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SAFETY ANALYSES OF NON-ACCIDENT- AND ACCIDENT-CAUSED
RELEASES FROM RAILROAD TANK CARS

BY

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ABSTRACT

SAFETY ANALYSES OF NON-ACCIDENT- AND ACCIDENT-CAUSED RELEASES FROM RAILROAD TANK CARS

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Spills of hazardous materials from railroad tank cars occur as a result of two distinct groups of causes. Accident-caused releases are due to incidents where the train or tank car derails or is involved in a collision that causes damage to the car such that some or all of its contents are spilled. Non-accident-caused releases are generally not the result of damage inflicted upon the car but rather, because of some failure of the tank's containment elements, principally the fittings but occasionally due to failure of the tank itself. Although both types are "accidental", the latter are often referred to as non-accident releases or "NARs". Because non-accident and accident-caused releases are due to different processes, different approaches are used to prevent or mitigate the effects of these events. The two principal chapters in this thesis (2 and 3), describe research that investigates options to reduce certain types of non-accident and accident-caused releases, respectively.

In Chapter 2, data from a set of full-scale tank car impact tests conducted in 1997 were reanalyzed using a more sophisticated statistical approach to evaluate the relative performance of different tank car surge pressure reduction devices (SPRDs) that are intended to prevent releases due to burst frangible disks. A new technique was developed to develop estimated probabilities of pressure surges exceeding 100 psi, 132 psi and 165 psi. These probabilities were then used to estimate the number of NARs expected to occur on tank cars equipped with that each type of

SPRD. Finally, estimated performance of each SPRD was compared to its Damiani Ratio, a calculation based on certain dimensional characteristics of the SPRD and known to be strongly correlated to SPRD's effectiveness at attenuating pressure surges.

In Chapter 3, a new metric for assessing the consequences of an accident-caused hazardous material spill is developed. This metric called "Release Risk" is defined as the expected value of the quantity lost from a tank car given that it is in an accident. Important elements considered are the probabilities of release and expected quantities of release from the tank- and non-tank components of a tank car, and the effect of increasing tank thickness in increasing accident exposure and reducing the expected quantity released. The metric is then used as the objective function in an optimal tank car thickness model and the results are compared to the model when the more traditional metric, release probability is used as the objective function. The results of this comparison indicate that the two different objective functions result in different solutions regarding the safety design of railroad tank cars.

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FOREWORD

The main chapters in this thesis, Chapters 2 and 3, are presented as independent manuscripts intended for academic journal submission. Chapter 2 is in press as a report published by the RSI-AAR Railroad Tank Car Safety Research and Test Project and a modified version will be submitted to a journal to be determined. Chapter 3 is currently in press in the Transportation Research Record, the Journal of the Transportation Research Board. A comprehensive list of all references cited in the thesis is included at the end.

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CHAPTER 1

INTRODUCTION

1.0 Introduction

Every year, a large variety and quantity of hazardous materials are transported by rail in North America. The majority of rail transport of hazardous materials is in tank cars. In 2002, 75% of the approximately 1.26 million car loads in the U.S and Canada were in tank cars (BOE 2004). Modern industrialized society greatly depends on these materials in daily life, for manufacturing, agriculture, health care, and public utilities to name a few; however, transportation of hazardous materials also incurs certain risks.

Regardless of mode, the increasing volume of hazardous materials shipments, punctuated by several recent accidents, has raised concerns regarding the safety of rail transportation. In 1989, Abkowitz et al. (1989) provided a list of critical issues related to hazardous materials transportation that includes regulatory environment, information systems, accident analysis, hazard mitigation, risk assessment, routing, community preparedness, and incident management. This list remains valid today and my research is focused on two of these items, hazard mitigation and risk assessment.

A key aspect affecting hazardous materials transportation safety is “packaging”, i.e., the design of vessels that transport hazardous materials. As mentioned above, tank cars transport the majority of rail shipments and tonnage of hazardous materials. Studies of their design are

therefore important, both with regard to assessing risk and understanding how to reduce it. In the context of tank cars, package design refers to the ability of the car and various features of the tank and its fittings to endure the physical environment it is exposed to in transit, including both ordinary and extraordinary factors (Barkan et al. 2005). Industry and government agencies have developed extensive specifications, regulations and practices for hazardous materials transportation by tank car (Heller 1970; Dalrymple 1997; AAR 2003; BOE 2004) that are intended to minimize the likelihood of a spill (Barkan et al. 2005).

Spills of hazardous materials from railroad tank cars occur as a result of two distinct groups of causes. Accident-caused releases are due to incidents where the train or tank car derails or is involved in a collision that causes damage to the car such that some or all of its contents are spilled. Non-accident-caused releases are generally not the result of damage inflicted upon the car but rather, because of some failure of the tank's containment elements, principally the fittings, but occasionally due to failure of the tank itself. Although both types are "accidental", the latter are often referred to as non-accident releases or "NARs". Because non-accident and accident-caused releases are due to different processes, different approaches are used to prevent or mitigate the effects of these events.

1.1 Non-Accident-Caused Release

Typically NARs are the result of leaks from valves and fittings on tank cars. Although NARs usually involve smaller leak quantities than accident-caused releases, NARs occur more than 20 times as frequently (BOE 2004). From a risk analysis point of view, NARs are considered a high frequency, low consequence event. Nevertheless, NARs occasionally result in

large quantity high-consequence events (U.S. DOT 1995). Even small quantity releases may cause injuries, and damage to property and the environment. Furthermore, the occurrence of an NAR disrupts a shipment, interferes with railroad transportation operations, and is inconsistent with industry and government objectives of safe and reliable transportation of hazardous materials.

There are a variety of operational approaches to reduce NARs (BOE 2004; Elliot & Mitchell 2002) and there is also work to improve the design of railroad tank cars to make them less susceptible to certain types of NAR. Until the late 1990s, the most frequent cause of NARs was from tank car pressure relief vents (BOE 2004) and they remain a significant problem. Although frangible disks serve an important pressure relief role in accidents, they sometimes burst prematurely during normal transportation. It is believed that this occurs because of surges of the lading within the tank. The broken disk, if undetected, allows fumes to escape and liquid to spill during transportation, and thus represents an NAR (Barkan et al. 2000).

NARs caused by releases from pressure relief vents, have been reduced significantly since the 1990s. This is the result of several measures taken by the government and industry. These include implementation of pressure relief vent surge pressure reduction devices (SPRDs) for tank cars in federal hazard Class 8 (corrosive material) service (BOE 2004). The SPRD is intended to reduce the velocity of the flow into the nozzle when the lading surges momentarily while the tank car is in transit (Barkan et al. 2000). In essence, SPRDs were designed to reduce the surge pressure from the lading during transportation without affecting the capability of the pressure relief vent to function during the high-pressure condition that might occur due to a thermally induced over-pressure event.

In Chapter 2, data from a set of full-scale tank car impact tests conducted in 1997 were reanalyzed using a more sophisticated statistical approach to evaluate the relative performance of different tank car SPRDs in preventing releases due to burst frangible disks. A new technique was developed to calculate the probabilities of pressure surges exceeding 100 psi, 132 psi and 165 psi. These probabilities were then used to estimate the number of NARs expected to occur on tank cars equipped with each type of SPRD. Finally, estimated performance of each SPRD was compared to its Damiani Ratio, a calculation based on certain dimensional characteristics of the SPRD and known to be strongly correlated to SPRD's effectiveness at attenuating pressure surges. The objective of this work was to develop a basis for a performance standard to evaluate the adequacy of SPRDs in service.

1.2 Accident-Caused Release

For the past several years, the rate of railroad accident-caused releases of hazardous materials has been fluctuating between 27 and 37 incidents per million carloads (BOE 2004). Although significantly lower than the rate of about 200 incidents per million carloads in 1982 (Barkan et al. 2000), further reduction of accident-caused hazardous material releases remains an important objective.

Two of the principal elements in the reduction of railroad hazardous material transportation risk are prevention of accidents, and prevention of spills from railcars involved in accidents (Barkan et al. 1991). Train accidents declined substantially in the 1980s and more gradually in the 1990s due to improvements in track design and maintenance, as well as improvements in equipment and training (Dennis 2002; Gallamore 1999). The result is that the

annual accident rate has been reduced from approximately 12 accidents per million-train miles in 1980 (Harvey et al. 1987) to about 4 accidents per million-train miles in 2002 (Anderson & Barkan 2004).

Changes in tank car safety design to make them more resistant to damage in accidents have also contributed to the improvement in the safety record (Phillips & Role 1989; Barkan et al. 2000). Although analysis of the degree of hazard posed by different products is ongoing, in general higher hazard materials are shipped in cars with tanks constructed of thicker and stronger steels. Additionally, these cars may be equipped with head shields and more damage-resistant top fittings designs.

In Chapter 3, a new metric for assessing the consequences of an accident-caused hazardous material spill is developed. This metric called “Release Risk” is defined as the expected value of the quantity lost from a tank car given that it is in an accident. Important elements considered are the probabilities of release and expected quantities of release from the tank- and non-tank components of a tank car, and the effect of increasing tank thickness in increasing accident exposure and reducing the expected quantity released. The metric is then used as the objective function in an optimal tank car thickness model and the results are compared to the model when the more traditional metric, release probability, is used as the objective function. The results of this comparison indicate that the two different objective functions result in different solutions regarding the safety design of railroad tank cars.

1.3 Conclusions

When dealing with risk, there are different approaches available. This is particularly so when dealing with a complex activity such as hazardous materials transportation. As common carriers, railroads cannot simply avoid the risk, and although they are insured, the premiums for coverage are increasingly costly. Consequently, railroads have no real choice other than to manage the risk as effectively as possible. As noted above, NARs are considered a high frequency, low consequence event. Because of their frequent occurrence, they are the subject of ongoing activity to reduce them. On the other hand, accident-caused releases are much less common, but the potentially severe consequences of a major release have made efforts to reduce them an important focus as well.

Risk estimation and risk evaluation are generally regarded as the main elements in risk assessment. The former includes acquisition of appropriate data to estimate the probabilities of events of interest, and combine the probabilities with the associated consequences of the events (Philipson & Napadensky 1982). This thesis describes risk estimations work in reducing both non-accident and accident-caused releases. The next phase of risk assessment, risk evaluation, involves assessing the level of significance of the estimated risk to consider any alternative or risk mitigation strategy to reduce the risk.

In Chapter 4, besides addressing the limitations and other issues related to approaches or results from the analyses in Chapters 2 and 3, future work and some research needs are discussed, especially with regard to extending the work presented in Chapter 3. The main objective is to consider the estimated risk compared to prospects for spending resources to mitigate risk. It is of interest to perform the risk acceptability evaluation to justify any strategy in

improving tank car safety design. Ultimately, this will lead to an efficient and practical approach in determining an optimal tank car design for specific groups of commodities.

CHAPTER 2

A NEW STATISTICAL APPROACH TO ESTIMATING SURGE PRESSURE REDUCTION DEVICES' PERFORMANCE FOR REDUCING HAZARDOUS MATERIALS RELEASES FROM RAILROAD TANK CARS

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2.0 Introduction

Over the past decade, the railroad chemical and tank car industries, along with U.S and Canadian regulators, have placed a high priority on the reduction of non-accident-caused releases (NARs). Typically NARs are the result of leaks from valves and fittings on tank cars. Although NARs usually involve smaller leak quantities than accident-caused releases, NARs occur more than 20 times as frequently (Figure 2.1). From a risk analysis point of view, NARs are considered a high frequency, low consequence event. Nevertheless, NARs occasionally result in large quantity high-consequence events (U.S. DOT 1995). Even small quantity releases may cause injuries, and damage to property and environment. Furthermore, the occurrence of an NAR disrupts a shipment, interferes with railroad transportation operations, and is inconsistent with industry and government objectives of safe and reliable transportation of hazardous materials.

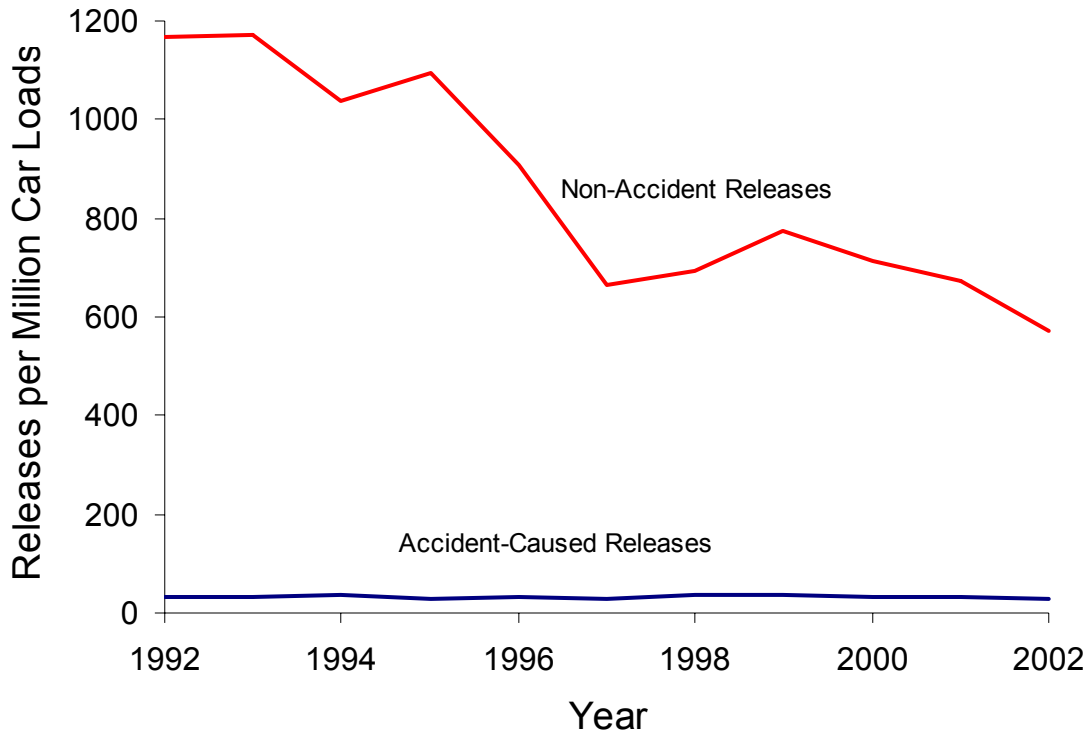


Figure 2.1 Releases per million carloads (BOE 2004).

In 1995, the Association of American Railroads (AAR) collaborated with the Railway Association of Canada (RAC), chemical shippers, and tank car manufacturers and owners to initiate the North American Non-Accident Release Reduction Program (NANARRP). Active participation among all the parties includes data collection and distribution, information sharing and awareness programs (BOE 2004). Subsequently, the Non-Accident Release Risk Index (NARRI) was developed as a metric for assessing NAR severity (Elliot & Mitchell 2002), and aided the industry in prioritizing which types of NARs to target for reduction.

Complementing the operational aspects of these programs is work to improve the design of railroad tank cars to make them less susceptible to certain types of NAR. Until the late 1990s, the most frequent cause of NARs was from tank car pressure relief vents (Figure 2.2), and they

remain a significant problem. Introduced in the early 20th century for tank cars carrying corrosive materials, the pressure relief vent is a device designed to prevent or forestall over-pressuring the tank in the event of exposure to fire. By contrast to the recloseable pressure relief valve, pressure relief vents use a frangible (breakable) disk that bursts at its rated pressure, and must be replaced each time an over-pressure event occurs. However, frangible disks have frequently burst prematurely during transportation. It is believed that this occurs because of surges in the lading. The broken disk, if undetected, allows fumes to escape and liquid to spill during transportation, and thus represents an NAR (Barkan et al. 2000).

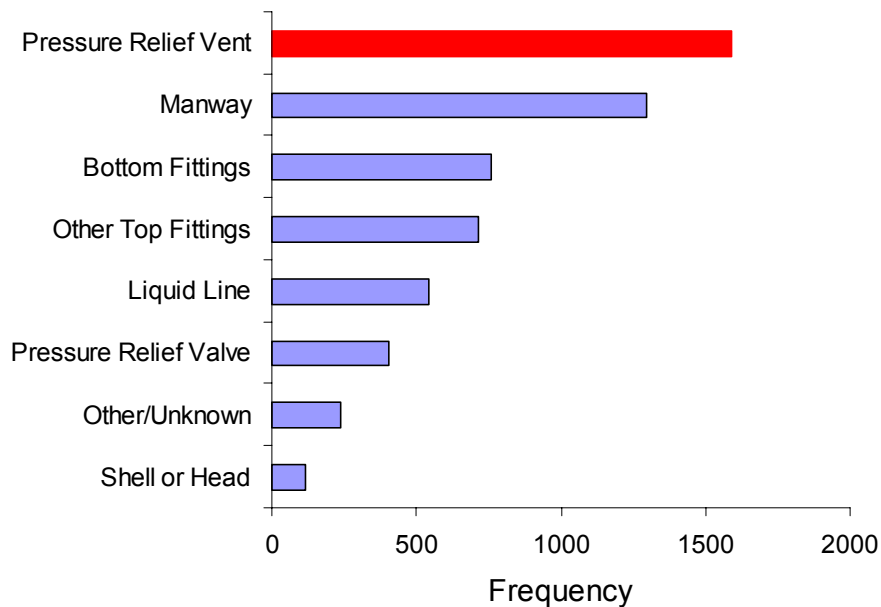


Figure 2.2 Sources of non-accident caused releases from railroad tank cars 1992-1996 (BOE 2004).

NARs caused by releases from pressure relief vents, have been reduced significantly (Figures 2.3, 2.4) since the 1990s. This is the result of several measures taken by the government and industry. These include implementation of pressure relief vent surge pressure reduction devices (SPRDs) for tank cars in federal hazard Class 8 (corrosive material) service (BOE 2004). The SPRD is intended to reduce the velocity of the flow into the nozzle when the

lading surges momentarily while the tank car is in transit (Barkan et al. 2000). In essence, SPRDs were designed to reduce the surge pressure from the lading during transportation without affecting the capability of the pressure relief vent to function during the high-pressure condition that might occur due to a thermally induced over-pressure event.

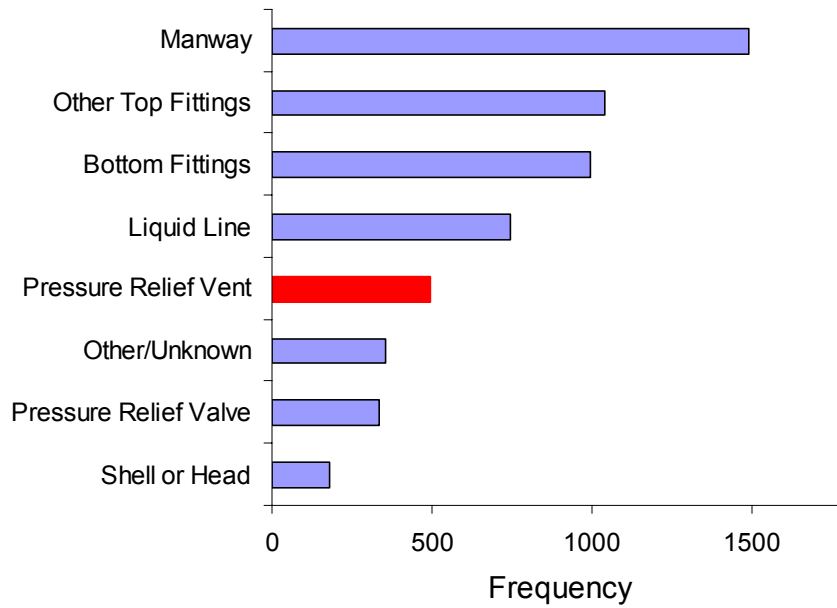


Figure 2.3 Sources of non-accident caused releases from railroad tank cars 1997-2002 (BOE 2004).

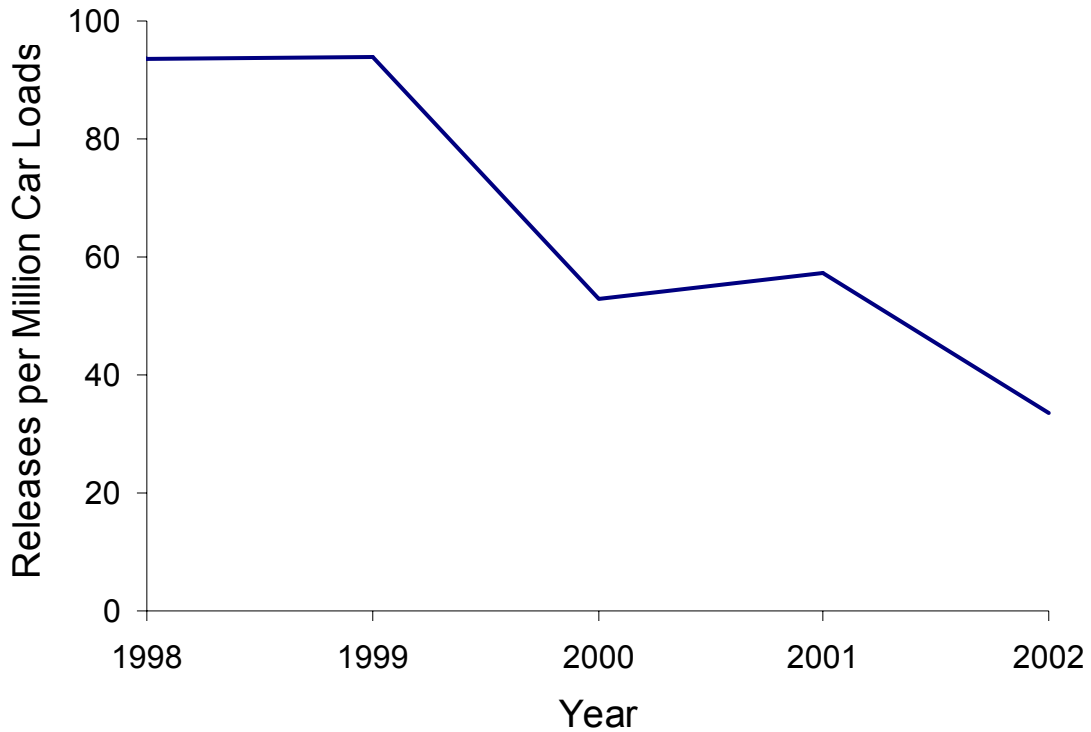


Figure 2.4 NARs per million carloads from pressure relief vents (BOE 2004).

There are about a dozen different SPRD designs currently in use. These were developed by tank car and pressure relief vent manufacturers and other suppliers. During the 1990s, a lack of performance data to measure SPRD effectiveness in service led the AAR, the Railway Progress Institute (now Railway Supply Institute), the Chlorine Institute and the Federal Railroad Administration to jointly undertake a study to evaluate SPRD performance in reducing NARs from tank car pressure relief vents (Treichel et al. 1998).

Full-scale impact tests were conducted on SPRDs for three nozzle diameters, 2, 3 and 6-1/2 inches (Table 2.1). A controlled test for each nozzle in which no SPRD was in place was conducted to establish a baseline for comparison with SPRD performance. A general-service DOT-111A100W1 tank car was used, and up to 30 impacts were conducted for each control condition, and at least 10 impacts were conducted for each SPRD (Barkan et al. 2000). The

experiment was conducted in such a way to maximize the frequency of getting high surges while maintaining typical real-service conditions. To accomplish this, impacts of 1,000,000 ft-lbs were generated, the fill level in the car was 99.5%, and the vent nozzles were mounted midway between the center and the end of the tank.

Table 2.1 Impact Test Matrix for SPRDs and Nozzle Diameter (Barkan et al. 2000)

Device	Nozzle Diameter		
	2 inch	3 inch	6 1/2 inch
None (Control)	x	x	x
Midland A-425-15-CS	x		x
Midland A-424	x		x
A425-15-CS & A-424			x
Hydro-Damp 70	x		
1-inch orifice plate	x		
Perforated pipe	x		
GA/Salco sieve		x	x
ACF inverted cone		x	
Union Tank milkstool			x
Midland milkstool			x
Surge chamber			x
Hydro-Damp 20 (internal)			x
Hydro-Damp 20 (external)			x
Longitudinal half pipe			x
Tranverse half pipe			x

As an extension of that study, the focus of this work is to use data from the impact test in a more refined approach to evaluate relative performance among different SPRDs, as a step towards identifying a minimum acceptable performance level.

2.1 Methods

Peak pressure at the frangible disk location was recorded for each impact test. The disk in a tank car pressure relief vent is designed to fracture at 33% of the tank burst pressure. For

DOT-111 general-purpose tank cars, this corresponds to 165 psi. The peak pressure for each impact test is the highest pressure sustained for one or more milliseconds. This interval was selected because previous testing suggested that frangible disks survive pressure higher than their rated burst pressure if the exposure lasts less than one millisecond. The purpose of the SPRD is to reduce transient liquid surge pressures below the disk's rated burst pressure long enough for the transient surge to subside. Treichel et al. (1998) in the previous test found that all SPRDs resulted in average peak pressures below 165 psi (Figure 2.5) in the impact tests.

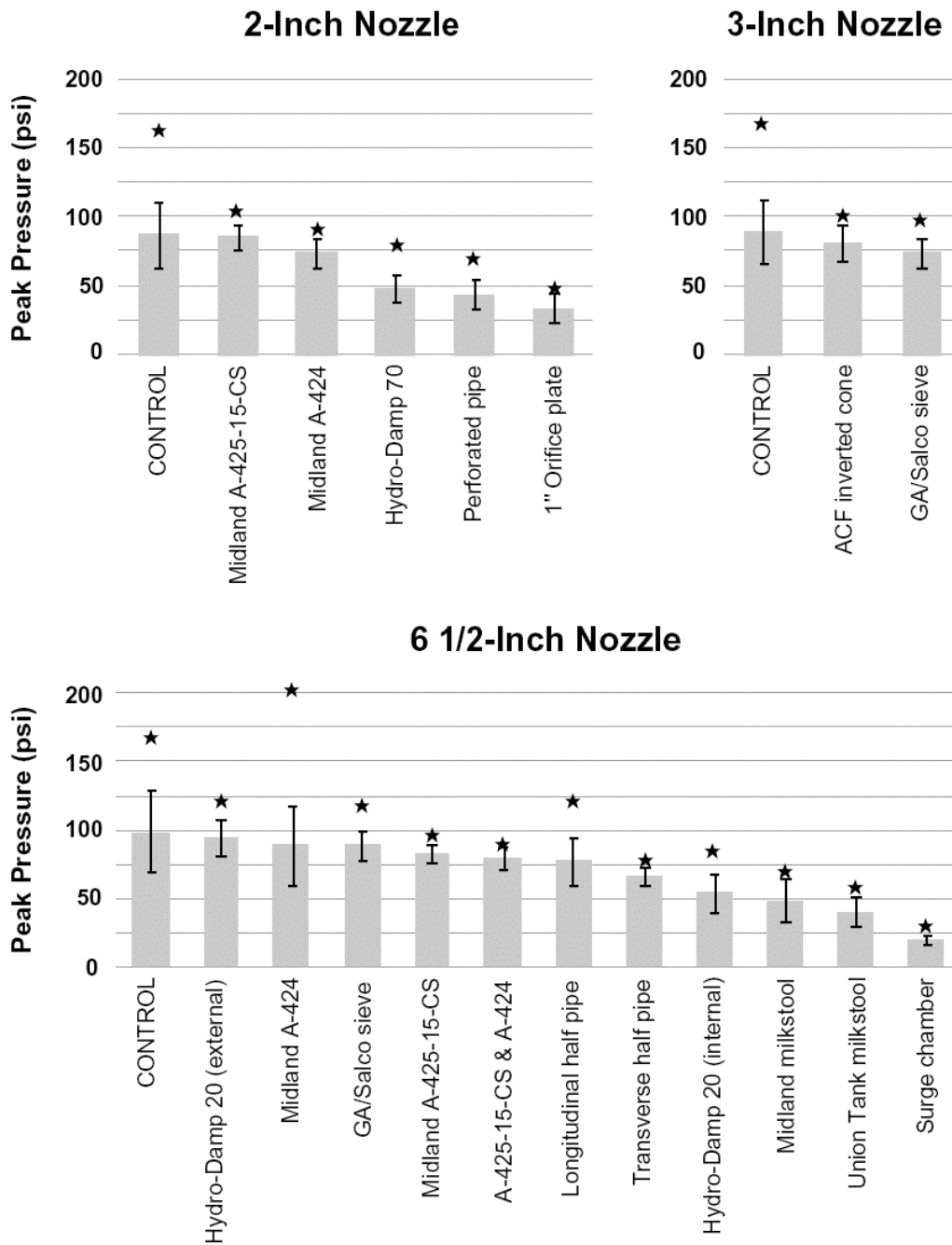


Figure 2.5 Histograms showing the effect of SPRDs on peak pressure in 2-inch, 3-inch and 6-1/2-inch-nozzle-diameter pressure relief vent nozzles (Treichel et al. 1998) (error bars indicate one standard deviation above and below the mean. Asterisks indicate the highest peak pressure observed for the specified condition).

Although the mean peak pressures recorded were well below 165 psi, some SPRDs did allow peaks over 165 psi on individual trials. Furthermore, field data indicate that all of the SPRDs have allowed releases in service. Therefore, estimation of the probability that an SPRD will exceed the maximum pressure of 165 psi is necessary to evaluate its performance. The mean is a measure of the central tendency of peak surge pressure distribution; however, of much more interest and importance are the extreme high values in the distribution. An SPRD with a lower mean peak pressure may still have a higher probability of exceeding the disk burst pressure due to the variability in its performance, and thus would be less effective in preventing NARs. Figure 2.6 shows two peak pressure probability distributions (given one “surge event”¹) for two different types of SPRD to illustrate the situation mentioned above (techniques used in estimating the probability distribution will be explained in the following section). Although the longitudinal half-pipe has a lower mean peak pressure than the Hydro-Damp Style 20 (external), the half-pipe is estimated to have a higher probability of exceeding the peak pressure of 165 psi (represented as the area below the curves and to the right of the dashed line in the inset of Figure 2.6).

¹ “Surge event” refers to any event or set of circumstances in transportation that creates a pressure surge with the potential to exceed the frangible disk’s rated burst pressure.

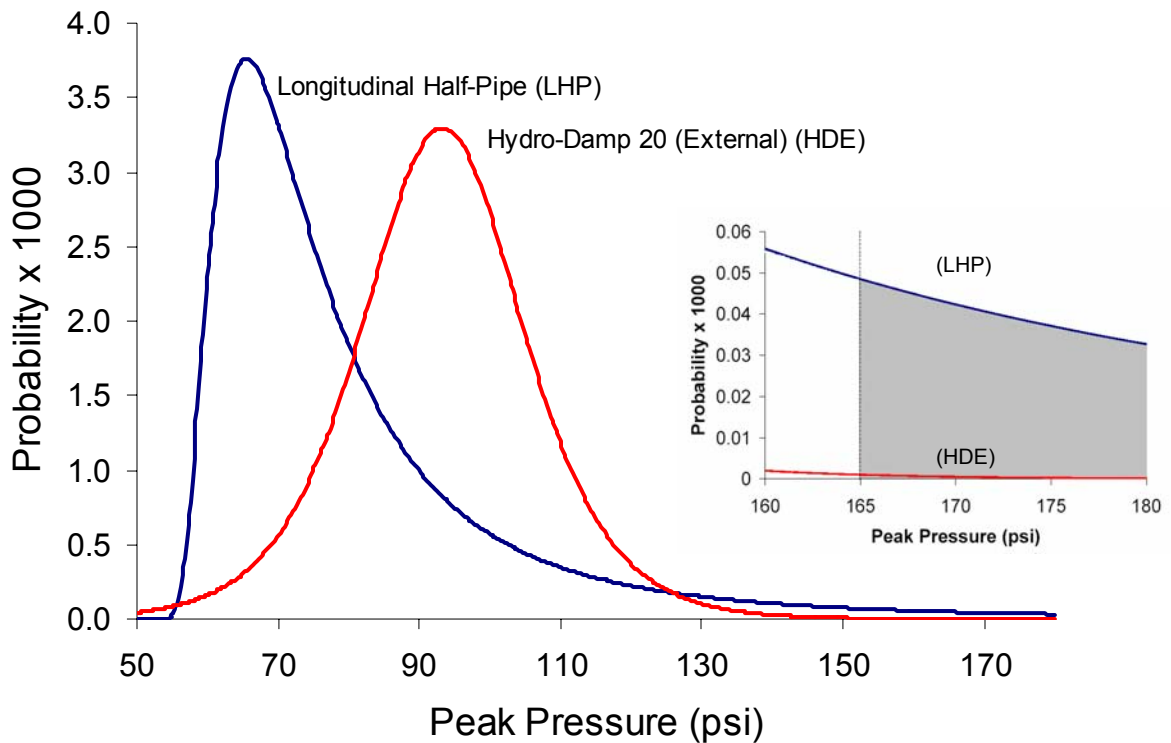


Figure 2.6 Representative probability densities of the pressure in the 6 1/2-inch pressure relief vent nozzle for two different SPRDs.

In general, each SPRD was tested 10 times (Barkan et al. 2000). These small sample sizes mean that estimation of the distribution of surge pressures for each SPRD is challenging, especially at the tails of the distribution, and requires use of a non-traditional statistical approach. A new method, the Fitted Distributions Averaging Method (FDAM), is introduced to estimate the probability that an SPRD will exceed 165 psi peak pressure when faced with one surge event. In addition, the probabilities of exceeding 100 psi and 132 psi were also estimated to provide further insight regarding the method and the likely effectiveness of different SPRDs. 100 psi corresponds to the previous requirement to design frangible disks to rupture at the tank test pressure for the DOT-111 general-purpose tank car, and 132 psi was chosen because it was

halfway between the old and new threshold values and offers a margin of safety compared to 165 psi.

2.1.1 Fitted Distributions Averaging Method (FDAM)

We developed a technique called Fitted Distributions Averaging Method (FDAM) to analyze the data sets of peak pressures. For each test condition (controls and SPRDs), we determined a set of acceptable distributions by using a Goodness-of-Fit (GoF) test. Then we aggregated all of these distributions to develop an average fitted distribution.

The Anderson-Darling (A-D) test is the GoF test used in this study. Although the Kolmogorov-Smirnov (K-S) test is the more common GoF test used for data with small samples, the A-D test has an advantage over the K-S test in this analysis as it gives more weight to the tails of the distribution, which is the region of interest in this analysis.

GoF tests may be able to give the best distribution that fits a data set, but because of the small size of our samples, there may be many distributions that are not rejected. An aggregation of several estimated probabilities from multiple statistical distributions that fit the data may provide a better and more robust estimate. Therefore, we considered a group of acceptable distributions, and estimated the unknown probabilities of interest by averaging the values from all acceptable distributions' functions. For example, peak pressure data from the ACF Inverted Cone for the 3-inch diameter nozzle follows Logistic, Normal and Weibull distributions, as determined by the A-D test (Figure 2.7). All three distributions were accepted, and the average estimated probability values at each discrete pressure threshold were calculated. The SPRD's

performance level is deduced from the averaged fitted distributions. Our calculation to estimate the probability of exceeding a specific threshold pressure for an SPRD is shown below:

$$P_{ave}(> p_i) = \sum_{j=1}^D P_{dist_j}(> p_i) / D$$

where:

$P_{ave}(> p_i)$ = average estimated probability of exceeding pressure threshold I ,

$dist_j$ = a set of acceptable statistical distributions that fit an impact test data for an SPRD, $j=1, \dots, D$, and

D = number of acceptable distributions.

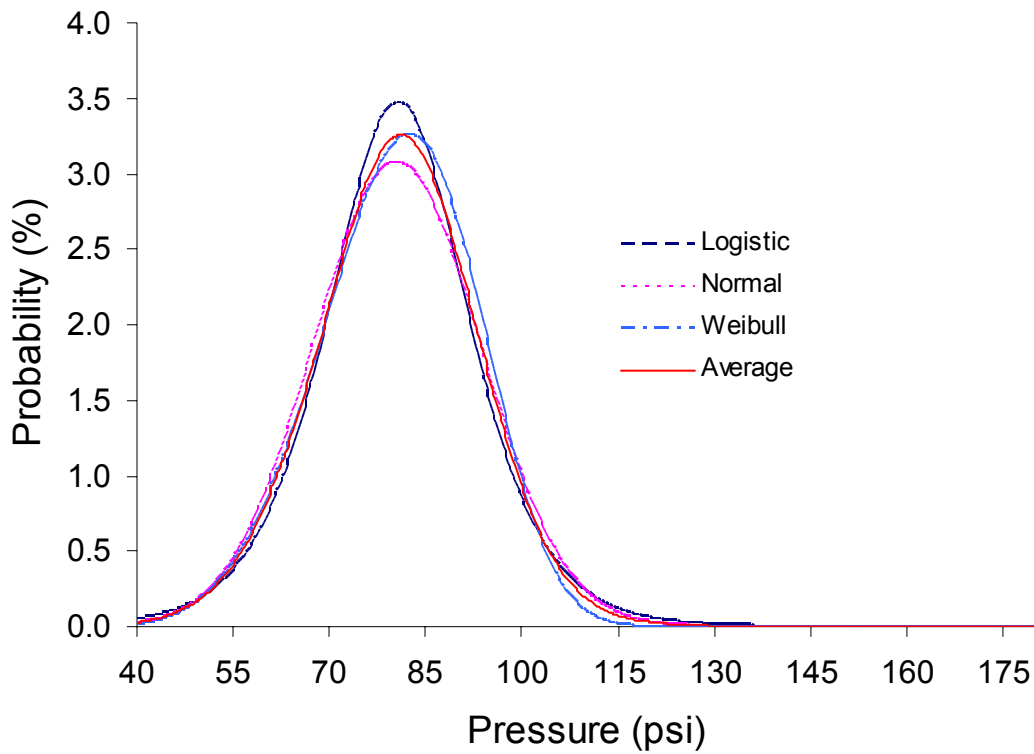


Figure 2.7 FDAM illustration for ACF Inverted Cone for 3-inch nozzle diameter.

2.1.2 Analysis Procedures

Initially, data for each SPRD were exported to Palisade's BestFit software to determine relevant distributions that may fit the data (BestFit 2004). BestFit implemented GoF algorithms to test up to 27 distributions. The program automatically performed the A-D test for each distribution, and ranked the relevant distributions by their test values (Figure 2.8).

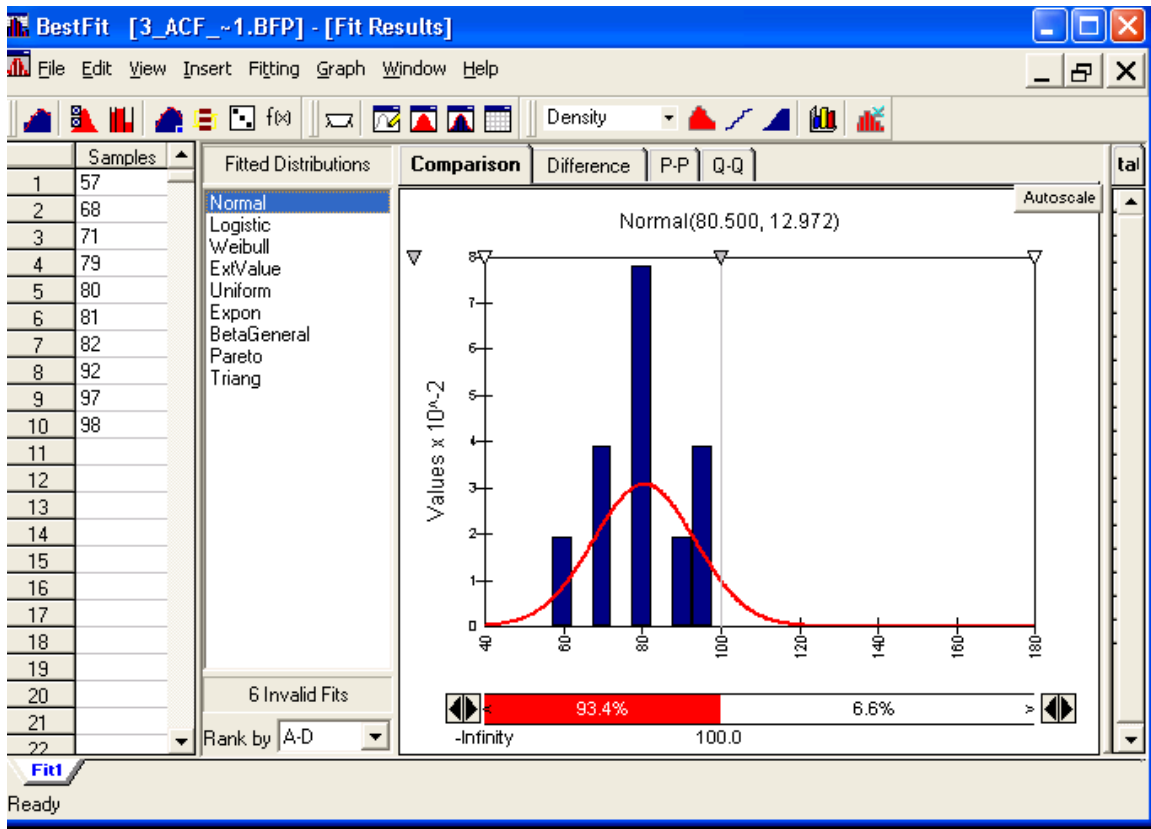


Figure 2.8 BestFit was used to determine relevant distributions from peak pressure data for each SPRD-nozzle combination (data shown are for the 3-inch-nozzle-diameter ACF Inverted Cone).

The relevant distributions were then tested using NIST's Dataplot, a software system for scientific visualization, statistical analysis, and non-linear modeling (Dataplot 2004). Dataplot has an advantage over BestFit in that Dataplot can perform the A-D test explicitly. BestFit calculates the A-D test value for a distribution, but cannot perform the hypothesis test to compare

the test value with the distribution-specific critical value. As an example, Dataplot was used to test whether a data set fit a normal distribution. The A-D test value of 0.2911 was compared to the critical value at the 95% confidence level, which is 0.683 (Figure 2.9). Since the test value is smaller than the critical value, the hypothesis that the data come from a normal distribution cannot be rejected. This process was repeated for all relevant distributions determined by BestFit.

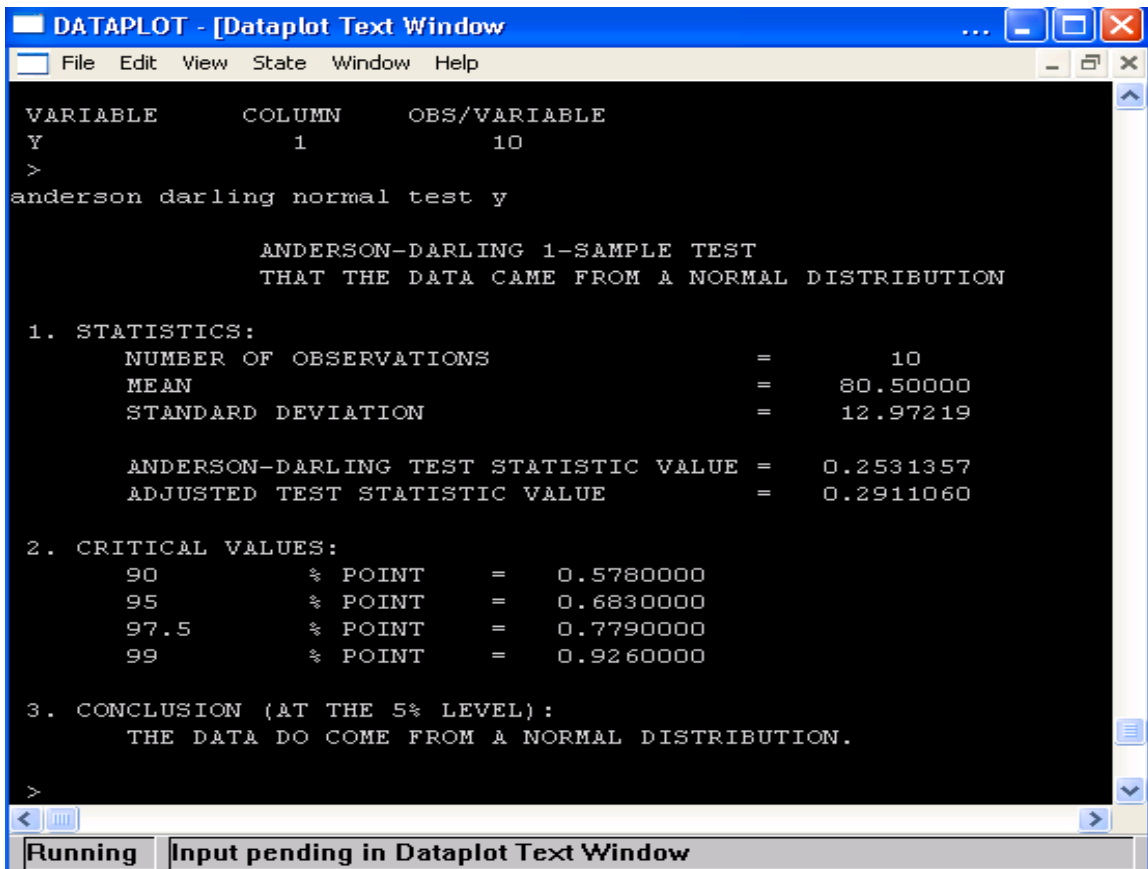


Figure 2.9 Screenshot from Dataplot showing results of a test of an SPRD’s data’s fit to a normal distribution.

As mentioned above, the A-D test was chosen because it is a commonly used GoF method for small samples, and it gives better attention at the tail of a distribution, which is specifically needed in this study. In addition, as compared with the K-S test that is a

distribution-free test, the A-D test requires an assumption about the distribution of errors to calculate the critical value. The advantage of this is that it allows a more sensitive test, while its major disadvantage is that the critical value must be calculated for each distribution. Numerous statistical packages including Dataplot have the capability to test normal, lognormal, exponential, Weibull, extreme value type 1, logistic, double exponential and uniform distributions. However, critical values for other statistical distributions cannot be calculated due to the non-existence of closed formulas. As such, in a few cases, a heuristic approach based on intuitive and graphical properties was used to consider some distributions for some specific data. This approach was only used to eliminate distributions with shapes that are clearly different from the observed data distribution.

2.2 Results

2.2.1 2-Inch Diameter Nozzle

TABLE 2.2 shows the estimated probabilities in percentage for 2-inch diameter SPRDs to exceed 100 psi, 132 psi and 165 psi. Percentage improvement is calculated by finding the ratio between each SPRD's estimated probabilities and the probabilities when no SPRD was used (i.e., control experiments). Note that 100% improvement is approximate; there is at least some very small probability of a high peak surge with all SPRDs. Figures 2.10, 2.11 and 2.12 show the SPRDs ranked by their estimated probability to exceed 100 psi, 132 psi and 165 psi,

respectively. The vertical bar indicates the ranges of estimated peak pressures from all acceptable distributions for each SPRD.

Table 2.2 2-Inch-Nozzle-Diameter SPRDs' Estimated Performance

Estimated Probability (%) of Exceeding Specified Pressure Thresholds Given One Surge Event

SPRD	100 psi		132 psi		165 psi	
	Percent		Percent		Percent	
	Average	Improvement	Average	Improvement	Average	Improvement
None (Control)	13.029100	0.00	1.814508	0.00	0.290101	0.00
Midland A-425-15-CS	4.772500	63.37	0.000873	99.95	0.000001	100.00
Midland A-424	1.131526	91.32	0.003086	99.83	0.000011	100.00
Hydro-Damp 70	1.224664	90.60	0.360343	80.14	0.116390	59.88
1-inch Orifice Plate	0.000373	100.00	0.000001	100.00	0.000000	100.00
Perforated Pipe	0.682767	94.76	0.350002	80.71	0.222671	23.24

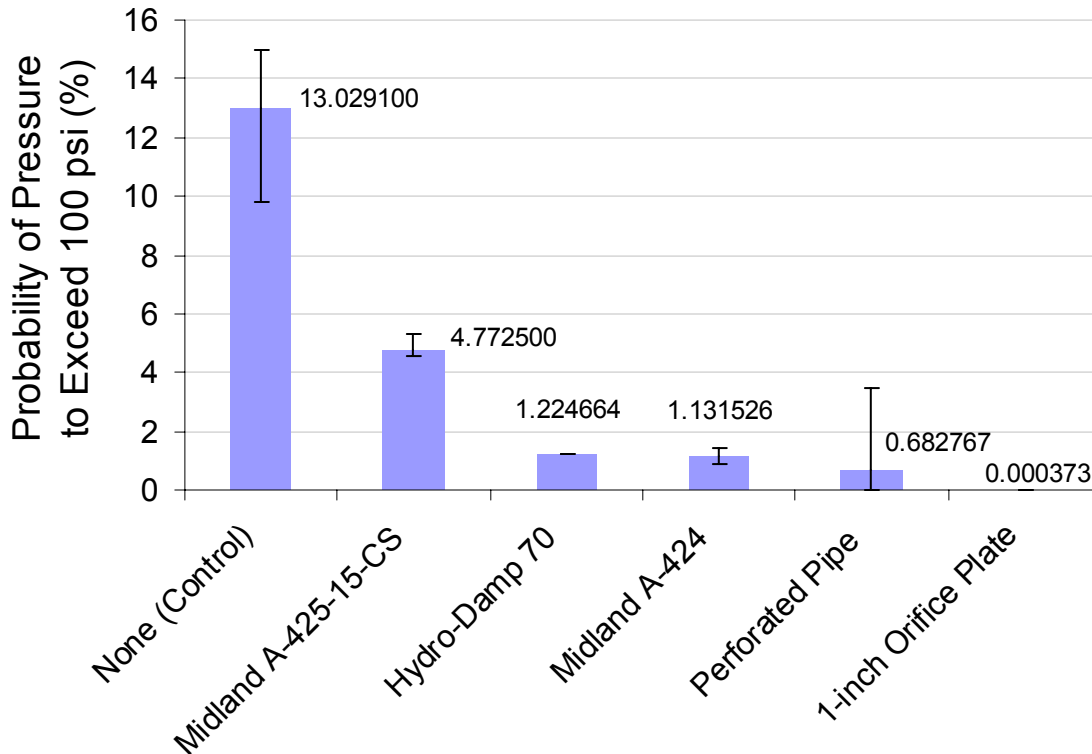


Figure 2.10 2-inch-nozzle-diameter SPRDs ranked by their estimated probabilities of allowing a peak pressure exceeding 100 psi given a surge event (bars indicate range among different distributions fitted to each SPRD).

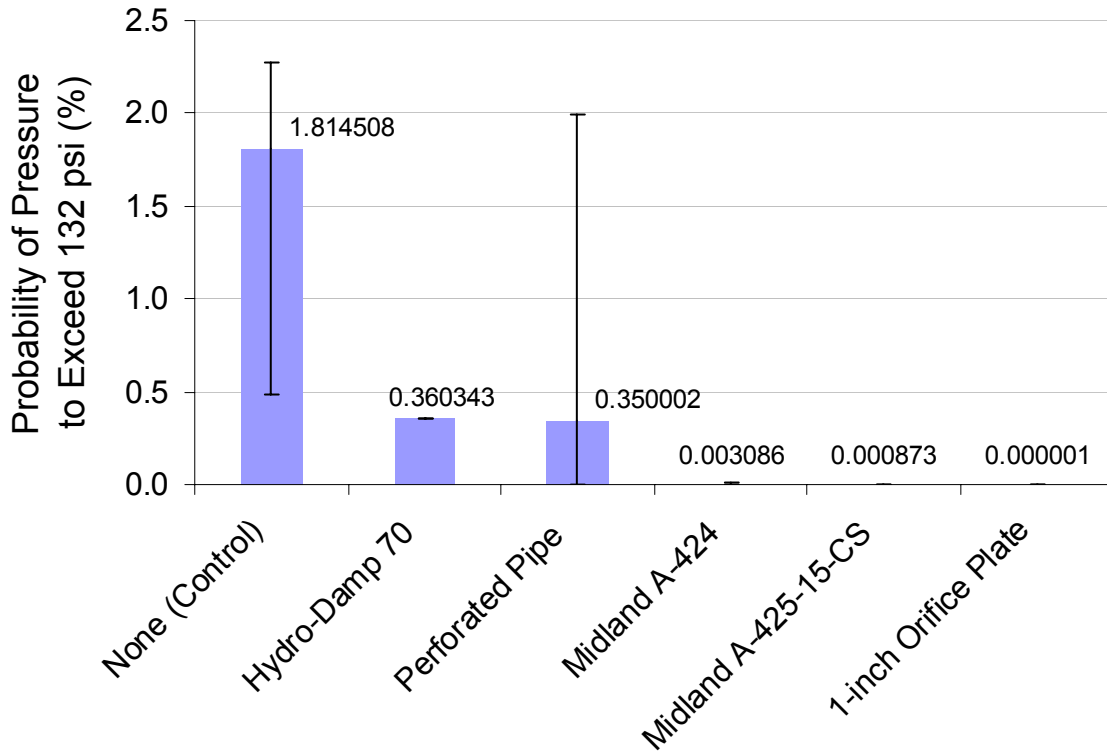


Figure 2.11 2-inch-nozzle-diameter SPRDs ranked by their estimated probabilities of allowing a peak pressure exceeding 132 psi given a surge event (bars indicate range among different distributions fitted to each SPRD).

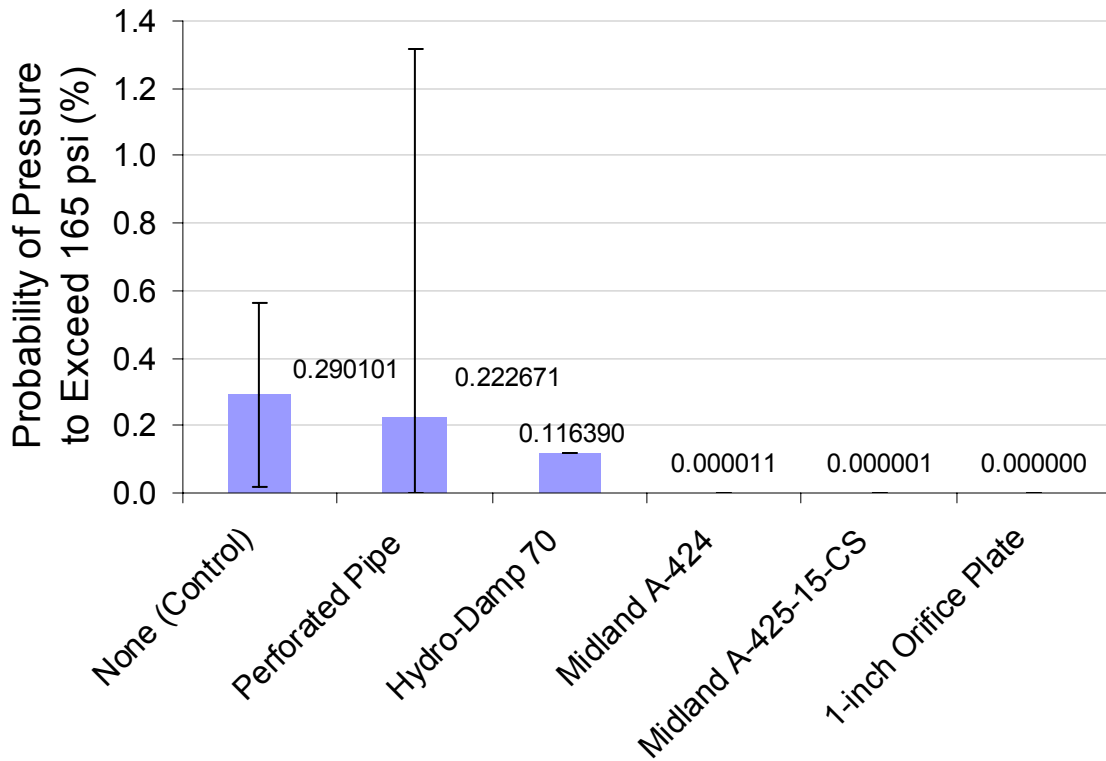


Figure 2.12 2-inch-nozzle-diameter SPRDs ranked by their estimated probabilities of allowing a peak pressure exceeding 165 psi given a surge event (bars indicate range among different distributions fitted to each SPRD).

2.2.2 3-Inch Diameter Nozzle

Table 2.3 shows the estimated probabilities in percentage for 3-inch diameter SPRDs to exceed 100 psi, 132 psi and 165 psi. Figures 2.13, 2.14 and 2.15 show the SPRDs ranked by their estimated probability to exceed 100 psi, 132 psi and 165 psi, respectively.

Table 2.3 3-Inch-Nozzle-Diameter SPRDs' Estimated Performance

Estimated Probability (%) of Exceeding Specified Pressure Thresholds Given One Surge Event

SPRD	100 psi		132 psi		165 psi	
	Percent		Percent		Percent	
	Average	Improvement	Average	Improvement	Average	Improvement
None (Control)	20.159161	0.00	3.989680	0.00	1.057937	0.00
GA/Salco Sieve	2.406121	88.06	0.199286	95.00	0.052703	95.02
ACF Inverted Cone	5.957637	70.45	0.028278	99.29	0.000285	99.97

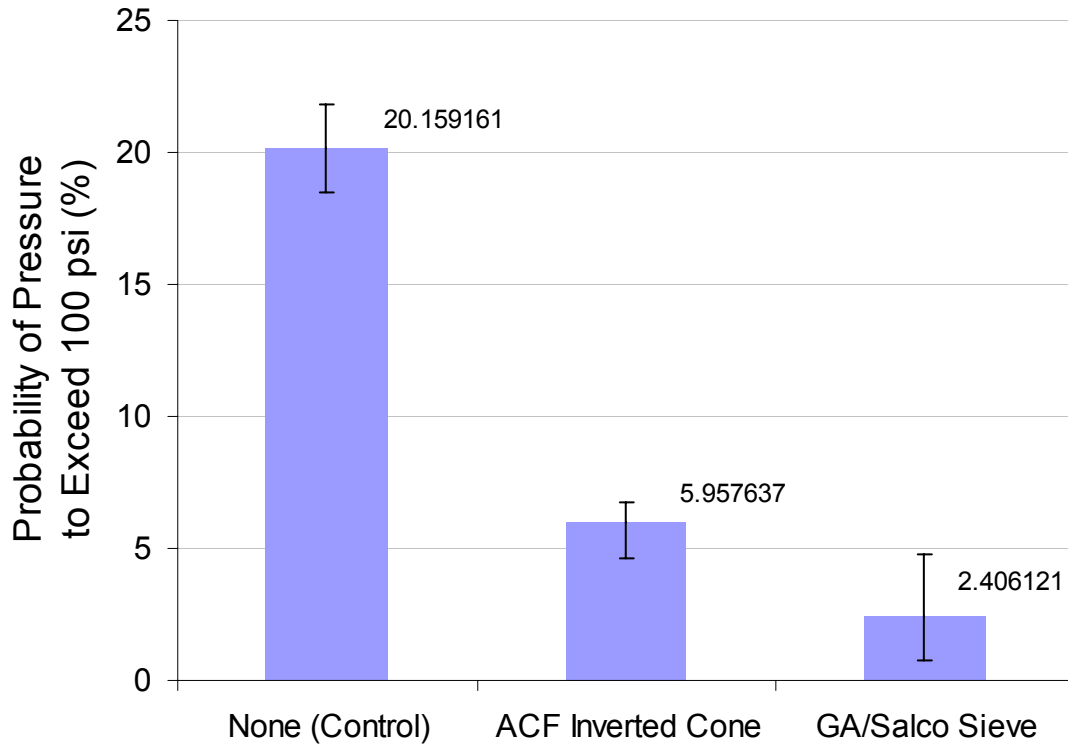


Figure 2.13 3-inch-nozzle-diameter SPRDs ranked by their estimated probabilities of allowing a peak pressure exceeding 100 psi given a surge event (bars indicate range among different distributions fitted to each SPRD).

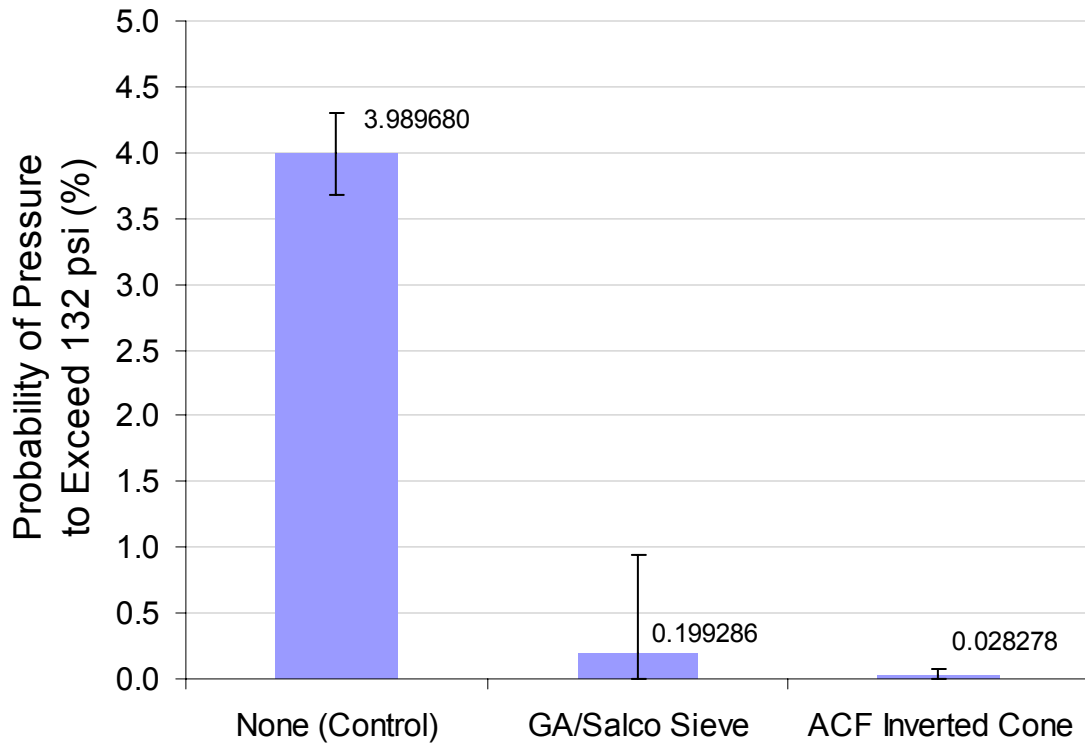


Figure 2.14 3-inch-nozzle-diameter SPRDs ranked by their estimated probabilities of allowing a peak pressure exceeding 132 psi given a surge event (bars indicate range among different distributions fitted to each SPRD).

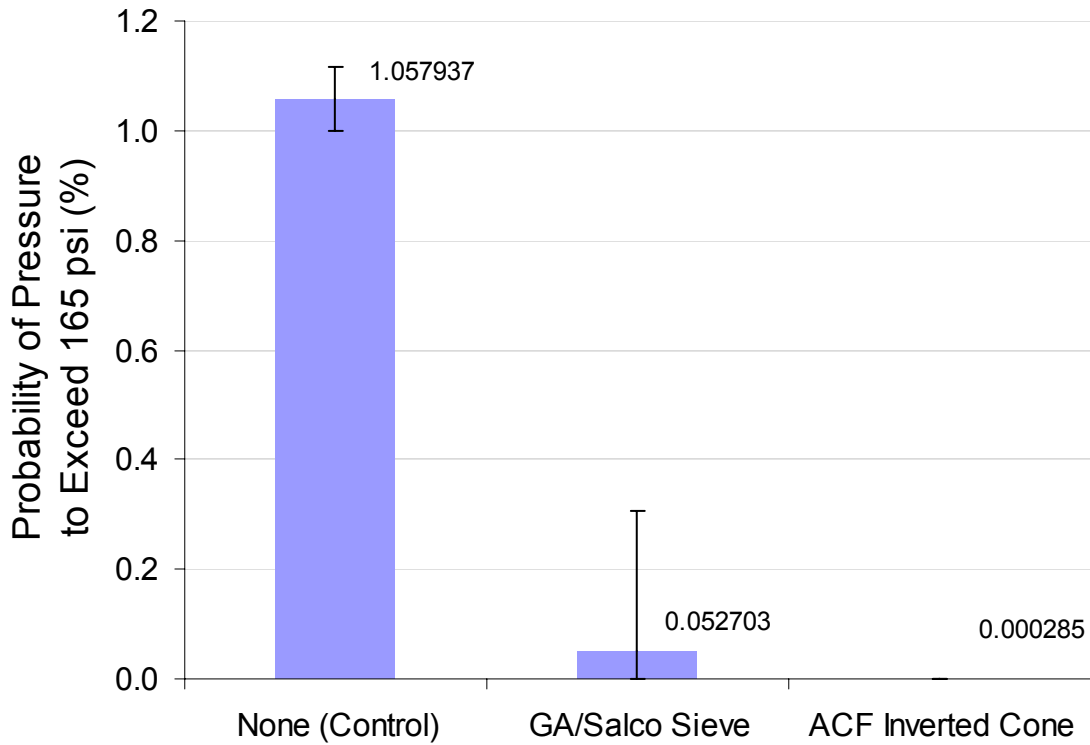


Figure 2.15 3-inch-nozzle-diameter SPRDs ranked by their estimated probabilities of allowing a peak pressure exceeding 165 psi given a surge event (bars indicate range among different distributions fitted to each SPRD).

2.2.3 6-1/2-Inch Diameter Nozzle

Table 2.4 shows the estimated probabilities in percentage for 6-1/2-inch diameter SPRDs to exceed 100 psi, 132 psi and 165 psi. Figures 2.16, 2.17 and 2.18 show the SPRDs ranked by their estimated probability to exceed 100 psi, 132 psi and 165 psi, respectively.

Table 2.4 6-1/2-Inch-Nozzle-Diameter SPRDs' Estimated Performance

Estimated Probability (%) of Exceeding Specified Pressure Thresholds Given One Surge Event

SPRD	100 psi		132 psi		165 psi	
	Percent		Percent		Percent	
	Average	Improvement	Average	Improvement	Average	Improvement
None (Control)	31.618954	0.00	12.770399	0.00	6.304140	0.00
Midland A-425-15-CS	1.207380	96.18	0.001507	99.99	0.000002	100.00
Midland A-424	19.970175	36.84	4.601135	63.97	1.413285	77.58
A425-15-CS & A-424	0.912854	97.11	0.006631	99.95	0.000059	100.00
GA/Salco Sieve	11.987001	62.09	0.345048	97.30	0.038424	99.39
Union Tank Milkstool	0.037176	99.88	0.001343	99.99	0.000045	100.00
Midland Milkstool	0.463724	98.53	0.015869	99.88	0.000472	99.99
Surge Chamber	0.000520	100.00	0.000027	100.00	0.000001	100.00
Hydro-Damp 20 (internal)	1.668360	94.72	0.540560	95.77	0.276424	95.62
Hydro-Damp 20 (external)	31.456283	0.51	0.997281	92.19	0.083041	98.68
Longitudinal Half Pipe	14.767076	53.30	4.682756	63.33	2.107698	66.57
Transverse Half Pipe	0.009000	99.97	0.000011	100.00	0.000000	100.00

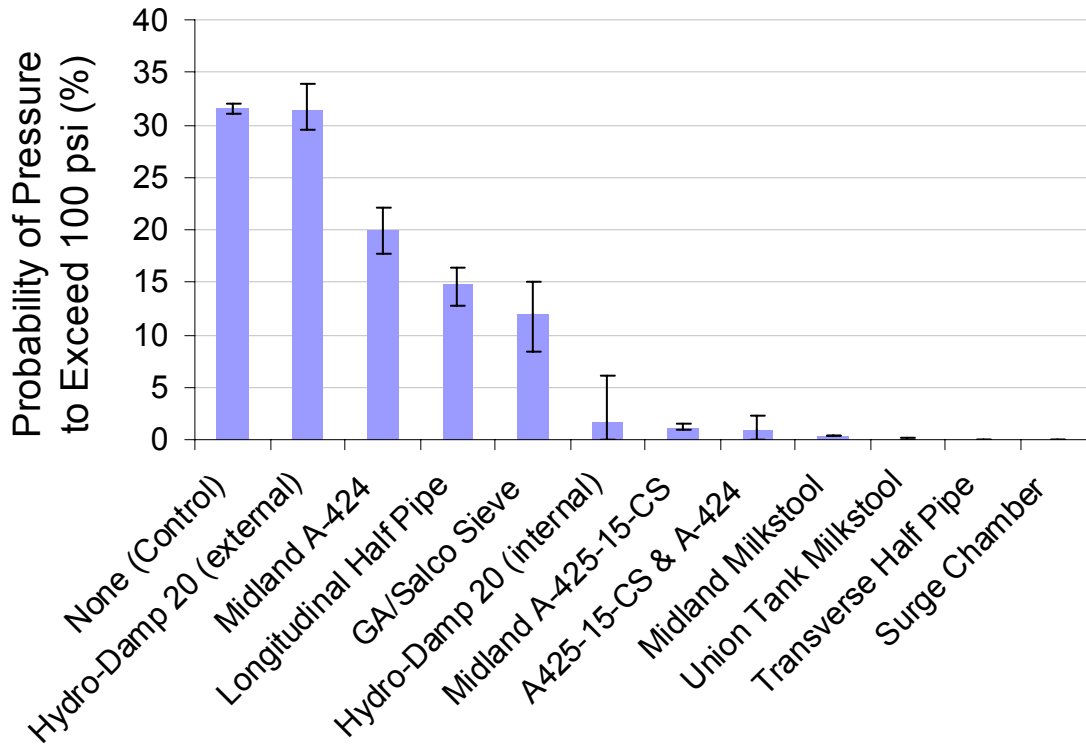


Figure 2.16 6-1/2-inch-nozzle-diameter SPRDs ranked by their estimated probabilities of allowing a peak pressure exceeding 100 psi given a surge event (bars indicate range among different distributions fitted to each SPRD).

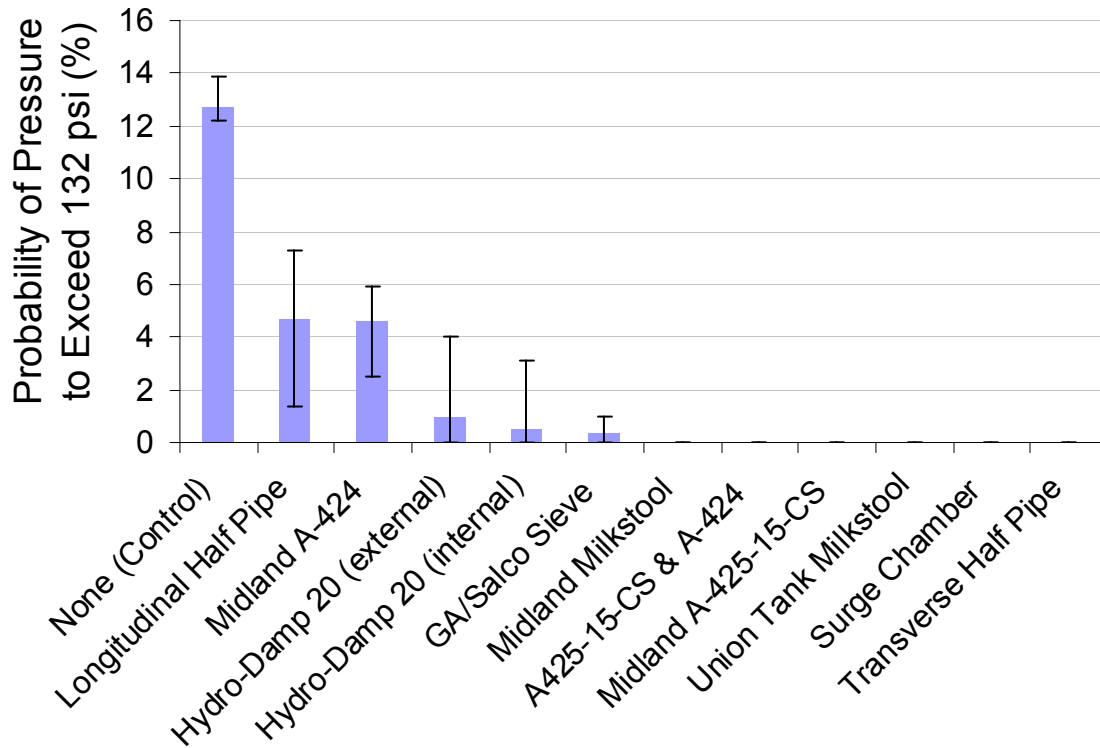


Figure 2.17 6-1/ 2-inch-nozzle-diameter SPRDs ranked by their estimated probabilities of allowing a peak pressure exceeding 132 psi given a surge event (bars indicate range among different distributions fitted to each SPRD).

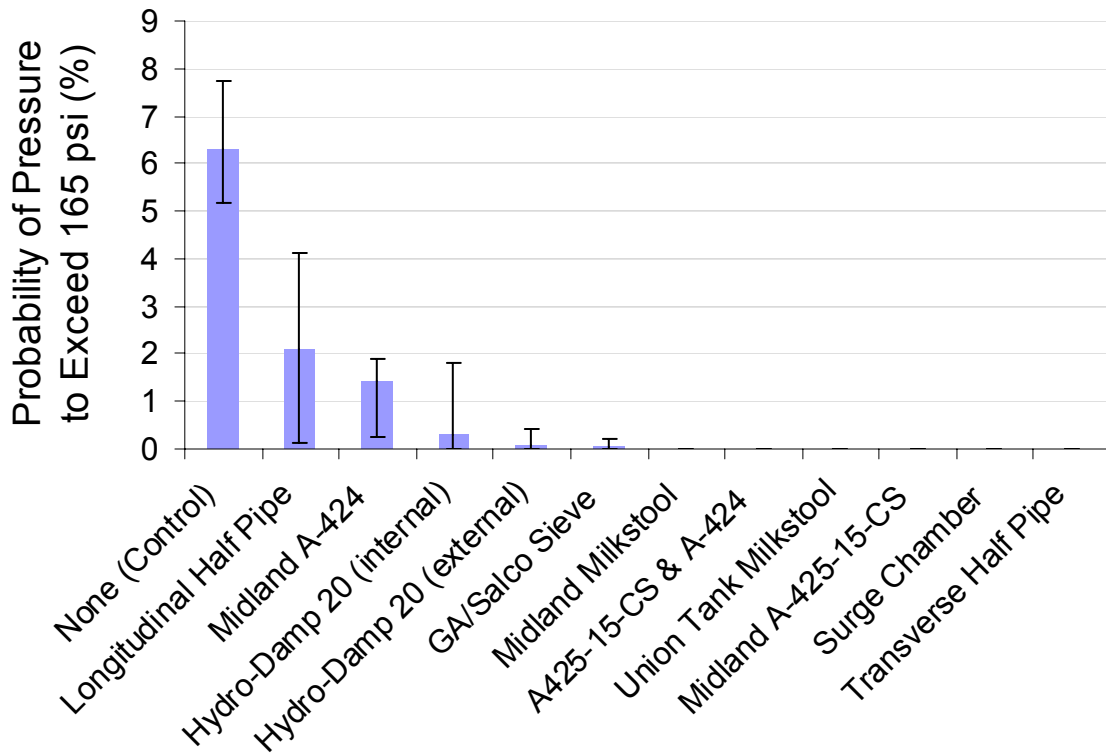


Figure 2.18 6-1/2-inch-nozzle-diameter SPRDs ranked by their estimated probabilities of allowing a peak pressure exceeding 165 psi given a surge event (bars indicate range among different distributions fitted to each SPRD).

2.2.4 Derivation of Estimated NARs for Each SPRD

The particular objective of this study is to estimate the probability of a peak pressure surpassing a threshold, given a surge event and a particular SPRD-nozzle combination.

However, we recognize that it may be easier to apply the results if they are stated in terms of the expected number of burst-disc NARs given a number of shipments with cars equipped with a particular SPRD-nozzle combination. Such an expected NAR rate cannot presently be known with precision. However, the following method may provide a useful approximation.

The approach is to use the rate per surge event at which peak pressures exceed the rupture disc rating in the impact tests (i.e., NARs per surge event), together with the rate per carload of burst discs (i.e., NARs per trip), to estimate the number of surge events per trip. The latter estimate is independent of which SPRD may be in use, and so it can then be combined with the probability estimates derived in this study for exceeding the 165 psi threshold to approximate the rate of NARs per trip in present-day service for any given SPRD-nozzle combination.

Mathematically, the relationship is

$$\text{NARs per trip} = \text{NARs per surge} \times \text{Surge events per trip}$$

The impact tests described in Barkan, et al. (2000), included 90 impacts under control conditions, i.e., no SPRD in place. Of those, we used 20 control impacts for the 2-inch-vent nozzle diameter and 30 control impacts with each of the 3- and 6-1/2-inch vent nozzle diameters. These data suggest a simple estimate of the probability of a peak pressure exceeding a given threshold during one surge event, for a given nozzle diameter, namely the number of observations exhibiting a peak above the threshold divided by total number of control impacts. For thresholds of 100 psi or less, this is at least somewhat reliable because there were 20 or 30 observations for each of the three controls. So using these data, we can estimate the probability of a peak of at least 100 psi given one surge event.

For nozzle diameter i , disc rating p^* , m control impacts and n observations from nozzle diameter i with peaks above p^* , where S represents surge events per trip,

$$\begin{aligned} (\text{NARs per trip})_i &= [P_i(\text{pressure} > p^* \mid \text{surge event})] S_i \\ &\approx (n_i/m_i) S_i \end{aligned}$$

Therefore,

$$S_i = (\text{NARs per trip})_i / (n_i/m_i)$$

Note that although S can be assumed to be independent of whether there is an SPRD in place, the differing control results for the different nozzle diameters suggest that S varies with i. If the surge pressure phenomenon is related to the sealing off of the bottom opening of the nozzle by the surging lading, then this would be a physical basis for hypothesizing that it does vary with i.

Table 2.5 shows the calculation of n/m at 100 psi for the control data from the impact tests.

Table 2.5 Peak Pressures above 100 psi for the Control Cases in the Barkan et al. (2000), Impact Test Data

Nozzle Diameter	Number of Control Impacts	Impacts That Generated Peak Pressures Over 100 psi	Observed Probability of Peak Pressure Over 100 psi
(i)	(m_i)	(n_i)	(n_i/m_i)
2"	20	2	0.10
3"	30	5	0.17
6-1/2"	30	11	0.37

The threshold of 100 psi was chosen because the n/m formulation is more reliable at that pressure level, and because during the years of 165 psi discs, the population of cars unequipped with SPRDs (i.e., the “control” cars) has been decreasing, perhaps rapidly. In order to estimate S, test data for the control condition must be combined with field data from the control condition, and this is only possible (and even then, only approximate) for years prior to 1994, when two events occurred that cause the effects of disc ratings and SPRDs to become more intertwined from that time forward: the railroad industry mandated that SPRDs be installed on all new tank cars with pressure relief vents, and the 165 psi became mandatory by federal regulation, making 100 psi discs obsolete.

A field study of tank cars in Hazard Class 8 service, completed in 1992, found that cars with no SPRD experienced 3.7 ruptured discs per 1,000 loaded car trips (Barkan et al. 2000). This rate would include some 60 psi discs and a few 45 psi discs, used prior to 1994 on DOT-111 cars with a tank test pressure of 60 psi or 45 psi, respectively. We can assume that 60 psi and 45 psi discs would have a higher rate of NARs per trip than the 100 psi discs then used in the majority of the pressure relief vents. On the other hand, some SPRDs were in service at that time. Considering these factors, a rate of 3.7 NARs per 1,000 trips is a gross approximation of the rate for cars with 100 psi discs and no SPRDs. Unfortunately, different NAR rates for different nozzle diameters cannot be determined from that study, so we used the 3.7 estimate universally here.

With this approximation, we can convert the probability of an NAR given a surge event into an estimate of surge events per trip (Table 2.6). That number will be independent of the SPRD-nozzle combination in use, and therefore can be applied to the results of this study to convert them into NAR-per-trip rates.

Table 2.6 Estimation of NAR Rates per 1,000 Trips with 100 psi Rupture Discs for Different Nozzle Diameters

Nozzle Diameter	NARs at 100 psi per 1,000 Loaded Tank Car Trips	Observed Probability of Peak Pressure Over 100 psi, Given One Surge Event (n_i/m_i)	Estimated Surge Events per 1,000 Loaded Tank Car Trips (S_i)
2"	3.7	0.1	37
3"	3.7	0.17	22.2
6-1/2"	3.7	0.37	10.09

The results in the rightmost column of Table 2.6 can be applied to the probabilities in Tables 2.2, 2.3 and 2.4 to convert them into estimates of NARs per trip. The relationship is the same as for the controls above; for SPRD j on nozzle i ,

$$(\text{NARs per trip})_{ij} = [P_{ij}(\text{pressure} > p^* \mid \text{surge event})] S_i$$

Tables 2.7, 2.8 and 2.9 show the results.

Table 2.7 Estimation of NAR Rates per 1,000 Trips with 165 psi Rupture Discs for Different SPRDs on a 2-Inch-Nozzle-Diameter

SPRD	Estimated Surge Events per 1,000 Loaded Tank Car Trips for 2"ID Nozzle (S_2)	$P_{ij}(\text{pressure} > 165 \text{ psi given a surge event) in \% from Table 2.2}$	Estimated NARs at 165 psi per 1,000 Loaded Tank Car Trips for 2"ID Nozzle
1" Orifice Plate	37.00	0.000000	0.000000
Midland A-425-15-CS	37.00	0.000001	0.000000
Midland A-424	37.00	0.000011	0.000004
Hydro-Damp 70	37.00	0.116390	0.043064
Perforated Pipe	37.00	0.222671	0.082388
None (Control)	37.00	0.290101	0.107337

Table 2.8 Estimation of NAR Rates per 1,000 Trips with 165 psi Rupture Discs for Different SPRDs on a 3-Inch-Nozzle-Diameter

SPRD	Estimated Surge Events per 1,000 Loaded Tank Car Trips for 3"ID Nozzle (S_3)	$P_{ij}(\text{pressure} > 165 \text{ psi given a surge event) in \% from Table 2.3}$	Estimated NARs at 165 psi per 1,000 Loaded Tank Car Trips for 3"ID Nozzle
ACF Inverted Cone	37.00	0.000285	0.000105
GA/Salco Sieve	37.00	0.052703	0.019500
None (Control)	37.00	1.057937	0.391437

Table 2.9 Estimation of NAR Rates per 1,000 Trips with 165 psi Rupture Discs for Different SPRDs on a 6-1/2-Inch-Nozzle-Diameter

SPRD	Estimated Surge Events per 1,000 Loaded Tank Car Trips for 6-1/2"ID Nozzle ($S_{6.5}$)	Pij(pressure > 165 psi given a surge event) in % from Table 2.4	Estimated NARs at 165 psi per 1,000 Loaded Tank Car Trips for 6-1/2"ID Nozzle
Transverse Half Pipe	22.20	0.000000	0.000000
Surge Chamber	22.20	0.000001	0.000000
Midland A-425-15-CS	22.20	0.000002	0.000000
Union Tank Milkstool	22.20	0.000045	0.000010
A425-15-CS & A-424	22.20	0.000059	0.000013
Midland Milkstool	22.20	0.000472	0.000105
GA/Salco Sieve	22.20	0.038424	0.008530
Hydro-Damp 20 (external)	22.20	0.083041	0.018435
Hydro-Damp 20 (internal)	22.20	0.276424	0.061366
Midland A-424	22.20	1.413285	0.313749
Longitudinal Half Pipe	22.20	2.107698	0.467909
None (Control)	22.20	6.304140	1.399519

2.2.5 Damiani Ratio and Its Relationship to SPRD Performance

The ratio between the protected volume of the space between the opening into the SPRD, and the frangible disc to the area of the opening into the SPRD is sometimes referred to as Damiani's Ratio, after Ben Damiani, a former chief engineer for Union Tank Car Company who championed this concept as a means of surge protection. The opening meters the amount of liquid that can rise into the protected volume. The larger the volume, the lower the per-unit compressive effect of the rising liquid on the atmosphere trapped between it and the frangible disc. Since the inertial effect on the rising liquid column is brief (about 20 mS), the larger the V:a ratio, the more likely it is that the liquid will begin to drop before the trapped atmosphere can be compressed to a critical level.

Previous work confirmed that there is a significant inverse relationship between an SPRD's Damiani ratio and the average peak pressure allowed by that SPRD (Barkan et al. 2000). Figure 2.19 depicts the relationship between Damiani ratio and the estimated improvements over

the controls from Tables 2.2, 2.3 and 2.4 above. All SPRDs that are estimated to offer less than near-total protection at 165 psi have Damiani ratios lower than 40 inches. However, there is a range above that in which no SPRDs exist, so it is unknown how devices between 40 and 80 inches would perform. Note that 100% improvement is approximate; there is at least some very small probability of a high peak surge with all SPRDs. Damiani ratios for some complicated SPRDs were harder to measure and are less precise than others.

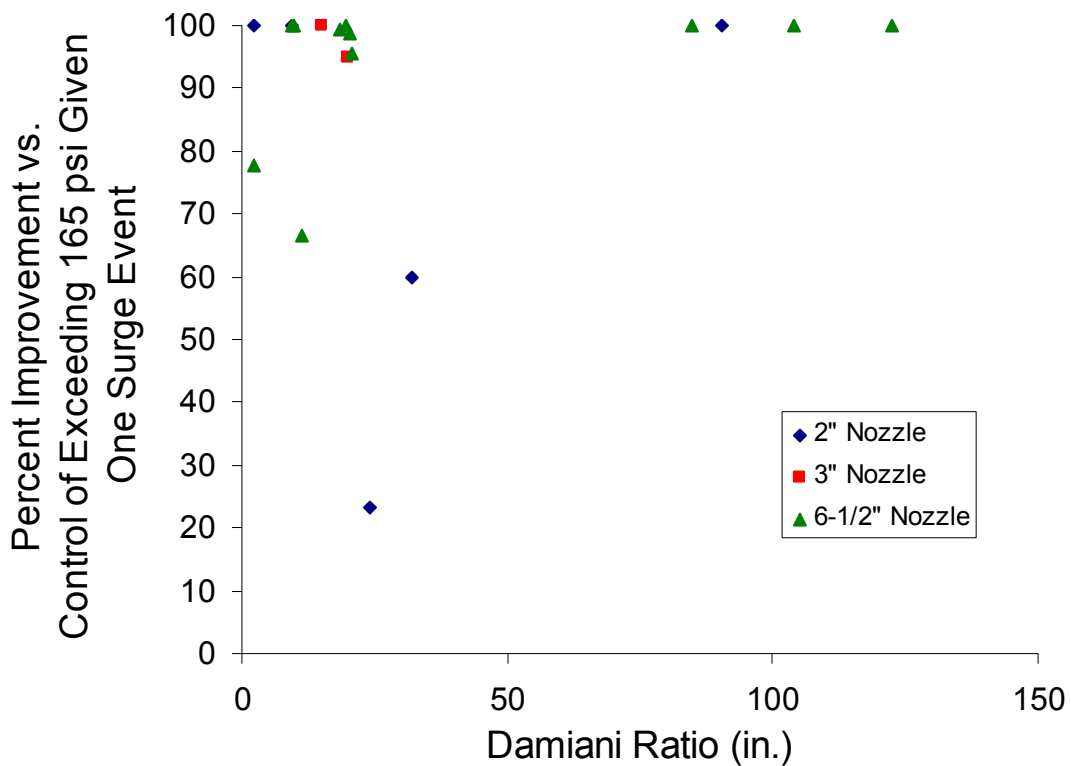


Figure 2.19 Relationship between Damiani Ratio and estimated improvement over no SPRD (Control).

2.3 Discussion & Conclusions

Our objective was to estimate the probability of experiencing a peak pressure in excess of a given threshold pressure for each SPRD. The lower the estimated probability of an SPRD allowing a surge pressure event above the specified pressure, the more effective is its performance.

Results are given for pressure thresholds of 100 psi, 132 psi and 165 psi. Although 165 psi is the standard frangible disk rating, the results for lower thresholds may be somewhat more reliable than those for 165 psi because less extrapolation was necessary to fit the curve near the lower thresholds. The lower thresholds represent a factor of safety as well.

Although this study's analysis of the tails of statistical distributions of peak pressures leaves some uncertainty regarding performance in the field, these results provide the most comprehensive data available to assess the relative effectiveness of SPRDs in reducing NARs from pressure relief vents.

Readers who wish to apply the results of this study towards determining requirements for SPRDs have a number of potential approaches. The estimated NAR rates, or the underlying averaged-estimated probabilities of allowing high peak pressures, could be used to develop performance standards. In addition, the Damiani ratios could be used to set design requirements. Some combination of the two is also possible.

CHAPTER 3

RELEASE RISK AND OPTIMIZATION OF RAILROAD TANK CAR SAFETY DESIGN

Published as: Saat, M.R. & Barkan, C.P.L. (2005). Release Risk and Optimization of Railroad Tank Car Safety Design. In-press Transportation Research Record, TRB, National Research Council, Washington, D.C.

3.0 Introduction

For the past several years, the rate of railroad accident-caused releases of hazardous materials has been fluctuating between 27 and 37 incidents per million carloads (BOE 2004). Although significantly lower than the rate of about 200 incidents per million carloads in 1982 (Barkan et al. 2000), further reduction of accident-caused hazardous material releases remains an important objective. In 2002, there were approximately 1.7 million rail shipments of hazardous materials in the U.S. and Canada, and approximately 75% of these were transported in tank cars (BOE 2004).

Two of the principal elements in the reduction of railroad hazardous material transportation risk are prevention of accidents, and prevention of spills from railcars involved in accidents (Barkan et al. 1991). Train accidents declined substantially in the 1980s and more gradually in the 1990s due to improvements in track design and maintenance, as well as improvements in equipment and training (Dennis 2002; Gallamore 1999). The result is that the annual accident rate has been reduced from approximately 12 accidents per million-train miles in

1980 (Harvey et al. 1987) to about 4 accidents per million-train miles in 2002 (Anderson & Barkan 2004).

Changes in tank car safety design to make them more resistant to damage in accidents have also contributed to the improvement in the safety record (Barkan et al. 2000). Although analysis of the degree of hazard posed by different products is ongoing, in general higher hazard materials are shipped in cars with tanks constructed of thicker and stronger steels. Additionally, these cars may be equipped with head shields and more damage-resistant top fittings designs.

The objective of this study is to develop a new metric for quantifying hazardous materials releases, and to apply this metric by extending the work done by Barkan et al. (2005) to evaluate tank car thickness and safety. They used optimality techniques to consider tank car design so as to minimize the probability of release and developed a model that considered the tradeoff between improved damage resistance of the tank and increased accident exposure due to the reduced capacity of the car. The objective function in their model was probability of release. In this paper we consider a new metric as the objective function in which the quantity lost is accounted for as well as the probability of release. Previous authors (Phillips et al. 1995; Treichel 1996) have considered accident-caused release probability and the quantity lost due to different sources of damage to the tank car, but they have not previously been combined into a single metric to evaluate tank car safety design. In this paper, we develop the concept of “release risk” and then develop a new version of the optimal tank thickness model in which we use this new metric.

3.1 Tank Car Damage Resistance

There are two general types of tank-car damage that can lead to releases in an accident; 1) tank-caused, which includes damage to the head and shell, and 2) non-tank-caused, which includes damage to other tank car components, principally the top and bottom fittings.

The nature of accident-caused damage to tank and non-tank components of a tank car is distinct, and different approaches are used to enhance damage resistance. The usual approach to reducing tank-causes is to increase the strength of the tank. This may be accomplished by increasing its thickness, using head protection, and/or application of a tank jacket. Additionally, the tank material properties may be improved by use of higher tensile strength and/or normalized steel.

Reducing non-tank-caused releases includes measures such as enclosing top fittings in a protective housing (BOE 2004), adding bottom fittings protection (Griger & Phillips 1992), and/or removing the bottom fittings completely (Barkan et al. 2005).

3.2 Tank Car Release Risk

The conditional probability of release given that a tank car is derailed in an accident is a useful metric for assessing the safety of tank cars. However, it does not take into account the quantity lost, and this amount varies depending on the part of the car that is damaged (Figure 3.1) (Phillips et al. 1995; Treichel 1996). As an example, for a general-purpose DOT-111 tank car with 0.4375 “ tank thickness, non-tank causes are the most frequent source of loss in accidents (Figure 3.2), but it results in the lowest average amount lost (Figure 3.3) (Phillips et al. 1995; Treichel 1996). Conversely, losses from tank-caused releases are less common, but result

in a larger average quantity lost. The reason for this disparity is that in accidents in which fittings develop a leak, it may often be small and stopped relatively quickly by response personnel. Conversely, a hole in the tank head or shell is often the result of impact damage from a rail or another railcar that punctures or tears open the tank. These may often be fairly large and difficult to plug before a large portion of the tank's contents have been lost. The rate of release and thus the quantity of release depend on the size of the puncture (Raj & Turner 1993), tank internal pressure and the viscosity of the commodity.

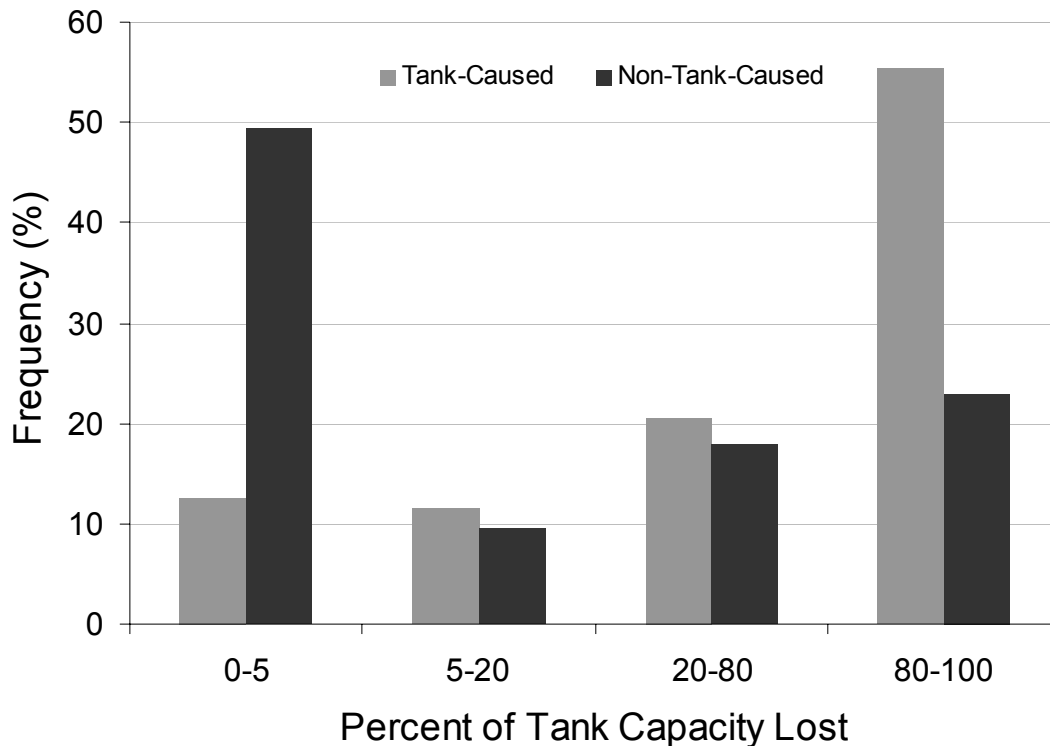


Figure 3.1 Frequency of releases of different sizes by source for non-insulated, non-pressure tank cars in accidents (Phillips et al. 1995).

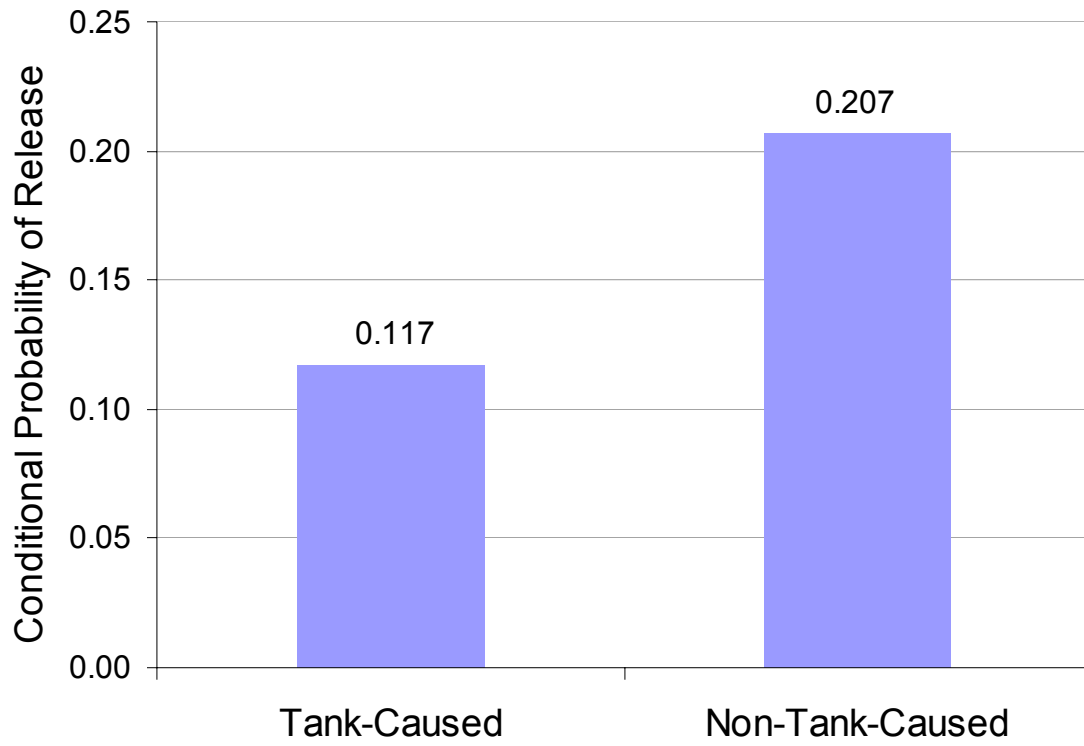


Figure 3.2 Conditional probability of release by source for general-purpose non-insulated DOT-111 tank cars (Phillips et al. 1995)

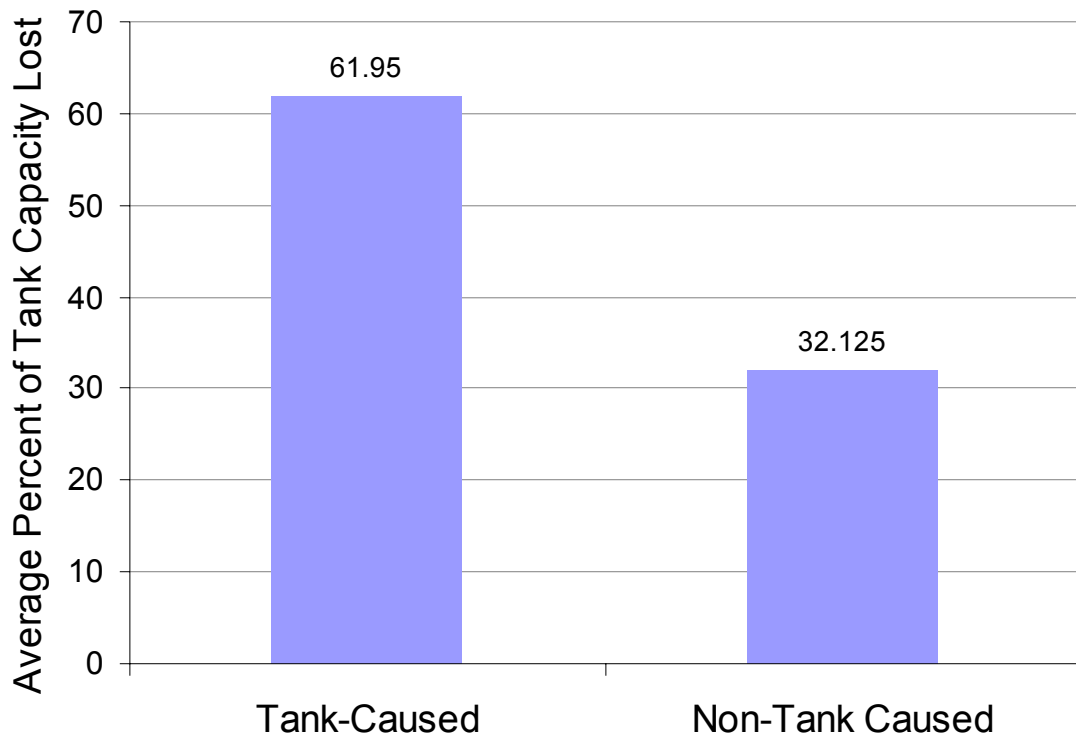


Figure 3.3 Average percentage of tank capacity lost by source for general-purpose non-insulated DOT-111 tank cars that lost lading in accidents (Phillips et al. 1995).

In addition to the hazard level of the commodity, the quantity of contents released affects the severity of a release incident. A larger release will generally result in a larger exposure area and consequent greater impact on people, property and the environment, and incur higher response, evacuation, and hazard mitigation costs. Therefore, when evaluating the benefit of applying various risk reduction options to tank cars, it may also be beneficial to consider the amount lost from different parts of the car.

To illustrate the idea of the metric, release risk, for the general-purpose tank car, consider the following example. The conditional probability of a tank-caused release given that a tank car is derailed in an accident is 0.117 and the conditional probability of a non-tank-caused release is 0.207(Phillips et al. 1995). The corresponding average amount of contents lost for each source is

62.0 and 32.1 percent of tank capacity, respectively. The product of the conditional probability and the average amount of contents lost is the expected value of the percentage lost, or release risk, given that a car is derailed or damaged in an accident (Figure 3.4). This example considers the average release risk for a particular type of tank car with a specific thickness. This study is intended to develop a more general release risk model for tank cars with different tank thicknesses. In addition, instead of considering the average percentage of tank capacity lost for each source, the distribution of release size (Figure 3.1) is taken into account in the development of the model described in the following section.

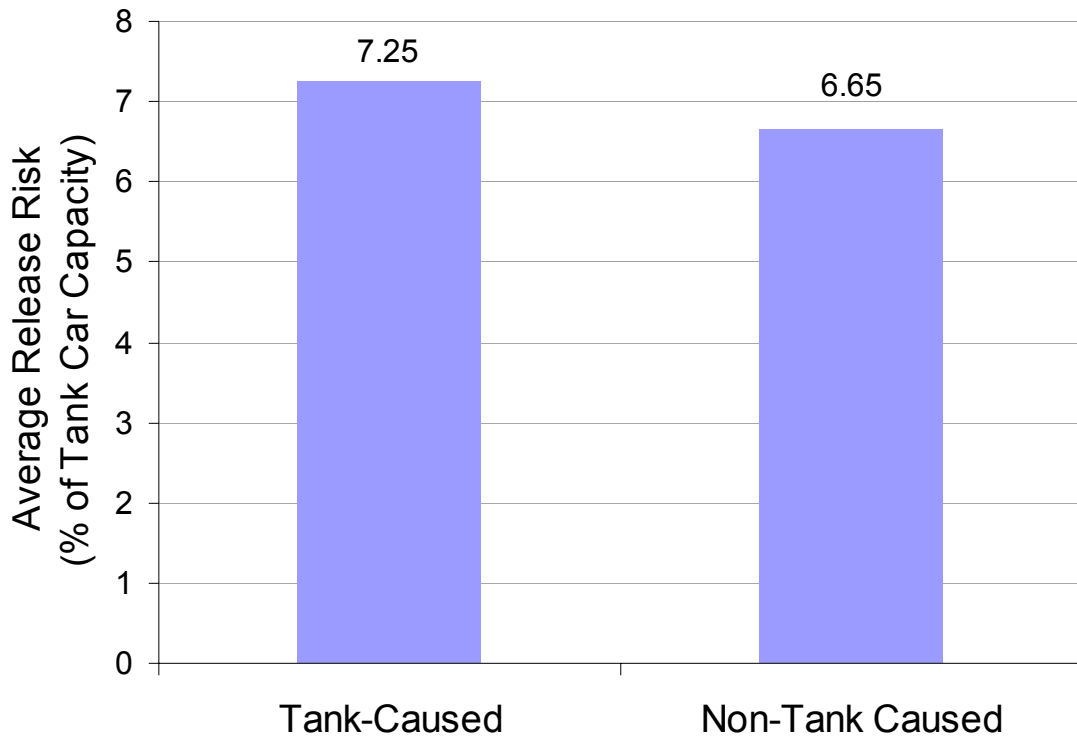


Figure 3.4 Average release risk by source for general-purpose non-insulated DOT-111 tank cars that lost lading in accidents.

3.3 Model Development

Risk is defined as the frequency of an event multiplied by the consequences of that event. In the context of the model described here we define frequency as the probability of release, and the consequence is defined as the quantity lost expressed as a percentage of the tank's total volumetric capacity. Important aspects considered in the development of the release model are, 1) the functional relationship between tank thickness and release risk due to damage to the tank (tank-caused releases), 2) the release risk due to damage to other tank car appurtenances (non-tank-caused releases) that are not directly affected by tank thickness, 3) the relationship between tank thickness, weight, capacity and number of shipments, and 4) the relationship between tank thickness, weight, capacity and expected quantity of release. All damage-caused release sources and discrete release sizes are incorporated in the release risk model as shown below:

$$R_R = \sum_{j=1}^n \sum_{i=1}^m R_{Ri,j}$$

where:

R_R = release risk for a tank car in percentage of tank capacity lost

n = number of release sources considered

m = number of release sizes considered

$R_{Ri,j}$ = release risk for release size i from release source j

3.3.1 Tank-Caused Release Source

The frequency of a tank-caused release of size i can be defined as:

$$F_{TRi} = P_{TRi|A} Z \quad (\text{Equation 1})$$

where:

F_{TRi} = frequency of tank-caused release of size i

$P_{TRi|A}$ = conditional probability of tank-caused release of size i given the car is derailed in an accident

$$= P_{Ri|TR} P_{TR|A}$$

where:

$P_{Ri|TR}$ = conditional probability of release size i given a tank-caused release occurrence

$P_{TR|A}$ = conditional probability of a tank-caused release occurrence given the car is derailed in an accident

Z = exposure to accident

$$= P_A M$$

where:

P_A = probability of a tank car derailed in an accident per mile traveled

M = number of car-miles

Thus, Equation 1 can be modified as follows:

$$F_{TRi} = P_{Ri|TR} P_{TR|A} P_A M \quad (\text{Equation 2})$$

The associated release consequence for tank-caused release is defined as:

V_{TRi} = average percentage of tank capacity lost for release size i in a tank-caused release occurrence

Using the four release sizes shown in Figure 3.1, the risk for tank-caused release of size i can be defined as the product of the associated frequency and consequence as expressed below:

$$R_{TR} = \sum_{i=1}^4 F_{TRi} V_{TRi} \quad (\text{Equation 3})$$

Expanding the tank-caused release risk definition in Equation 3, it can be seen that the accident exposure terms, P_A and M , appear as constants for each release size. If excluded from the release risk definition, a new term called “conditional tank-caused release risk” is introduced as follows:

$$R'_{TR} = \sum_{i=1}^4 P_{Ri|TR} P_{TR|A} V_{TRi}$$

where:

R'_{TR} = conditional tank-caused release risk given the tank car is damaged or derailed.

Hughes et al. (1998) published data on conditional tank-caused release probability with respect to tank thickness. Using the data and quantity of release data from Phillips et al. (1995) (Table 3.1), the relationship between tank thickness and conditional tank-caused release risk were calculated (Figure 3.5). We conducted a regression analysis in which we fitted the data to a negative exponential model to determine the functional relationship between tank thickness and the estimated conditional tank-caused release risk. Over the range of thicknesses in use for tank cars in North America, the conditional release risk conforms well ($R^2 = 0.8837$) to a negative exponential distribution of the following form:

$$R'_{TR} = v + we^{(-y t + z)}$$

where:

t = tank thickness

v, w, y and z are the regression coefficients in the negative exponential model

$$v = 0.40951$$

$$w = 4.72098$$

$$y = 6.35515$$

$$z = 3.22174$$

**Table 3.1 Tank-Caused Conditional Release Risk Expressed as a Percentage of Tank Capacity Lost
(Phillips et al. 1995, Hughes et al. 1998)**

Tank Thickness (in.)	Percentage Tank Contents													Calculated R'_{TR}	Fitted R'_{TR}
	P_{TRIA}	0 - 5			> 5 - 20			> 20 - 80			> 80 - 100				
		$P_{R1 TR}$	V_{TR1}	R'_{TR1}	$P_{R2 TR}$	V_{TR2}	R'_{TR2}	$P_{R3 TR}$	V_{TR3}	R'_{TR3}	$P_{R4 TR}$	V_{TR4}	R'_{TR4}		
0.4375	0.1170			0.037			0.168			1.200			5.849	7.254	7.750
0.5000	0.1090			0.034			0.157			1.121			5.465	6.777	5.344
0.5625	0.0430			0.014			0.062			0.443			2.158	2.676	3.726
0.6250	0.0440			0.014			0.063			0.451			2.198	2.726	2.639
0.6875	0.0270			0.009			0.039			0.279			1.359	1.685	1.908
0.7500	0.0280			0.009			0.040			0.288			1.404	1.741	1.417
0.8125	0.0190	0.125	2.5	0.006	0.115	12.5	0.027	0.205	50	0.193	0.555	90	0.939	1.165	1.087
0.8750	0.0070			0.002			0.010			0.075			0.365	0.452	0.865
0.9375	0.0160			0.005			0.022			0.160			0.779	0.966	0.716
1.0000	0.0000			0.000			0.000			0.000			0.000	0.000	0.615
1.0625	0.0030			0.001			0.004			0.029			0.140	0.173	0.548
1.1250	0.0260			0.008			0.037			0.261			1.274	1.580	0.502
1.2500	0.0060			0.002			0.009			0.062			0.300	0.372	0.452

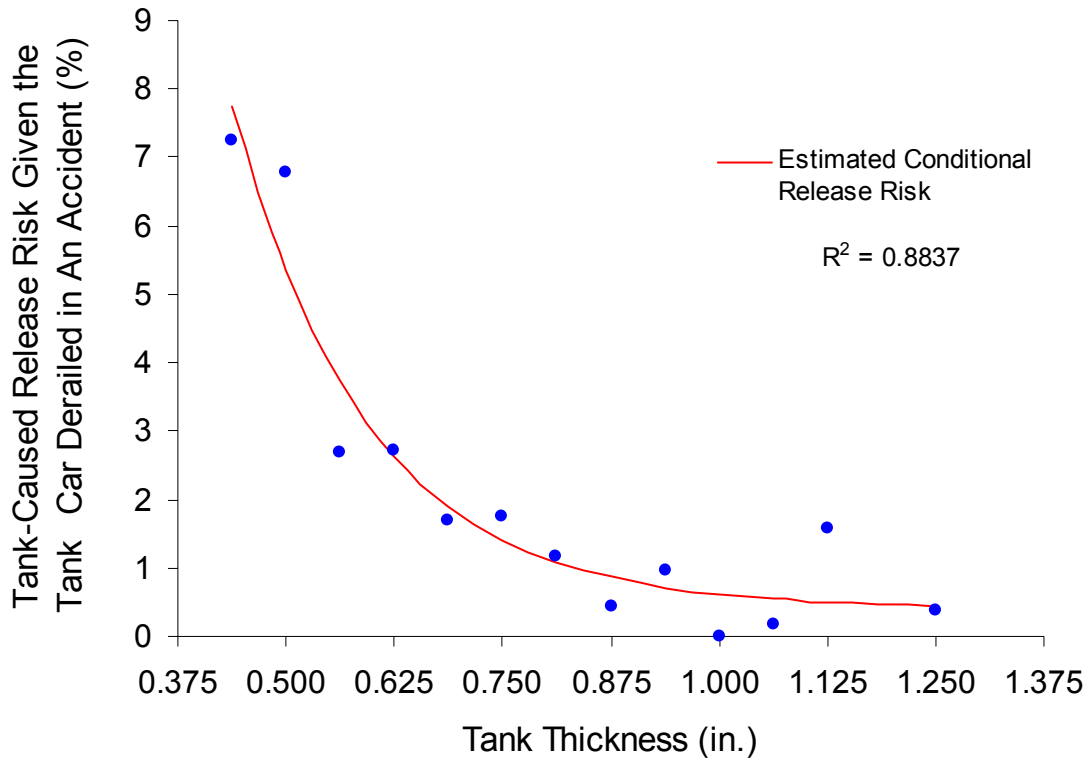


Figure 3.5 Conditional tank-caused release risk given a tank car is derailed or damaged in an accident as a function of tank thickness (t). Points represent data and line indicates regression function fitted to data.

The net tank-caused release risk is calculated by multiplying the conditional tank-caused release risk by the exposure terms, probability that a tank car will derail in an accident per car-mile, and number of car-miles. Using the fitted regression model above, tank-caused release risk as a function of tank thickness t can be modified as follows:

$$R_{TR}(t) = (v + we^{(-y t + z)}) P_A M \quad (\text{Equation 4})$$

3.3.2 Non-Tank-Caused Release Source

As mentioned above, non-tank-caused release risk does not depend on tank thickness.

The frequency of a release of size i can be defined as:

$$F_{NRi} = P_{NRi|A} Z \quad \text{(Equation 5)}$$

where:

F_{NRi} = frequency of non-tank-caused release of size i

$P_{NRi|A}$ = conditional probability of non-tank-caused release of size i given the car is derailed in an accident

$$= P_{Ri|NR} P_{NR|A}$$

where:

$P_{Ri|NR}$ = conditional probability of release size i given a non-tank-caused release occurrence

$P_{NR|A}$ = conditional probability of a non-tank-caused release occurrence given the car is derailed in an accident

Z is defined as above.

Thus, Equation 5 can be modified as follows:

$$F_{NRi} = P_{Ri|NR} P_{NR|A} P_A M \quad \text{(Equation 6)}$$

The associated release consequence for a non-tank-caused release of size i is defined as:

V_{NRi} = average percentage of tank capacity lost for release size i in a non-tank-caused release accident

The product of the associated frequency and consequence gives the non-tank-caused release risk:

$$R_{NR} = \sum_{i=1}^4 F_{NRi} V_{NRi}$$

Using the quantity lost data (Table 3.2), and holding the terms $P_{NR|A}$, P_A and M constant, the non-tank release risk can be simplified as follows:

$$R_{NR} = 32.125 P_{NR|A} P_A M \quad (\text{Equation 7})$$

Table 3.2 Tank Expected Non-Tank-Caused Release Quantity (Phillips et al. 1995)

<i>i</i>	Percentage Tank Contents			
	0 - 5	> 5 - 20	> 20 - 80	> 80 - 100
$P_{Ri NR}$	0.495	0.095	0.180	0.230
$V_{i,NR}$	2.5	12.5	50.0	90.0
$P_{Ri NR} V_{i,NR}$	1.2375	1.1875	9.0000	20.7000
V_{NR}	32.125			

3.3.3 Relationship between Tank Thickness, Tank Car Capacity, and Number of Shipments

The size of tank cars is generally optimized for the density of the specific product they are intended to transport (GATX 1994; UTC 1996). Products vary considerably in their density, and the size of a tank car is inversely related to the density of its intended product. The maximum weight of a loaded rail car is referred to as the Gross Rail Load (GRL). It consists of the car's empty weight plus the maximum lading weight. The empty or "light" weight of a car is the weight of the running gear and tank fittings, which are relatively constant, and weight of the tank itself, which varies with its size, thickness and whether or not it has a jacket and insulation.

Increasing the tank thickness to make a tank car more robust in an accident increases the weight of the tank. The maximum GRL for cars in unrestricted interchange is fixed, so the increase in the light weight due to the thicker tank reduces the capacity of the tank car.

Consequently, more shipments or car-miles are required to haul the same quantity of lading. The number of car-miles is directly proportional to tank thickness. Barkan et al. (2005) develop the variable “K” that is the proportional increase in the number of shipments required with respect to increased tank thickness. The term K is unique and tank-car specific as it depends on the volumetric capacity that corresponds to product density, the GRL, and the tank car light weight.

To illustrate the idea, consider a general-purpose DOT-111 tank car with a baseline thickness of 0.4375” and a capacity of 20,000 gallons. Using *IlliTank* (Saat 2003), a tank car size and weight program, the effect of increased tank thickness on the number of car-miles was calculated. The tank inside diameter and non-tank light weight constant were set at 110.25” and 33,000 lbs., respectively. The program solves the optimal tank size problem, and calculates the change in tank capacity for each tank thickness. For instance, for the baseline tank car used, an increase in 1/16th of an inch reduces the tank capacity by approximately 1%, and results in a corresponding increase in the number of shipments of about 1% (Table 3.3). In general the number of extra shipments is equal to $1/(1-p)$ times the baseline number of shipments, where p = the percentage reduction in tank capacity.

**Table 3.3 Effect of Increasing Tank Thickness on Tank Car Capacity and Number of Car-Miles
(K = 0.236)**

Tank Thickness (in.)	Nominal Lading (U.S. gallon)	Capacity Reduced	Number of Shipment	Proportion of Shipment Increased	Change in Tank Thickness
0.4375	20,000	0.00	1.00	0.00	0.00
0.5000	19,715	0.01	1.01	0.01	0.06
0.5625	19,437	0.03	1.03	0.03	0.13
0.6250	19,166	0.04	1.04	0.04	0.19
0.6875	18,902	0.05	1.06	0.06	0.25
0.7500	18,645	0.07	1.07	0.07	0.31
0.8125	18,394	0.08	1.09	0.09	0.38
0.8750	18,149	0.09	1.10	0.10	0.44
0.9375	17,909	0.10	1.12	0.12	0.50
1.0000	17,676	0.12	1.13	0.13	0.56
1.0625	17,447	0.13	1.15	0.15	0.63
1.1250	17,224	0.14	1.16	0.16	0.69
1.1875	17,006	0.15	1.18	0.18	0.75
1.2500	16,793	0.16	1.19	0.19	0.81
1.3125	16,585	0.17	1.21	0.21	0.88
1.3750	16,381	0.18	1.22	0.22	0.94
1.4375	16,182	0.19	1.24	0.24	1.00
1.5000	15,987	0.20	1.25	0.25	1.06

Car-miles are proportional to shipments, and thus tank thickness (Figure 3.6). Linear regression was used to calculate K, the proportion increase in shipments needed to compensate for the reduced capacity of a thicker but heavier tank. In the example above, $K = 0.236$ (Figure 3.6).

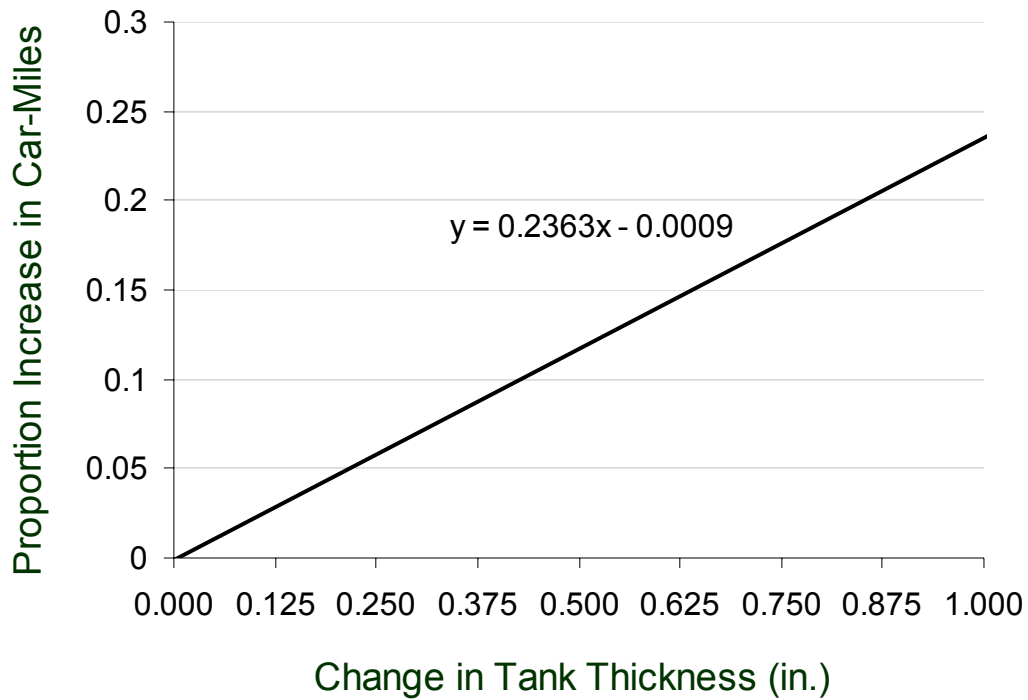


Figure 3.6 Increase in car-miles with respect to tank thickness for a 20,000 gallon, 263,000 lb. GRL non-insulated tank car.

The effect of increasing the number of car-miles is that the more robust tank car also has a correspondingly higher exposure to the chance of accident involvement. To account for the increased number of car-miles with respect to tank thickness t , the accident exposure term, Z , can be modified as follows:

$$Z(t) = P_A M [1+K(t-t')] \quad \text{(Equation 8)}$$

where:

t = tank thickness

t' = base tank thickness

K = proportion increase in shipments due to the change in tank thickness

Incorporating Equation 8 into Equations 4 and 7, the tank-caused release risk and non-tank-caused release risk with respect to tank thickness, t can be rewritten as follows:

$$R_{TR}(t) = [v + we^{(-y t + z)}] P_A M [1+K(t-t')] \quad (\text{Equation 9})$$

$$R_{NR}(t) = 32.125 P_{NR|A} P_A M [1+K(t-t')] \quad (\text{Equation 10})$$

The sum of $R_{TR}(t)$ and $R_{NR}(t)$ is the net release risk for a tank car in percentage of tank capacity lost with respect to tank thickness t :

$$R_R(t) = [P_A M (1+K(t-t'))] [[v + we^{(-y t + z)}] + 32.125 P_{NR|A}] \quad (\text{Equation 11})$$

3.3.4 Relationship between Tank Thickness, Tank Car Capacity, and Expected Quantity of Release

In addition to the tradeoff between reduced release probability and increased accident exposure with increased tank thickness as discussed above, the reduction in expected quantity lost due to the reduced volumetric capacity is also a factor to be considered. The lower volume of heavier and thus smaller tanks reduces risk from both tank- and non-tank caused releases because tank cars with lower capacity have less quantity to release. In Barkan et al. (2005)'s formulation of the tank car thickness optimality model, they considered probability of release. In the following section, we consider the effect of modification of this model using minimization of quantity released as the objective function, and focus on the effect this has on optimal tank thickness.

3.4 Evaluating Risk Reduction with Increasing Tank Thickness

The release risk model presented so far estimates the percentage of tank capacity lost for a tank car derailed in an accident. When comparing the risk between tank cars that have different tank thicknesses, the absolute release quantity, in terms of volume or mass, should be calculated. As noted above, *ceteris paribus*, thicker tank cars have lower capacities. As such, for tank cars with different safety designs, an identical release risk in terms of percent tank capacity corresponds to different absolute quantities of release. The expected gallon capacity lost can be calculated as follows:

$Q_R(t)$ = expected gallon capacity lost for a tank car with tank thickness t

n = number of tank- or non-tank release sources considered

$R_j(t)$ = release risk from source j in percentage of tank capacity lost with tank thickness t

$Cap(t)$ = gallon capacity for a tank car with tank thickness t

The corresponding mass of material expected to be released for a specific chemical can be calculated using its density.

3.4.1 Example Risk Reduction Calculation with Increasing Tank Thickness

Barkan et al. (2005) developed a model in which minimization of release probability was the objective function. The tank-caused probability of release was a negative exponential function, as is the case here, and the non-tank-caused release probability was a monotonically increasing linear function (Figure 3.7). Therefore, the benefit of having a thicker tank represented by the decreasing probability of a tank-caused release, $P_{TR}(t)$ was offset by the

increase in non-tank caused probability of release, $P_{NR}(t)$. They found that there was an optimal tank thickness, t^* , when release probability, $P_R(t)$ was minimized.

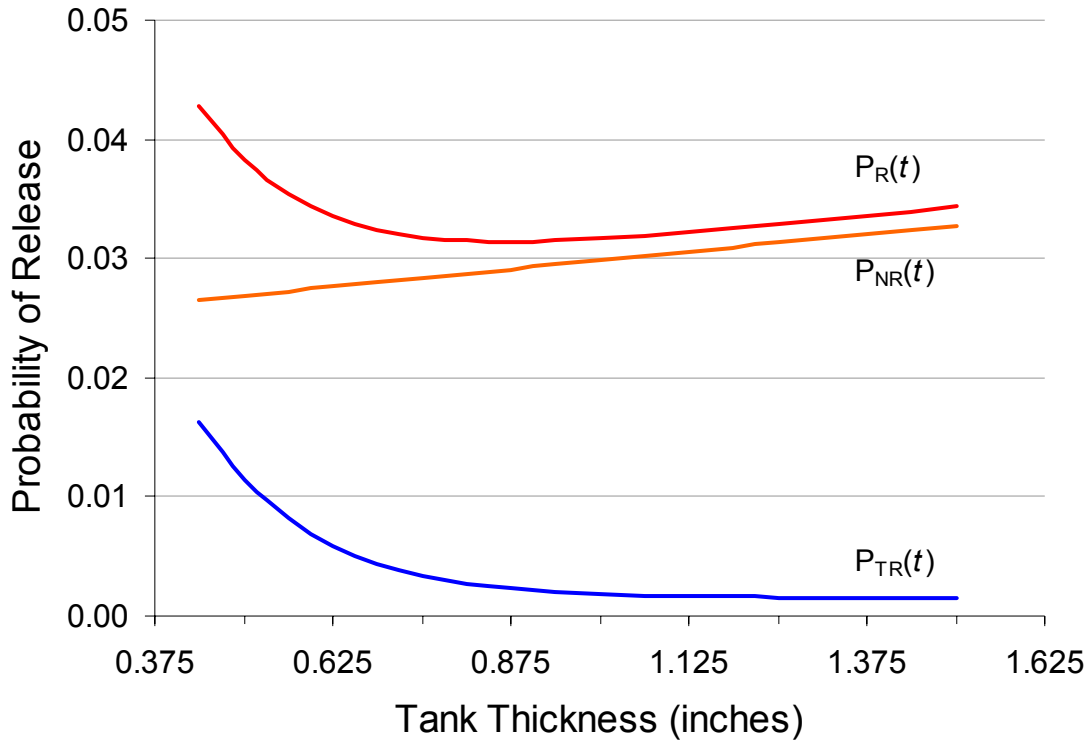


Figure 3.7 The probabilities $P_R(t)$, $P_{NR}(t)$, and $P_{TR}(t)$ as a function of tank thickness (t), per million car-miles (Barkan et al. 2005).

We considered the same 20,000 gallon, non-insulated tank car with $K = 0.236$ using minimization of $Q_R(t)$ as the objective function. The average railcar derailment rate per car-mile, P_A , used was 1.28×10^{-7} (Anderson & Barkan 2004) and a baseline of one million car-miles (M). For the non-tank-caused release risk calculation, the conditional probability of release given a tank car derailed in an accident is constant, $P_{NR|A} = 0.207$ (Phillips et al. 1995).

The baseline tank thickness, t' , is 0.4375", and release risk and expected gallon capacities lost from the tank- and non-tank-components were evaluated with respect to increased t in 1/16th inch increments (Table 3.4). We used the model to calculate the expected quantity lost from the

tank- and non-tank-components (Figures 3.8 and 3.9). The scale of the ordinate is different in Figures 3.8 and 3.9 to emphasize the change in sign of the slope for the non-tank quantity lost.

The same data, along with the sum of the two sources are shown in Figures 3.10.

Table 3.4 Calculated Values for the Tank-Caused, Non-Tank-Caused and Total Release Risks and Expected Gallon Capacities Lost (K=0.236)

t, in.	R _{TR} (t), % Tank Capacity	R _{NR} (t), % Tank Capacity	R _R (t), % Tank Capacity	Cap(t), Gallon	Q _{TR} (t), Gallon	Q _{NR} (t), Gallon	Q _R (t), Gallon
0.4375	0.99	0.85	1.84	20,000	198.39	170.24	368.63
0.5000	0.69	0.86	1.56	19,715	136.84	170.30	307.14
0.5625	0.49	0.88	1.37	19,437	95.45	170.35	265.80
0.6250	0.35	0.89	1.24	19,166	67.62	170.39	238.01
0.6875	0.26	0.90	1.16	18,902	48.90	170.43	219.33
0.7500	0.19	0.91	1.11	18,645	36.32	170.46	206.78
0.8125	0.15	0.93	1.08	18,394	27.86	170.48	198.34
0.8750	0.12	0.94	1.06	18,149	22.17	170.49	192.67
0.9375	0.10	0.95	1.05	17,909	18.35	170.51	188.85
1.0000	0.09	0.96	1.05	17,676	15.77	170.51	186.28
1.0625	0.08	0.98	1.06	17,447	14.05	170.51	184.55
1.1250	0.07	0.99	1.06	17,224	12.88	170.50	183.38
1.1875	0.07	1.00	1.07	17,006	12.10	170.49	182.59
1.2500	0.07	1.02	1.08	16,793	11.57	170.47	182.04
1.3125	0.07	1.03	1.10	16,585	11.22	170.44	181.66
1.3750	0.07	1.04	1.11	16,381	10.98	170.41	181.39
1.4375	0.07	1.05	1.12	16,182	10.82	170.38	181.20
1.5000	0.07	1.07	1.13	15,987	10.71	170.34	181.05
1.5625	0.07	1.08	1.15	15,796	10.63	170.30	180.93
1.6250	0.07	1.09	1.16	15,609	10.58	170.25	180.83
1.6875	0.07	1.10	1.17	15,425	10.55	170.20	180.74
1.7500	0.07	1.12	1.18	15,246	10.52	170.14	180.66
1.8125	0.07	1.13	1.20	15,070	10.50	170.08	180.58
1.8750	0.07	1.14	1.21	14,898	10.49	170.01	180.50
1.9375	0.07	1.15	1.22	14,729	10.48	169.94	180.42
2.0000	0.07	1.17	1.24	14,563	10.47	169.87	180.34

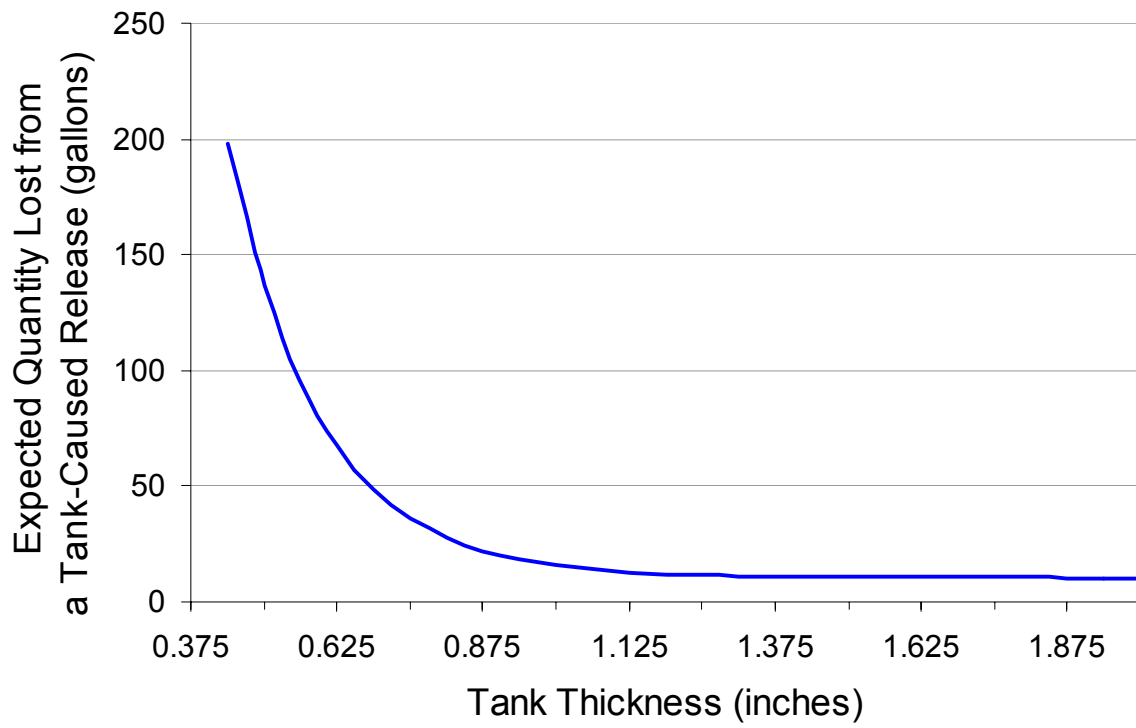


Figure 3.8 The expected quantity lost from a tank-caused release $Q_{TR}(t)$, as a function of tank thickness (t), per million car-miles.

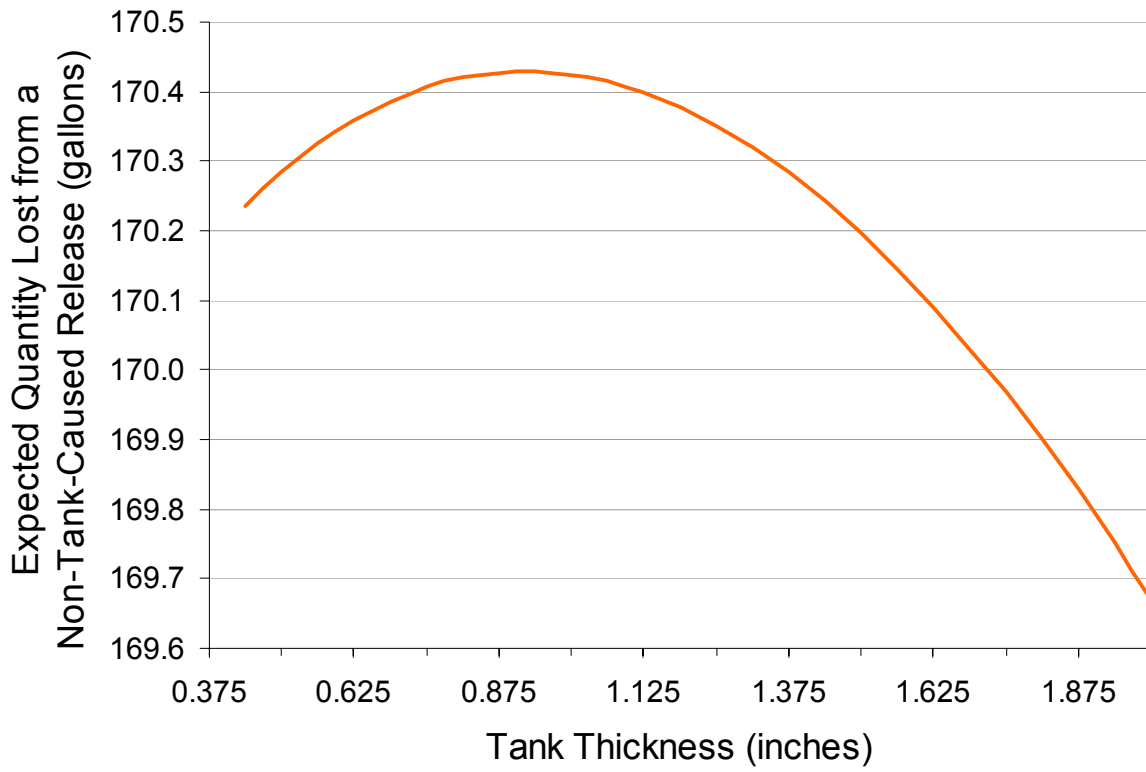


Figure 3.9 The expected quantity lost from a non-tank-caused release $Q_{NR}(t)$, as a function of tank thickness (t), per million car-miles.

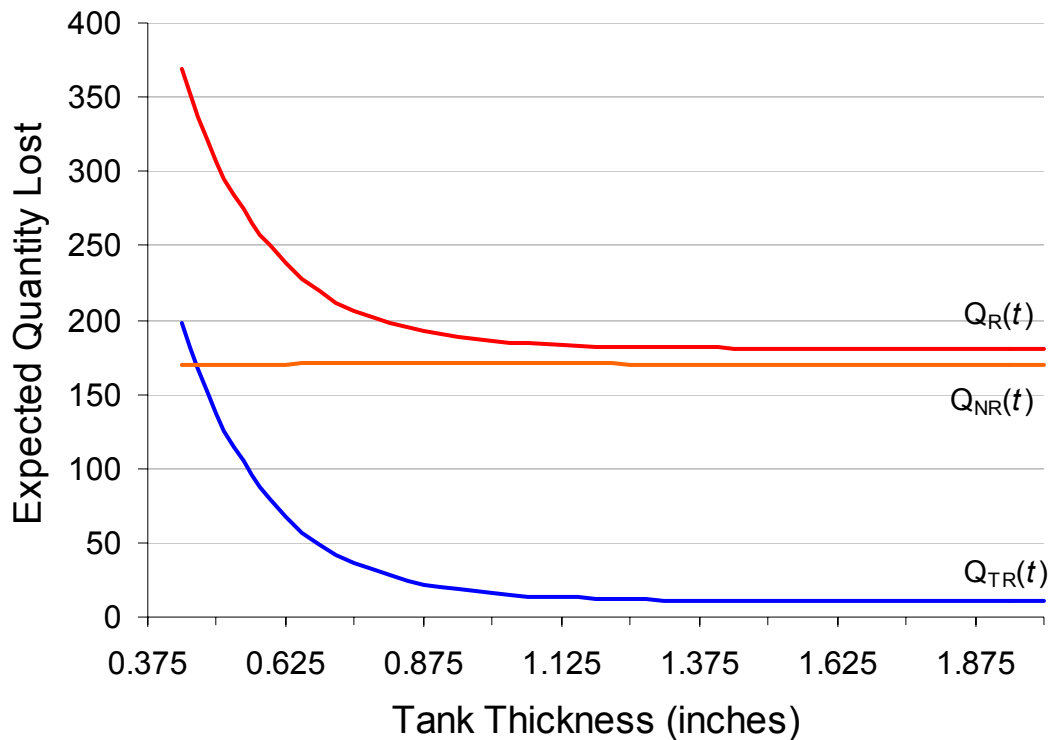


Figure 3.10 The expected gallons lost $Q_R(t)$, $Q_{TR}(t)$ and $Q_{NR}(t)$, as a function of tank thickness (t), per million car-miles.

For tank-caused releases, the safety benefit from increased tank thickness, due to both increased damage resistance and decreased capacity available to be released, dominate the incremental risk due to the increase in accident exposure over the entire range of tank thicknesses considered. As described above, the expected quantity lost from tank-caused releases follows a negative exponential distribution. Increasing the tank thickness provides no direct safety benefit in terms of improving non-tank components' damage resistance, but there is a reduction in their release risk due to the reduced capacity of the tank. The relationship between t and $Q_{NR}(t)$ is a concave function (Figure 3.9). There is an initial increase in the expected quantity released because of the increased exposure to accidents due to the decreased capacity. However, this is counteracted by the decline in the quantity available to be released as t increases. This

contrasts with the monotonically increasing function for $P_{NR}(t)$ in Barkan et al. (2005), and therefore does not have the same offsetting effect.

When minimization of expected quantity released is used as the objective function to optimize tank car thickness, there is no optima within the range of the tank thicknesses considered. Despite the initial positive slope of $Q_{NR}(t)$, $Q_{TR}(t)$ always dominates the overall release risk function (Figures 3.10). As such, $Q_R(t)$, is a continuously declining function of tank thickness over the range of thicknesses evaluated.

The contrast between the results of these two approaches is not intended to suggest that one is better than the other. Rather, they provide a framework that can be used depending on whether the objective is minimization of release probability, or minimization of expected quantity released. Either one may be appropriate depending on the characteristics of the particular hazardous material and the potential consequences of a spill.

3.5 Discussion & Conclusions

The metric release risk is potentially useful for assessing the benefit from changes in tank car safety design because unlike previous analyses, it simultaneously considers both release probability and release amount. The distribution of release quantity is not independent of the source of damage-caused leaks on tank cars in accidents, consequently changes in design will have different potential benefits in terms of risk reduction. In this paper we explore the implications of this with respect to one option for enhancing tank car safety, modification of tank thickness.

The analysis here indicates that reducing release risk may be accomplished by constructing tank cars with tanks that are thicker than is typical of most cars in service. However, tank cars constructed in this manner would be considerably more expensive to build and operate and the resultant reduction in risk would often not be justified. All regulated materials are not equally hazardous and in general, tank car safety specifications, including tank thickness, are commensurate with the degree of risk posed by the product.

The model presented here focuses on releases from tank and non-tank components. A more refined approach is being developed that will differentiate the head and shell elements of tank-caused release risk, and the top and bottom fittings in non-tank-caused release risk. The resultant metric can be used to analyze the effectiveness of each safety feature alone or in combination. Such analyses can ultimately be used in conjunction with the differential capital and operating costs associated with different tank car modifications, and the hazard characteristics of the products they transport, to enable tank car designs to be finely tuned to efficiently balance risk and cost.

CHAPTER 4

FUTURE WORK

4.0 Introduction

In this chapter I discuss some of the limitations of the work presented in Chapters 2 and 3 and briefly consider some future research needs and directions in the area of hazardous materials transportation safety. More detailed attention is given to the release risk work and efforts to improve tank car safety design as discussed in Chapter 3. This reflects the focus of my current research and the intended direction of my doctoral research.

4.1 Surge Pressure Reduction Devices' Performance Evaluation

The analyses discussed in Chapter 2 are based on a small data set for each SPRD from the full-scale tank car impact tests conducted in 1997. The objective of a performance-based standard is a desirable approach to evaluate the acceptability of SPRDs for service on tank cars. Ideally the standard would be developed from a statistically robust set of data from experiments that accurately mimic the physical environment tank cars experience. However, the cost of such testing is high. The experiments that produced the data analyzed in Chapter 2 cost well over \$100,000 to conduct. Furthermore, this approach requires a substantial, specialized, test facility. Full-scale testing has other limitations besides its high cost. As is evident in Chapter 2 there is

still a great deal of variability in the data collected, thereby requiring more tests in order to attain a satisfactory degree of confidence than would otherwise be necessary if the conditions inside a safety vent nozzle could be better controlled. Also, in order to achieve the high surge pressures that are the objective of the test, relatively high impact speeds were required. The resultant loads on the car approached the limit of what was likely to cause damage and still yielded a relatively small number of critically high surge pressure events.

Consequently, alternative approaches that enable more accurate and controlled simulation of surge pressure events in a tank car safety vent are preferable. Two such alternatives include development of a test stand and computer modeling.

- 1) Development of a system to mimic the physical conditions inside a tank car safety vent is a possible approach. However, this has been attempted and after extensive design and testing effort by the AAR and RSI, they were unable to develop an apparatus that reliably produced surge pressures comparable to those measured in the full scale tests (Treichel et al. 2004). Nevertheless, the concept is valid and further work could yield a satisfactory system, particularly with the benefit of knowledge that could be gained from a computer simulation model as described below.
- 2) A fluid dynamics model of the processes that occur within the tank car safety vent nozzle and SPRD could be developed. With proper validation of its accuracy it might be able to be used to evaluate current and future designs of SPRDs to determine the adequacy of their performance. An added benefit of this approach compared to purely experimental approaches is that it would facilitate understanding of the processes involved and thereby provide useful information on new, more effective SPRD designs.

4.2 Railroad Tank Car Safety Design and Risk

The release risk model presented in Chapter 3 focused specifically on releases from tank and non-tank components. The next logical step is to develop a more general model for optimizing tank car safety design. Such a model would differentiate between each of the principal safety elements of the tank car, specifically the head and shell elements for tank-caused releases, and the top and bottom fittings for non-tank-causes. Such a model could be used to analyze the effectiveness of each safety feature alone or in combination. Different tank car safety designs could then be compared with regard to a variety of optimization objectives, such as minimization of release probability or release risk, while also taking into account constraints such as weight, cost and product hazard. Analysis of tank car design features is part of a larger picture that involves a variety of interesting and important questions regarding hazardous materials transportation risk.

4.2.1 Costs and Risk

Analyses such as the ones described above could be used in conjunction with the differential capital and operating costs associated with different tank car modifications. For example, a tank car with a thicker shell requires more steel to manufacture and incurs higher material cost. A better understanding of tank car elemental cost distribution, such as material, equipment, labor and mark-up, is needed for a refined cost model. The challenge facing this approach is that this information is usually confidential and different for each tank car manufacturer.

Anand et al. (2005) used AAR data to estimate the incremental capital costs of different designs of tank car and the Surface Transportation Board's costed waybill data to estimate the operating cost of rail transport of chemicals. These values can be used to estimate the change in operating cost due to different numbers of shipments for different tank car designs. However, the STB costs do not fully account for the liability due to risk of a hazardous material spill. These risks can be substantial and may dramatically affect the economic viability of transportation of some hazardous materials. The release risk metric estimates the expected quantity of release due to transportation and can be combined with the hazard characteristics of a product and the probability distribution of spill site characteristics to determine the severity of the risk. Railroads, hazardous materials shippers, and tank car owners and lessors, all need to better understand the interplay between the various factors involved in order to make informed, rational decisions on a variety of questions about tank car design and railroad operating practices. There are a number of important questions or refinements that have a significant bearing on engineering decisions and public policy regarding hazardous materials transportation safety and risk.

4.2.2 Routing

An option for managing risk that is receiving a great deal of attention is rerouting of certain hazardous materials around some high-density population areas. However, there are substantial questions about the efficacy of this approach and a risk analysis of this practice would be timely. Important elements to consider are population density and the likelihood of accident for the primary and alternate routes. In general, avoiding high population areas will lengthen the route. This may or may not reduce the potential human exposure, but it will increase car miles

and thus exposure to accident. As such, it is important to quantitatively understand the tradeoffs and properly account for all of the pertinent variables.

4.2.3 Tank Car Design and Performance

There are several aspects to tank car design and performance in accidents that warrant further investigation, particularly in light of recent accidents. One aspect is consideration of different assumptions about quantity lost from tank cars in accidents. The work described here used statistical analysis of data from accidents and assumed that quantity lost was proportional to the size of the car. This may be the case for some forms of release but will probably not be for others. Related to this is the rate at which product is lost after a car has been damaged. For example if a tank car fails due to brittle fracture it can result in an almost instantaneous release of nearly all of a car's contents, whereas a serious ductile failure may also lead to the loss of an entire carload, but over a longer time span. These two scenarios may have different implications in terms of the hazard posed by the release.

In the event of a release, the dispersion characteristics of a product depend on its physical properties and the ambient conditions of the environment into which it is spilled. There are a number of quantitative models developed to calculate atmospheric dispersion, toxicity and the consequent impact of a release event. However, it is unclear how well they account for mitigating factors such as shelter-in-place. A related issue is to integrate the level of community preparedness and incident management in determining the severity of a hazardous material spill.

With regard to tank car safety design analyses, better understanding of the accident performance of all different types of cars in service would reduce the uncertainty of risk analyses for certain hazardous materials. For example, although tank-puncture resistance and performance is well understood for carbon steel tank cars (Phillips et al. 1995), comparable analysis is needed to understand the performance of aluminum and stainless steel tank cars.

4.3 Conclusions

Ultimately, the goal of future research should be to determine the optimal strategies or policies that maximize the safe and efficient transportation of hazardous materials. The safety benefit of a more robust tank car can be estimated based on the number of fatalities, injuries, evacuations, property damage and environmental impact that could be avoided as a result of various changes in design or operating practice. This raises the issue of how to consider the tradeoff between the incremental costs of a more robust tank car design and the reduction in risk. A multi-attribute normative decision analysis approach could be developed to model the tradeoff by incorporating risk tolerance and risk preference of parties involved.

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