumed to equal 280.5 psig
For the DOT-111 rail cars, the relief valve set pressure is assumed to equal 85 psig

It should be noted that there is much more variability in the relief valve set pressure for the DOT-111 rail cars than for the DOT-112 rail cars. However, for the purpose of the apples-to-apples comparison, all the fluids transported in DOT-111 rail cars were assumed to be equipped with 85 psig relief valves.

Using the fireball model within CANARY and the physical properties of the eight fluids described above, and assuming all the rail cars have 33,600 gallon water capacity. The fireball hazard impact results are presented in Table 10. Unlike the torch and pool fire models that assume a steady state flame, even for a short period of time, the fireball model allows for the fireball to grow and shrink and rise during its life. Thus, a methodology that allows the resultant fireballs to be compared is based on the integrated radiant dosage necessary to cause a fatality (the 1% fatality level is often thought of as the “onset of fatality”). This is developed from a probit equation. The results presented in Table 10 show how far the fireball impact will extend.

Table 10. Distance (ft) to Integrated Radiant Flux Causing 1% Fatality From Fireball Following Catastrophic Failure of Rail Car

Propane	**LPG (50/50 C3/*n*-C4)**	***n*-Butane**	**Bakken**	**Bakken-S**	**Denver Basin**	**Eagle Ford**	**Ethanol**
690	700	695	305	335	305	305	550

Defining the fluid temperature and pressure at the moment of vessel failure, defines the fluid density and flash fraction which in turn defines the mass available for consumption in the fireball. The variation in mass, due to the fluid properties, at elevated temperature and pressure, is the primary driving force in the results presented in Table 10.

Using the same model, the fireball size and duration of each fireball is computed and summarized in Table 11. As can be seen, none of the fireballs last longer than about 15 seconds. While these events are exciting, they often require a period of time of flame impingement (allowing the pressure and temperature in the vessel to build). Thus, evacuation plans for the immediate area can be employed.

Table 11. Fireball Diameter D (ft) and Fireball Duration T (sec)

	Propane	**LPG (50/50 C3/*n*-C4)**	***n*-Butane**	**Bakken**	**Bakken-S**	**Denver Basin**	**Eagle Ford**	**Ethanol**
D	670	680	675	405	430	405	405	750
T	13	13	13	9	9	9	9	14

Explosion Overpressure

Flash fires, torch fires, and pool fires generate localized overpressure (a deflagration) caused by the combustion of flammable vapor and air. For the materials that are the subject of this analysis, this overpressure is too low to cause any serious injury to persons or significant damage to structures.

That leaves catastrophic failures and flammable vapors in confined or congested spaces as the potential sources of energy available to produce significant overpressure. While press reports and descriptions of accidents often begin with "An explosion occurred …", are explosions really important factors in identifying the magnitude of hazards associated with the rail transport of liquefied gases, crude oils, and ethanol? Based on the following quotes from researchers and evidence from rail accidents, the answer is no.

The explosion overpressure model is based on the premise that the strength of the blast wave generated by a vapor cloud explosion (VCE) is dependent on the reactivity of the flammable gas involved; the presence (or absence) of structures such as walls or ceilings that partially confine the vapor cloud; and the spatial density of obstructions within the flammable cloud [10, 11], the average size of those obstacles, and the overall size of the vapor cloud [12, 13, 14, 15]. Quest's model reflects the results of several international research programs on vapor cloud explosions, which show that the strength of the blast wave generated by a VCE increases as the degree of confinement and/or obstruction of the cloud increases. The following quotations illustrate this point for propane and butanes.

> "On the evidence of the trials performed at Maplin Sands, the deflagration [explosion] of truly unconfined flat clouds of natural gas or propane does not constitute a blast hazard." [16] (Tests conducted by Shell Research Ltd., in the United Kingdom.)
>
> "Both in two- and three-dimensional geometries, a continuous accelerating flame was observed in the presence of repeated obstacles. A positive feedback mechanism between the flame front and a disturbed flow field generated by the flame is responsible for this. The disturbances in the flow field mainly concern flow velocity gradients. Without repeated obstacles, the flame front velocities reached are low both in two-dimensional and three-dimensional geometry." [17] (Tests conducted by TNO in the Netherlands.)

Researchers who have studied case histories of accidental vapor cloud explosions have reached similar conclusions for medium reactivity materials.

> "It is a necessary condition that obstacles or other forms of semi-confinement are present within the explosive region at the moment of ignition in order to generate an explosion." [18, 19]

> "A common feature of vapor cloud explosions is that they have all involved ignition of vapor clouds, at least part of which have engulfed regions of repeated obstacles." [20]

As all of the materials analyzed in this paper would fall into the medium reactivity category, the maximum overpressure achieved by a VCE in an open area would be about 0.4 psi. Since the explosion overpressure modeling is site specific, it is generally not conducted on a generic basis. However, it is instructive to review an accident in order to identify whether explosion overpressure was a significant contributor to the overall damage observed.

Lac Megantic

Around 1:15 a.m. on Saturday, July 6, 2013, an unattended train hauling Bakken crude derailed in the town of Lac Megantic, Quebec province, Canada. Many of the DOT-111 rail cars released Bakken crude during and after the derailment. The derailment occurred on a curve in the rail line and the contour of the surrounding ground allowed the oil to travel downhill in a south south-westerly direction. Most of the structures destroyed were in the path of the flowing, burning oil.

Many of the initial reports described "explosions" of rail cars involved in the derailment. While the catastrophic failure of a DOT-111 rail car was earlier shown to have the ability to produce a fireball, can any significant amount of overpressure be associated with such an event? A review of Figure 21 indicates no. The church shown in the photograph (Ste-Agnès Church) has multiple stained glass windows facing the derailment site. The photograph does not show any damage to these windows. In addition, other structures in the photograph do not show glass breakage. Since glass can break at overpressures in the range of 0.15 psi, it does not appear that significant overpressure was generated in this accident.

Summary

A review of the types and extents of possible hazards associated with the rail transport of eight common fluids was accomplished by developing an apples-to-apples comparison. To the extent possible, this paper sought to put the extent of potential hazards from the various rail car commodities in the proper perspective to one another. It is important to keep in mind that the relative frequency of the analyzed events was not included in this review, thus a risk-based comparison cannot be accomplished with the data presented in this paper alone.

Figure 21. Lac Megantic Ste-Agnès Church

Several conclusions can be made following this review.

- The primary hazard associated with all eight commodities transported in rail cars is exposure to fire radiation.
- The fire radiation impacts are larger for liquefied gas rail cars than for crude oil or ethanol rail cars.
- Fireballs involving crude oils and ethanol are possible when DOT-111 rail cars are used.
- In total, the hazard extents from ethanol rail cars are about the same as those of crude rail cars.
- The vapor pressure of the crude in rail cars (defined by the Reid vapor pressure) does not play a significant role in the extent of the potential hazards associated with rail transport of crude oil.

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