Statistical Approach to Estimating Surge Pressure Reduction Devices' Performance

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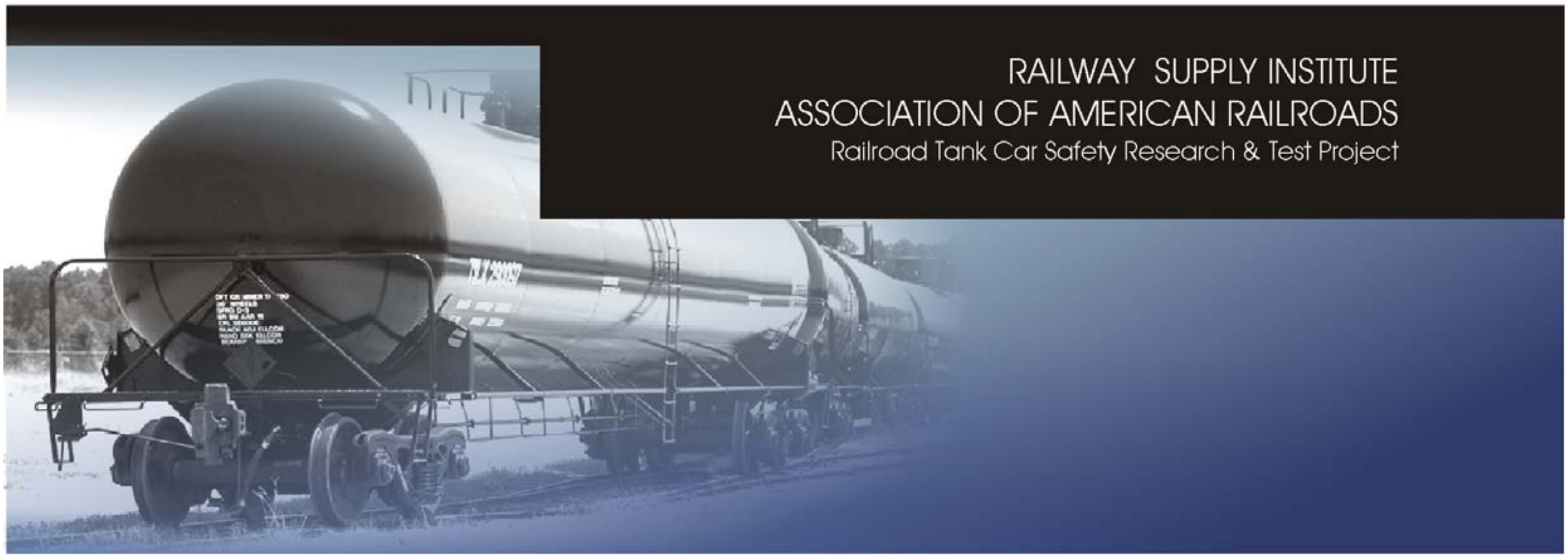

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13. ABSTRACT
Using data from a set of full-scale tank car impact tests conducted in 1997, new statistical approaches were applied in order to characterize the performance of a set of tank car pressure relief device surge pressure reduction devices (SPRDs) for pressure relief devices. The results enable the reader to better compare the SPRDs' ability to prevent high-pressure surges, to estimate the number of hazardous materials releases each would prevent given a number of trips, and to understand the effect of a design characteristic called the Damiani Ratio on SPRD performance.

Previous analyses of the 1997 tests were focused on comparing the average pressure peak allowed by SPRDs. However, the average pressure peak will generally not lead to a Non Accident Release (NAR). The probability of a peak of sufficient magnitude to exceed the 165 psi burst pressure of the typical rupture disc is a more appropriate measure of an SPRD's performance. In this report, we develop a new analytical technique that produces estimated probabilities of pressure surges peaking above 165 psi, 132 psi and 100 psi. These probability estimates are then used to estimate the number of NARs per 1,000 trips that each SPRD would be expected to allow with a 165 psi burst pressure. Finally, the SPRDs' estimated performance is compared to their Damiani Ratios, a calculation based on certain dimensional characteristics of the SPRD and known to be strongly correlated to average peak pressure allowed.

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EXECUTIVE SUMMARY

Using data from a set of full-scale tank car impact tests conducted in 1997, new statistical approaches were applied in this study in order to characterize the performance of a set of tank car surge pressure reduction devices (SPRDs) for pressure relief devices. The results enable the reader to compare the SPRDs' ability to prevent high-pressure surges, to estimate the number of hazardous materials releases each would prevent given a number of trips, and to understand the effect of a design characteristic called the Damiani Ratio on SPRD performance.

SPRDs are designed to prevent hazardous materials releases that are caused by transient pressure peaks within a tank car's pressure relief device nozzle during transportation. Non-reclosing pressure relief vents feature a rupture disc designed to burst at a specified pressure to preserve the tank in the case of a fire. However, a transient peak also can burst the disc, leaving the vent open for the remainder of the trip, causing a non-accident release (NAR) of the hazardous materials in the car.

The Association of American Railroads (AAR) Tank Car Committee has required all new tank cars with non-reclosing pressure relief vents to have SPRDs since 1994. SPRDs, as a group, are significantly effective at preventing hazardous materials releases from these vents, and therefore this action, combined with changes to the federal regulations that allowed higher start-to-discharge pressure thresholds in pressure relief devices, led to a significant decline in pressure relief vent NARs. However, there still were dozens of such releases annually, and few data available to allow comparison of the various SPRDs available, or to allow the Tank Car Committee to consider setting performance standards for SPRDs.

Previous analyses of the 1997 tests were focused on comparing the average pressure peak allowed by SPRDs. However, the average pressure peak will generally not lead to an NAR. The probability of a peak of sufficient magnitude to exceed the 165 psi burst pressure of the typical rupture disc is a more appropriate measure of an SPRD's performance. In this report, we develop a new analytical technique that produces estimated probabilities of pressure surges peaking above 165 psi, 132 psi and 100 psi. These probability estimates are then used to estimate the number of NARs per 1,000 trips that each SPRD would be expected to allow with a 165 psi burst pressure. Finally, the SPRDs' estimated performance is compared to their Damiani Ratios, a calculation based on certain dimensional characteristics of the SPRD and known to be strongly correlated to average peak pressure allowed.

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1.0 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 often (Figure 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 (Ref. 1). Even small quantity releases may cause injuries and property and environmental damage. Furthermore, the occurrence of an NAR disrupts shipment, interferes with railroad transportation operations, and is inconsistent with industry and government objectives of safe and reliable transportation of hazardous materials.

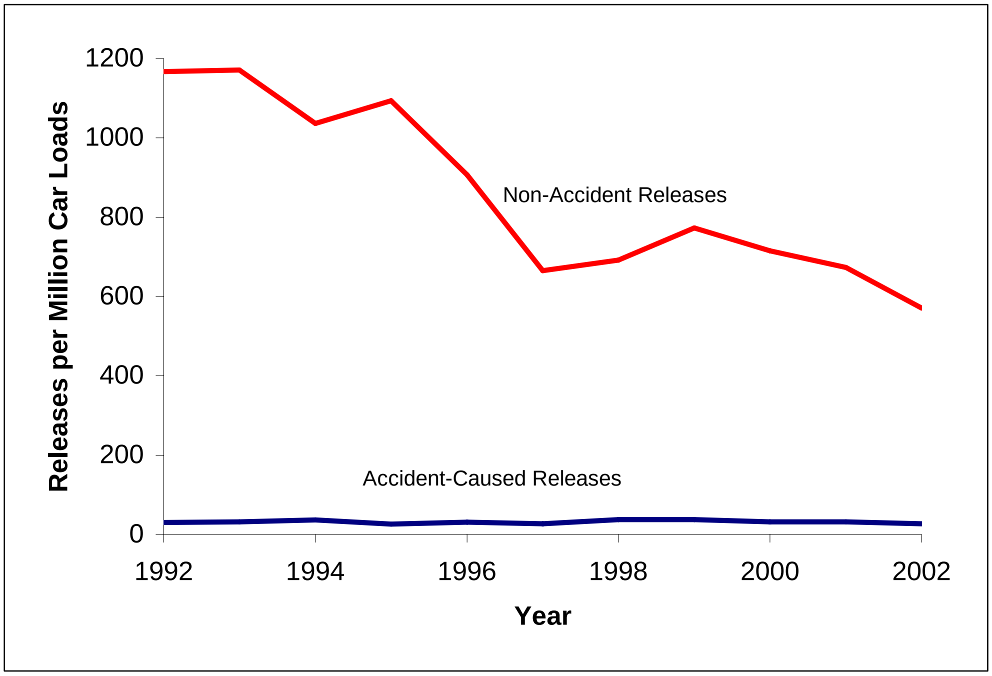

Figure 1. Releases per Million Carloads (Ref. 2)

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 (Ref. 2). Subsequently, the Non-Accident Release Risk Index (NARRI) was developed as a metric for assessing NAR severity (Ref. 3) 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 NARs. Until the late 1990s, the most frequent cause of NARs was from tank car pressure relief vents (Figure 2a).

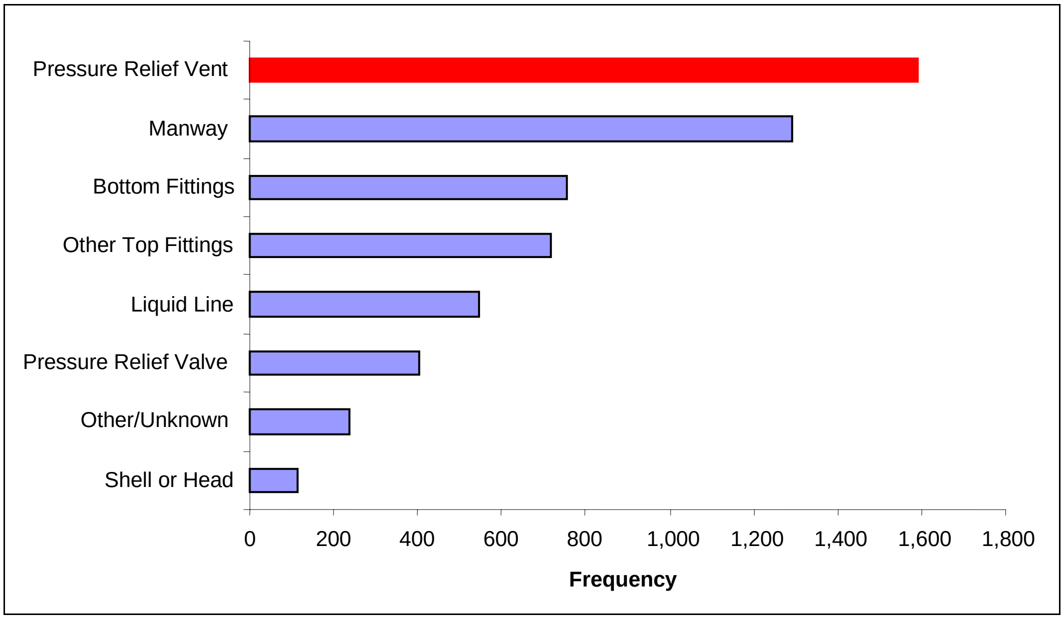

Figure 2a. Sources of Non-Accident Caused Releases from Railroad Tank Cars, 1992-1996 (Ref. 2)

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 reclosable 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. If undetected, the broken disk allows fumes to escape and liquid to spill during transportation, and thus represents an NAR (Ref. 4).

NARs caused by releases from pressure relief vents, have been reduced significantly since the 1990s (Figures 2b and 3). This is the result of several measures taken by government and industry, such as the implementation of pressure relief vent surge pressure reduction devices (SPRDs) for tank cars in federal hazard Class 8 (corrosive material) service (Ref. 2). 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 (Ref. 4). 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.

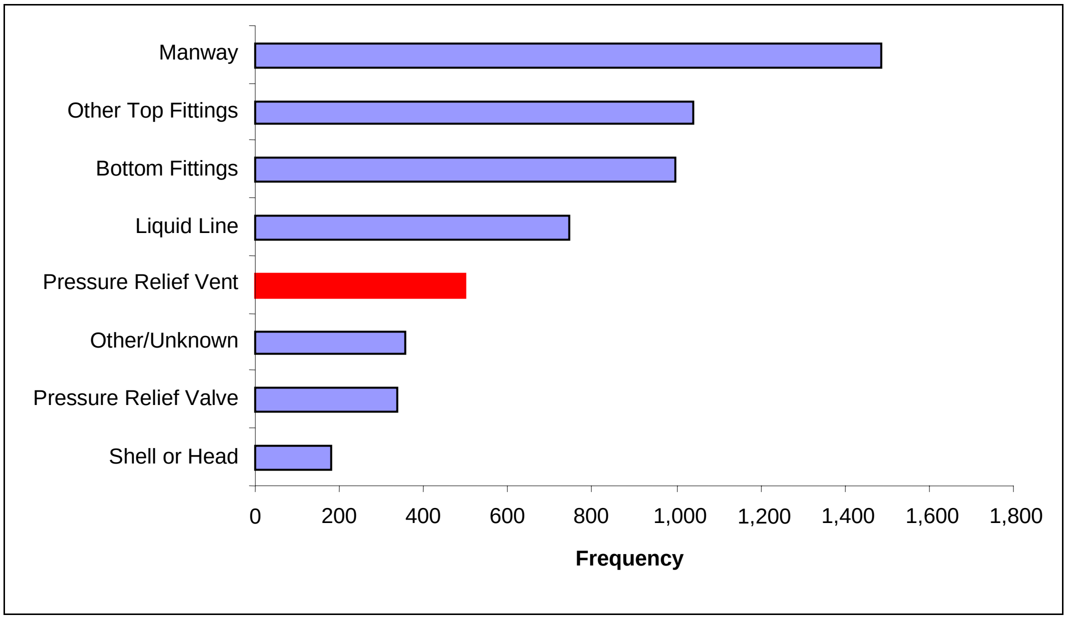

Figure 2b. Sources of Non-Accident Caused Releases from Railroad Tank Cars, 1997-2002 (Ref. 2)

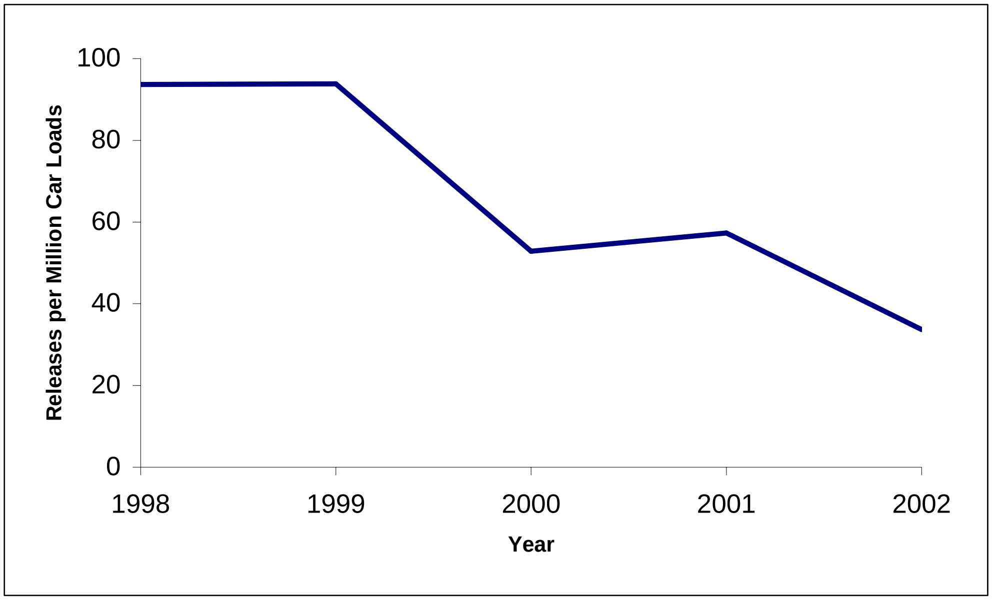

Figure 3. NARs per Million Carloads from Pressure Relief Vents

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 (Ref. 5).

Full-scale impact tests were conducted at ACF Industries' test ramp in St. Charles, Missouri, on SPRDs for three nozzle diameters; 2, 3, and 6.5 inches (Table 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 in the test. Up to 30 impacts were conducted for each control condition and at least 10 impacts were conducted for each SPRD (Ref. 4). 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 approximately 1,000,000 foot-pounds (ft-lbs) were generated, the fill level in the car was 99.5 percent, and the vent nozzles were mounted midway between the center and the end of the tank.

Table 1. Impact Test Matrix for SPRDs and Nozzle Diameter (Ref. 4)

Device	Nozzle Diameter		
	2 inch	3 inch	6.5 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.

2.0 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 percent of the tank burst pressure. For DOT-111 general-purpose tank cars, this corresponds to a peak pressure of 165 psi. The peak pressure for each impact test is the highest pressure sustained for one or more milliseconds. The 1-millisecond interval was selected because previous testing suggested that frangible disks survive pressure higher than their rated burst pressure if the exposure lasts less than 1 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. (Ref. 5) in the previous test found that all SPRDs resulted in average peak pressures below 165 psi (Figure 4) in the impact tests.

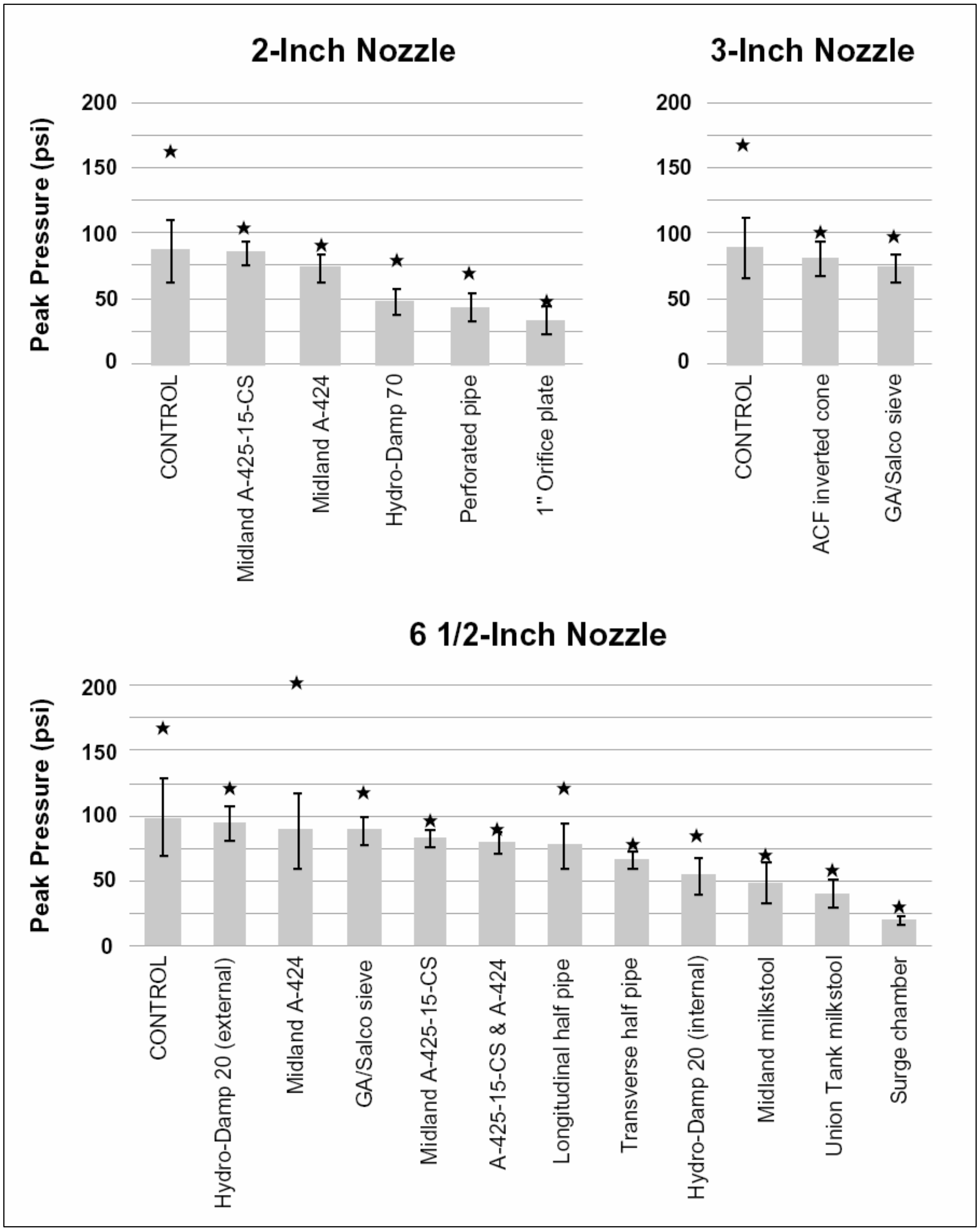

Figure 4. Histograms Showing the Effect of SPRDs on Peak Pressure in 2 inch, 3 inch, and 6.5 inch Nozzle-Diameter Pressure Relief Vent Nozzles (Ref. 5) (Error bars indicate one standard deviation above and below the mean. Asterisks indicate the highest peak pressure observed for the specified condition)

Although the mean peak pressures recorded were well below 165 psi peak pressure limit, 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 perfomance, and thus would be less effective in preventing NARs. Figure 5 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 5).

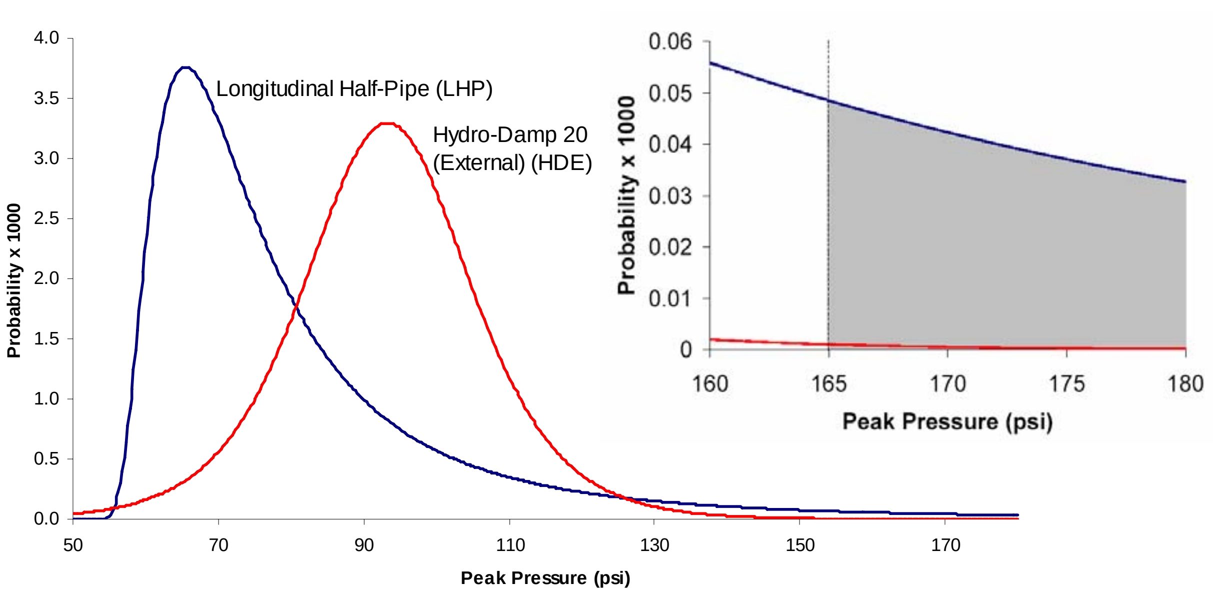

Figure 5. Representative Probability Densities of the Pressure in the 6.5 inch Pressure Relief Vent Nozzle for Two Different SPRDs

[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.

In general, each SPRD was tested 10 times (Ref. 4). 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.

3.0 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.

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 6). 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 in Equation 1:

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

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,…D, and

D = number of acceptable distributions.

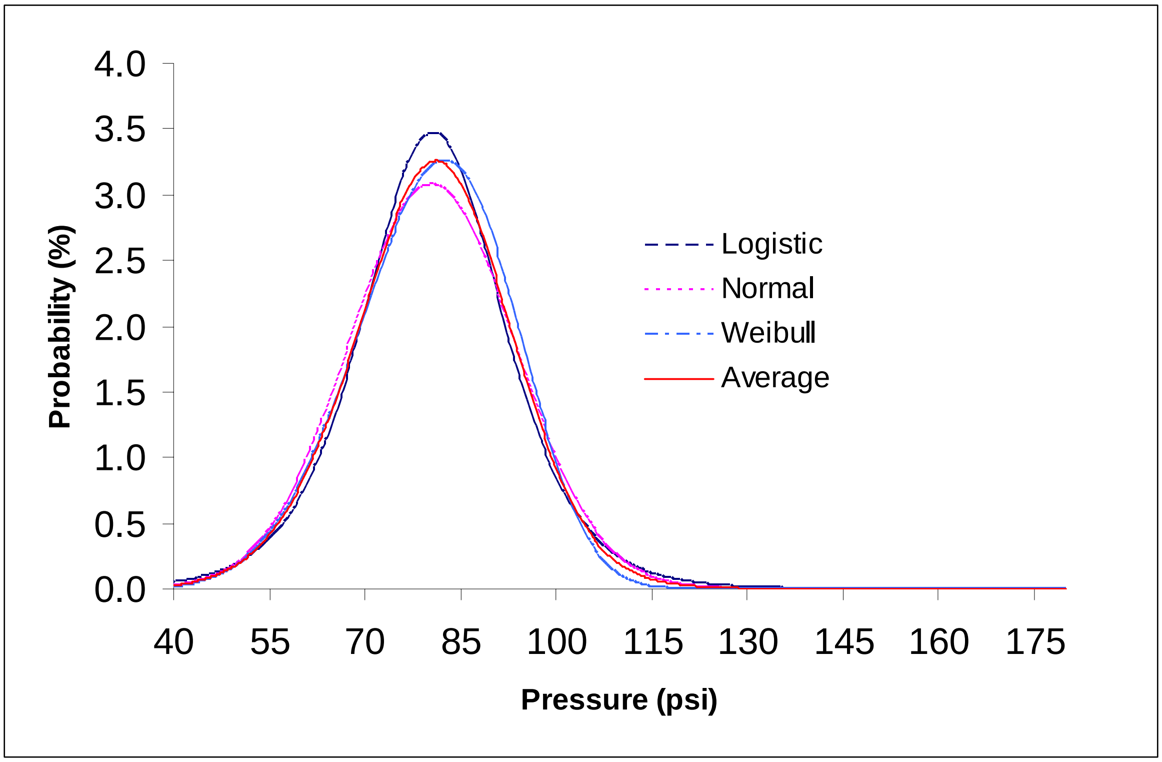

Figure 6. FDAM Illustration for ACF Inverted Cone for 3-inch Nozzle Diameter

5.0 ANALYSIS PROCEDURES

Initially, data for each SPRD were exported to Palisade's BestFit™ software to determine relevant distributions that may fit the data (Ref. 6). 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 7).

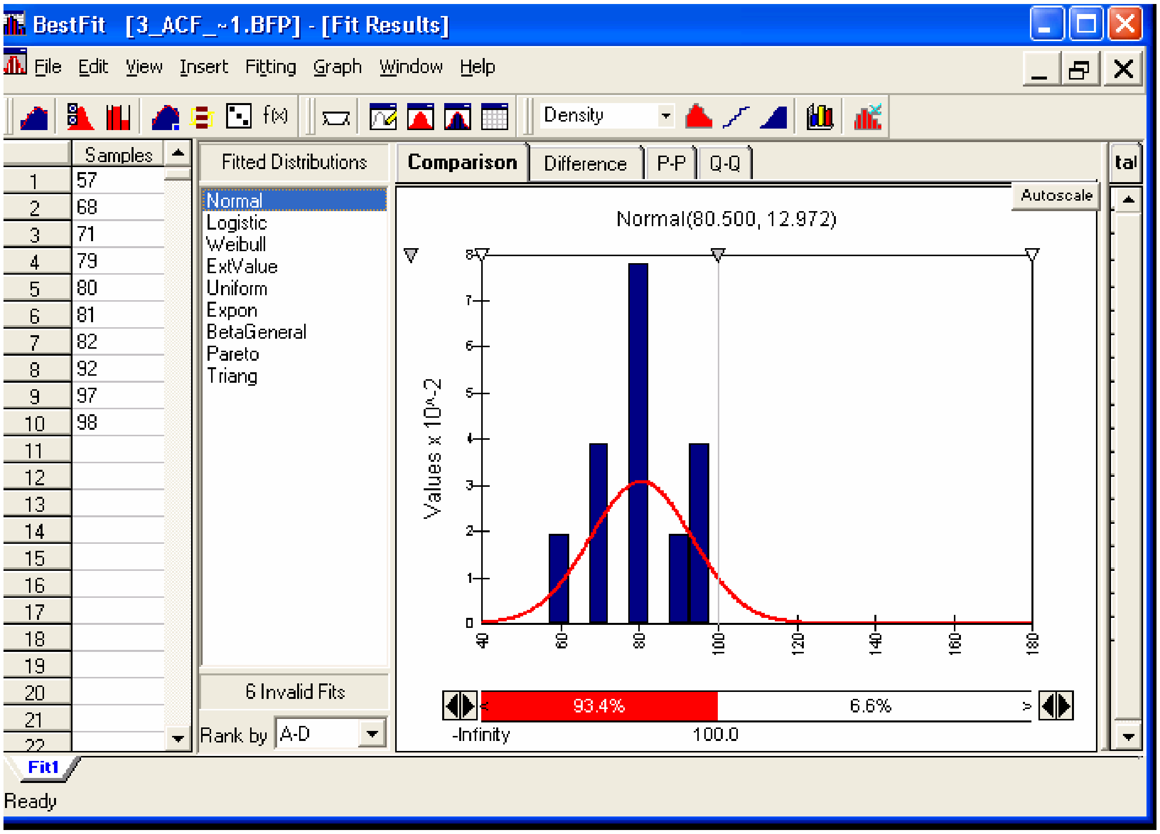

Figure 7. BestFit™ was Used to Determine Relevant Distributions from Peak Pressure Data for Each SPRD-Nozzle Combination (data shown are for the 3-inch nozzle-diameter ACF Inverted Cone)

The relevant distributions were then tested using NIST's Dataplot™ – a software system for scientific visualization, statistical analysis, and non-linear modeling (Ref. 7). 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 percent confidence level, which is 0.683 (Figure 8). 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™.

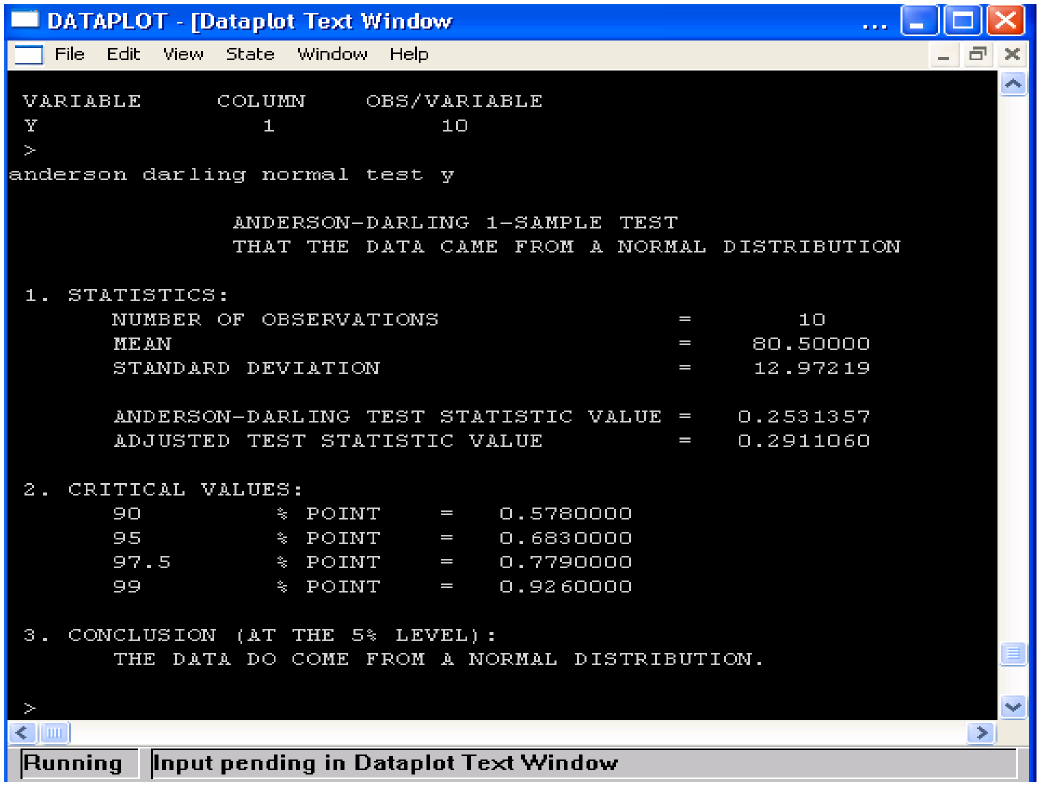

Figure 8. Screenshot from Dataplot™ Showing Results of a Test of an SPRD's Data's Fit to a Normal Distribution

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 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-form 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.

The limited sample size for each SPRD and the need to extrapolate to pressures of interest do incur uncertainty in the results, which should not be discounted. This is unavoidable given the available data. Nevertheless, this report offers the most comprehensive analysis that has been prepared for assessing SPRD performance.

6.0 RESULTS

6.1 The 2-Inch Diameter Nozzle

Table 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 (that is, control experiments). Note that 100 percent improvement is approximate; there is at least some very small probability of a high peak surge with all SPRDs. Figures 9a, b, and c 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-Inch Nozzle-Diameter SPRDs' Estimated Performance

SPRD	Estimated Probability Percent (%) of Exceeding Specified Pressure Thresholds Given One Surge Event					
	100 psi		132 psi		165 psi	
	Average	Percent Improvement	Average	Percent Improvement	Average	Percent 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

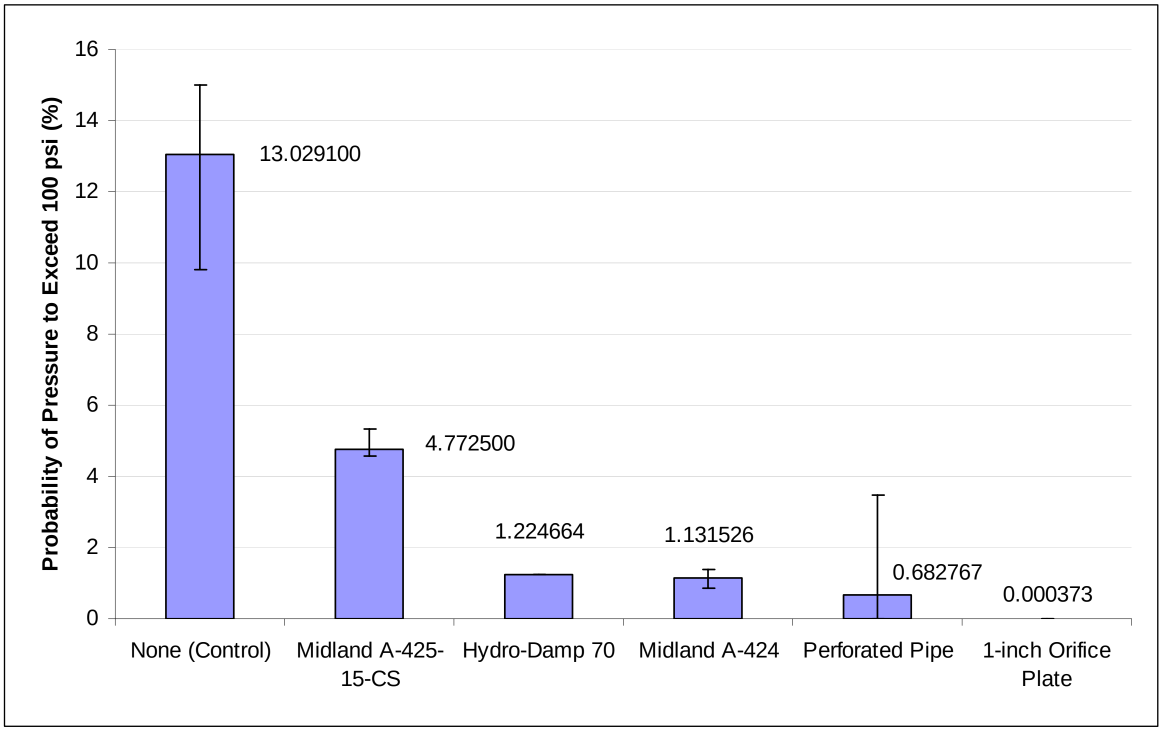

Figure 9a. 2-Inch Nozzle-Diameter SPRDs Ranked by their Estimated Probabilities of Allowing a Peak Pressure Exceeding 100 psi Given a Surge Event (Bars indicate range among different distributions fitted to each SPRD)

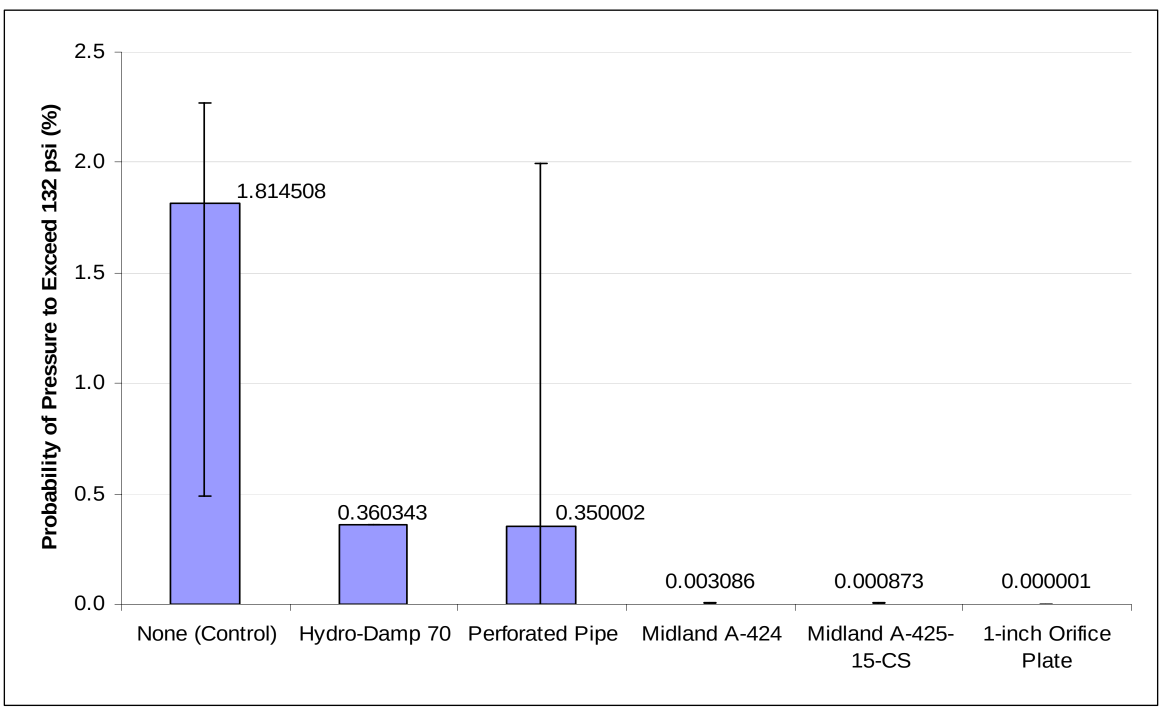

Figure 9b. 2-Inch Nozzle-Diameter SPRDs Ranked by their Estimated Probabilities of Allowing a Peak Pressure Exceeding 132 psi Given a Surge Event

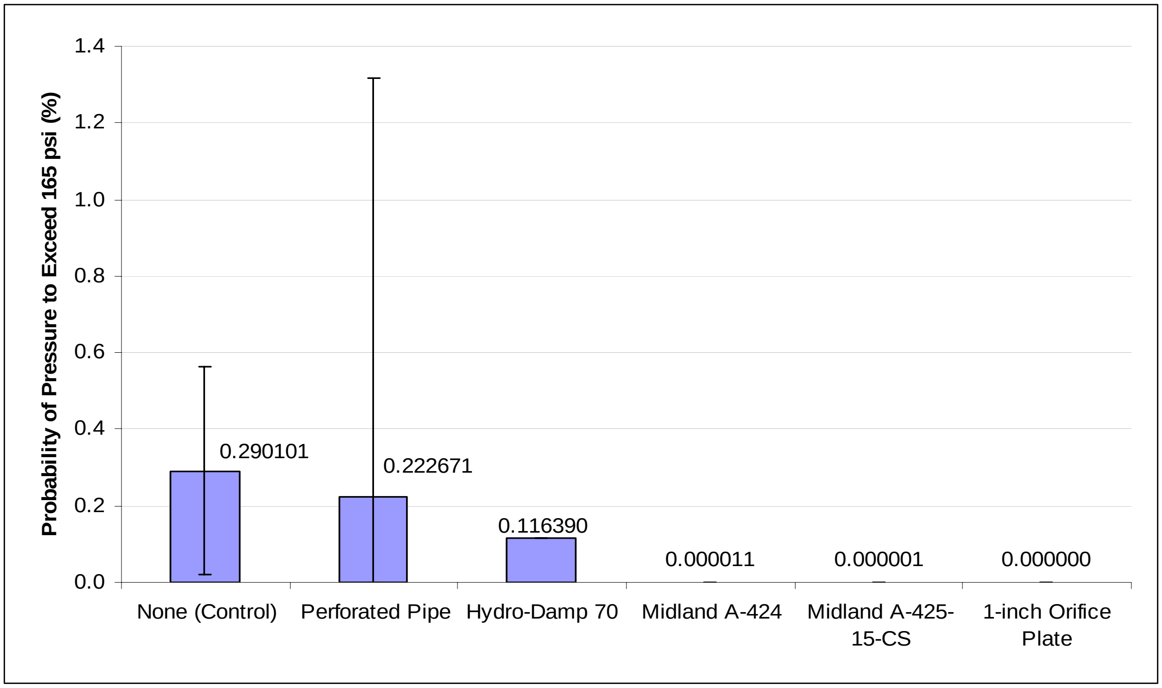

Figure 9c. 2-Inch Nozzle-Diameter SPRDs Ranked by their Estimated Probabilities of Allowing a Peak Pressure Exceeding 165 psi Given a Surge Event

6.2 The 3-Inch Diameter Nozzle

Table 3 shows the estimated probabilities in percentage for 3-inch diameter SPRDs to exceed 100 psi, 132 psi, and 165 psi. Figures 10a, b, and c show the SPRDs ranked by their estimated probability to exceed 100 psi, 132 psi, and 165 psi, respectively.

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

SPRD	Estimated Probability Percent (%) of Exceeding Specified Pressure Thresholds Given One Surge Event					
	100 psi		132 psi		165 psi	
	Average	Percent Improvement	Average	Percent Improvement	Average	Percent 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

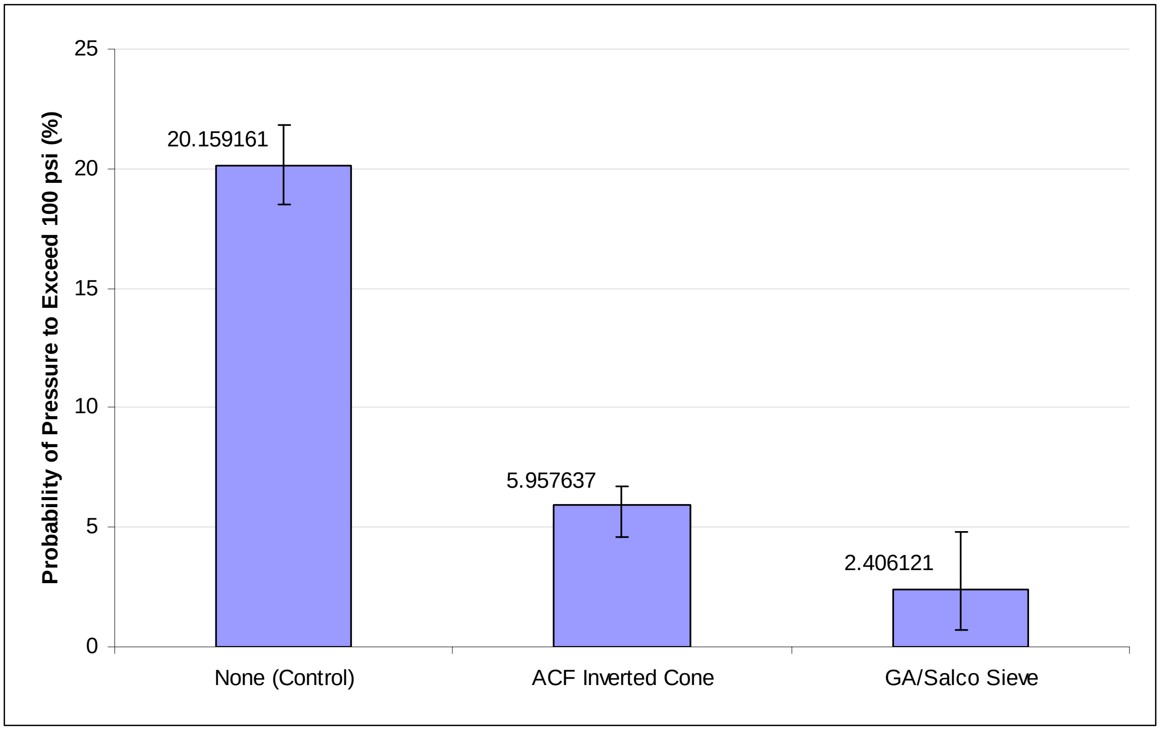

Figure10a. 3-inch Nozzle-Diameter SPRDs Ranked by their Estimated Probabilities of Allowing a Peak Pressure Exceeding 100 psi Given a Surge Event

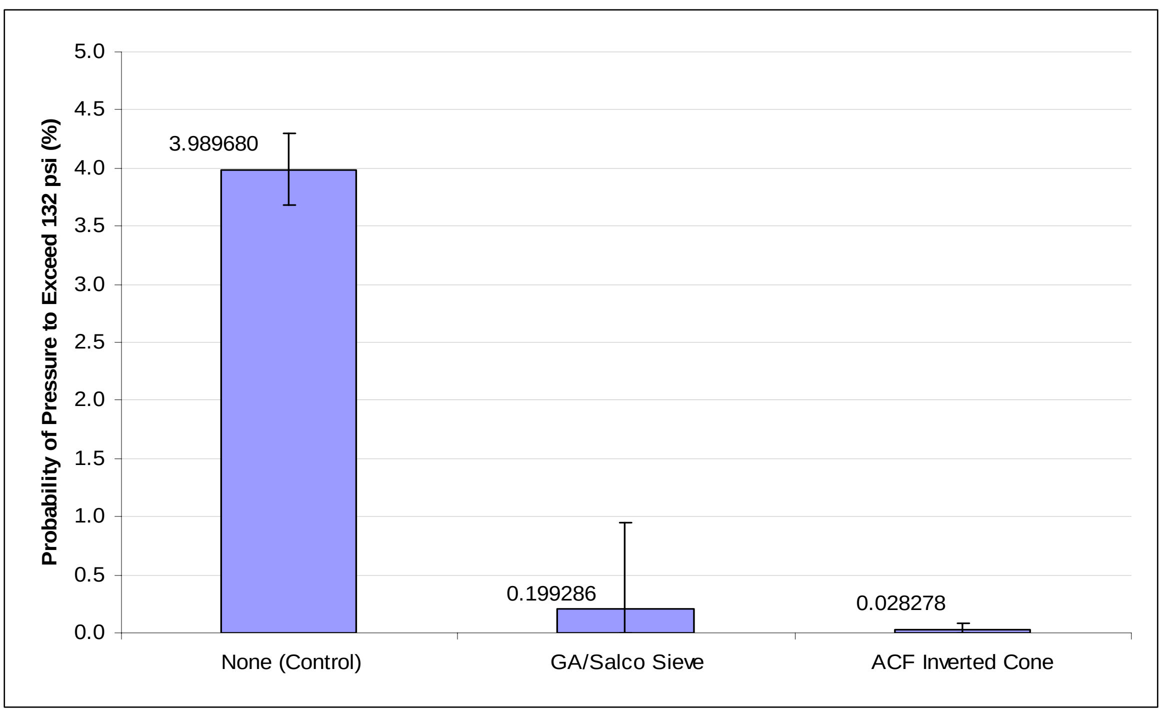

Figure 10b. 3-Inch-Nozzle-Diameter SPRDs Ranked by their Estimated Probabilities of Allowing a Peak Ressure Exceeding 132 psi Given a Surge Event

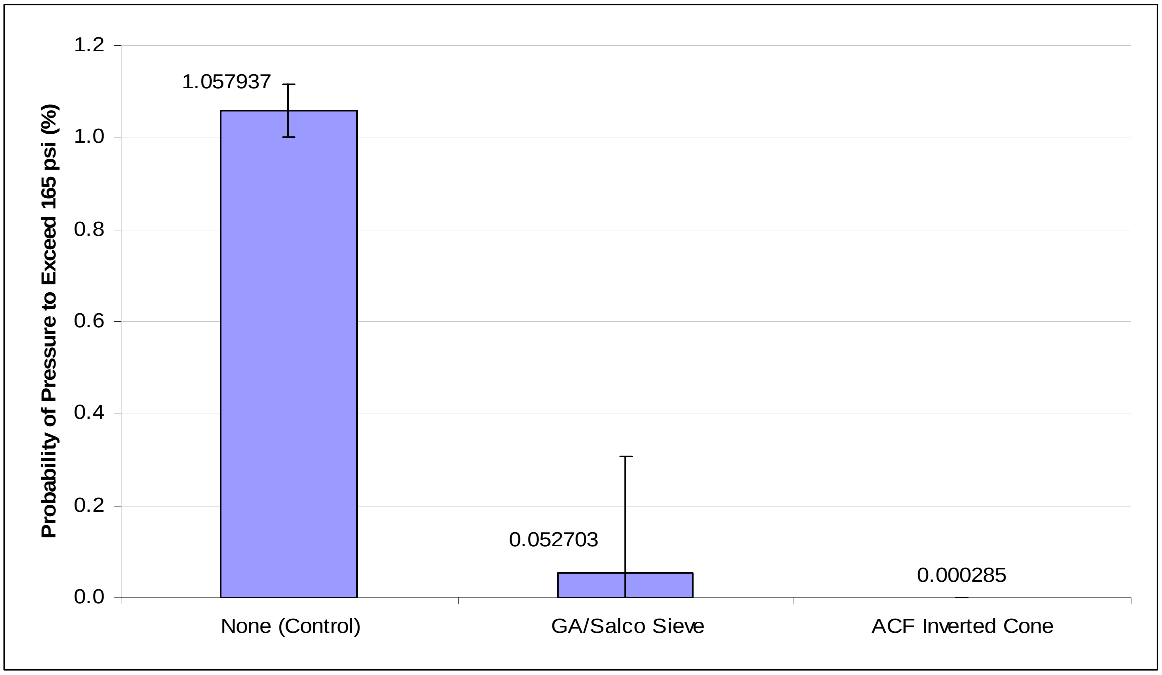

Figure 10c. 3-Inch Nozzle-Diameter SPRDs Ranked by their Estimated Probabilities of Allowing a Peak Pressure Exceeding 165 psi Given a Surge Event

6.3 The 6.5-Inch Diameter Nozzle

Table 4 shows the estimated probabilities in percentage for 6.5-inch diameter SPRDs to exceed 100 psi, 132 psi, and 165 psi. Figures 11a, b, and c show the SPRDs ranked by their estimated probability to exceed 100 psi, 132 psi, and 165 psi, respectively.

Table 4. 6.5-Inch Nozzle-Diameter SPRDs' Estimated Performance

SPRD	Estimated Probability Percent (%) of Exceeding Specified Pressure Thresholds Given One Surge Event					
	100 psi		132 psi		165 psi	
	Average	Percent Improvement	Average	Percent Improvement	Average	Percent 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

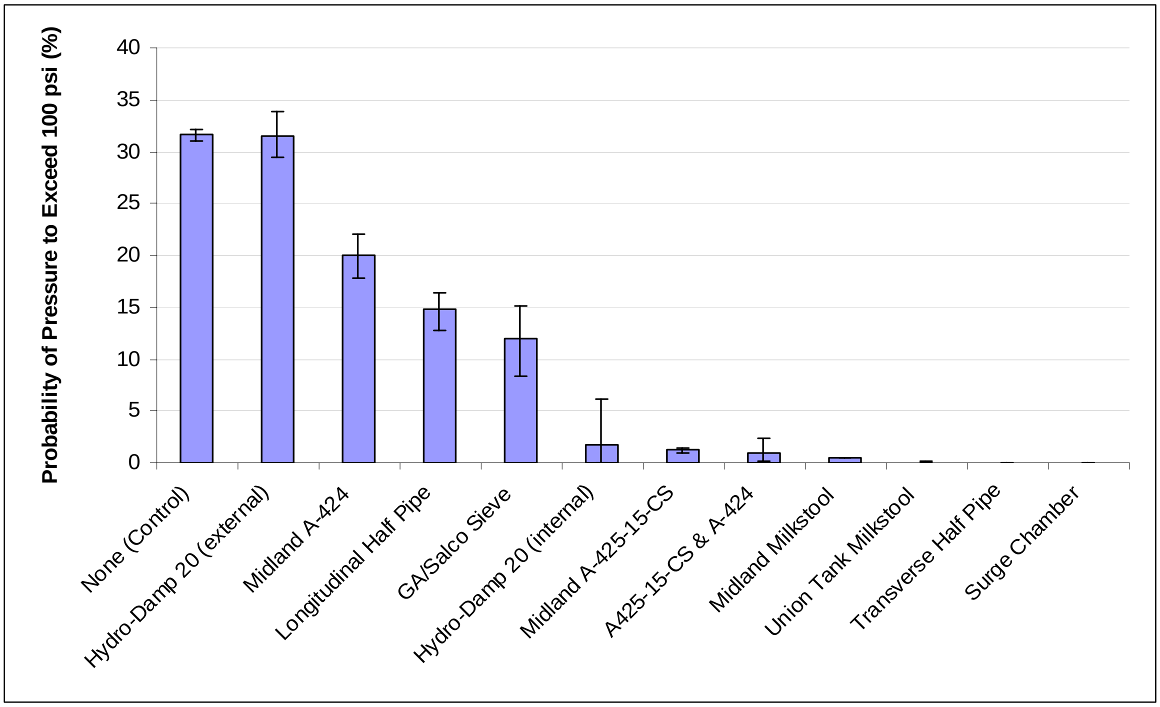

Figure 11a. 6.5-Inch Nozzle-Diameter SPRDs Ranked by their Estimated Probabilities of Allowing a Peak Pressure Exceeding 100 psi Given a Surge Event

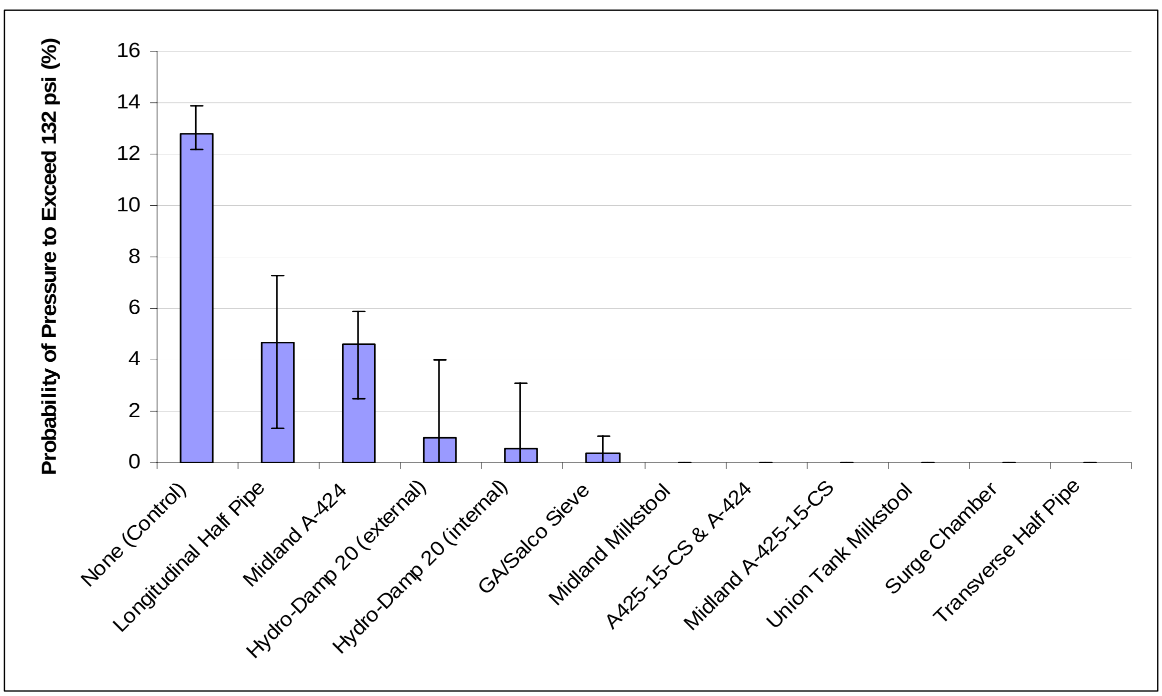

Figure 11b. 6.5-Inch Nozzle-Diameter SPRDs Ranked by their Estimated Probabilities of Allowing a Peak Pressure Exceeding 132 psi Given a Surge Event

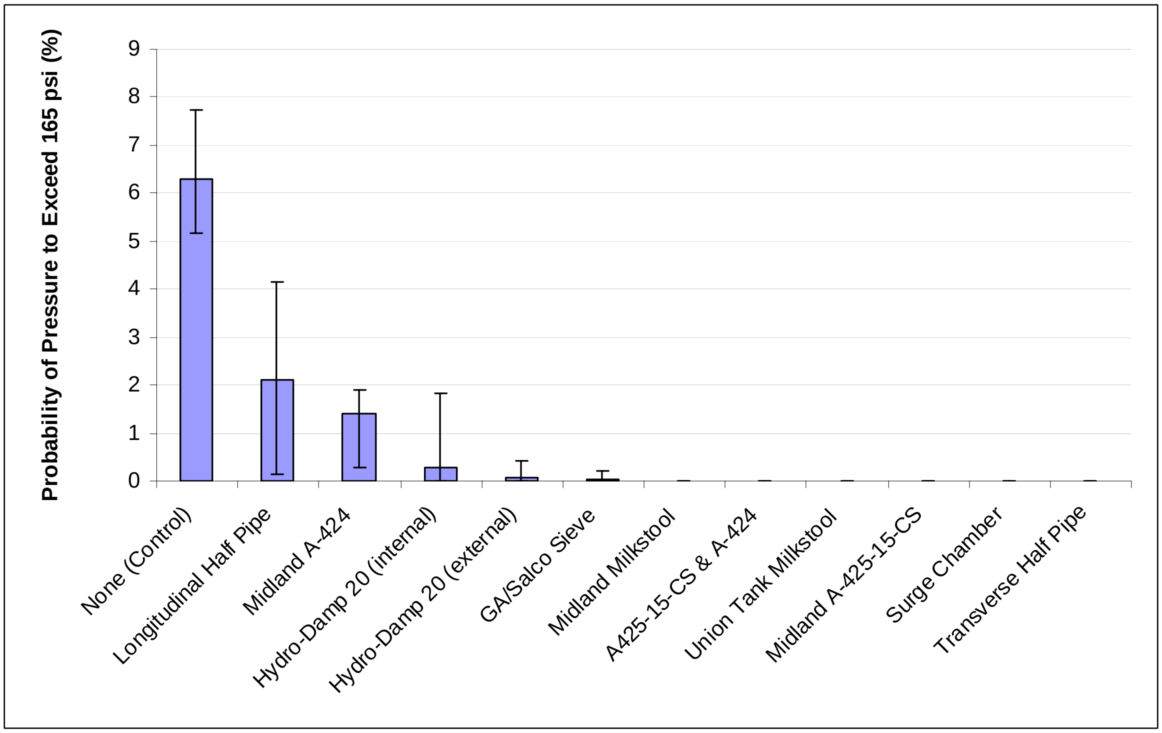

Figure 11c. 6.5-Inch Nozzle-Diameter SPRDs Ranked by their Estimated Probabilities of Allowing a Peak Pressure Exceeding 165 psi Given a Surge Event

6.4 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 rough approximation.

The approach of this study is to use the rate per surge event at which peak pressures exceed the rupture disc rating in the impact tests (that is, NARs per surge event, if we assume that surges in the field resemble the surges in the impact tests), together with the rate per carload of burst discs (that is, 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 Equation 2:

$$\text{NARs per trip} = \text{NARs per surge} \times \text{Surge events per trip} \qquad (2)$$

The impact tests described in Barkan, et. al. (Ref. 4), included 90 impacts under control conditions (that is, 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 6.5-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 using Equation 3.

$$(\text{NARs per trip})_i = [P_i(\text{pressure} > p^* \mid \text{surge event})]\, S_i \approx (n_i/m_i)\, S_i \quad (3)$$

for nozzle diameter (i), disc rating (p*), (m) control impacts, (n) observations from nozzle diameter (i) with peaks above (p*), and (S) represents surge events per trip.

Equation 4 follows:

$$S_i = (\text{NARs per trip})_i \,/\, (n_i/m_i) \quad (4)$$

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 were 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 5 shows the calculation of n/m at 100 psi for the control data from the impact tests.

Table 5. Peak Pressures above 100 psi for the Control Cases in the Barkan et. al. (Ref. 4), 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-inch	20	2	0.10
3-inch	30	5	0.17
6.5-inch	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 (that is, the "control" cars) has been decreasing, perhaps rapidly.

In order to estimate for S, test data for the control condition must be combined with field data from the control condition. 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 standard 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 (Ref. 4). 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 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 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-inch	3.7	0.10	37.00
3-inch	3.7	0.17	22.20
6.5-inch	3.7	0.37	10.09

The results in the rightmost column of Table 6 can be applied to the probabilities in Tables 2, 3, and 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. It can be represented as Equation 5:

$$(\text{NARs per trip})_{ij} = [P_{ij}(\text{pressure} > p^* \mid \text{surge event})]\ S_i \qquad (5)$$

Tables 7, 8, and 9 show the results.

Table 7. Estimation of NAR Rates per 1,000 Trips with 165 psi Rupture Discs for Different SPRDs on a 2 inch ID Nozzle Diameter

SPRD	Estimated Surge Events per 1,000 Loaded Tank Car Trips for 2-inch ID Nozzle (S_2)	Pij(pressure > 165 psi given a surge event) in percent from Table 2	Estimated NARs at 165 psi per 1,000 Loaded Tank Car Trips for 2-inch ID Nozzle
1-inch 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 8. Estimation of NAR Rates per 1,000 Trips with 165 psi Rupture Discs for Different SPRDs on a 3 inch ID Nozzle Diameter

SPRD	Estimated Surge Events per 1,000 Loaded Tank Car Trips for 3-inch ID Nozzle (S_3)	Pij(pressure > 165 psi given a surge event) in percent from Table 3	Estimated NARs at 165 psi per 1,000 Loaded Tank Car Trips for 3-inch ID Nozzle
ACF Inverted Cone	22.20	0.000285	0.000063
GA/Salco Sieve	22.20	0.052703	0.011700
None (Control)	22.20	1.057937	0.234862

Table 9. Estimation of NAR Rates per 1,000 Trips with 165 psi Rupture Discs for Different SPRDs on a 6.5 Inch ID Nozzle Diameter

SPRD	Estimated Surge Events per 1,000 Loaded Tank Car Trips for 6.5-inch ID Nozzle ($S_{6.5}$)	Pij(pressure > 165 psi given a surge event) in percent from Table 4	Estimated NARs at 165 psi per 1,000 Loaded Tank Car Trips for 6.5-inch ID Nozzle
Transverse Half Pipe	10.09	0.000000	0.000000
Surge Chamber	10.09	0.000001	0.000000
Midland A-425-15-CS	10.09	0.000002	0.000000
Union Tank Milkstool	10.09	0.000045	0.000005
A425-15-CS & A-424	10.09	0.000059	0.000006
Midland Milkstool	10.09	0.000472	0.000048
GA/Salco Sieve	10.09	0.038424	0.003877
Hydro-Damp 20 (external)	10.09	0.083041	0.008380
Hydro-Damp 20 (internal)	10.09	0.276424	0.027894
Midland A-424	10.09	1.413285	0.142613
Longitudinal Half Pipe	10.09	2.107698	0.212686
None (Control)	10.09	6.304140	0.636145

6.5 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 to 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 (Ref. 4). Figure 12 depicts the relationship between Damiani ratio and the estimated improvements over the controls from Tables 2, 3, and 4. All SPRDs that are estimated to offer less than near-total protection at 165 psi have Damiani ratios lower than 40 inches (though some with ratios that low do apparently offer near-total protection). 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 percent 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.

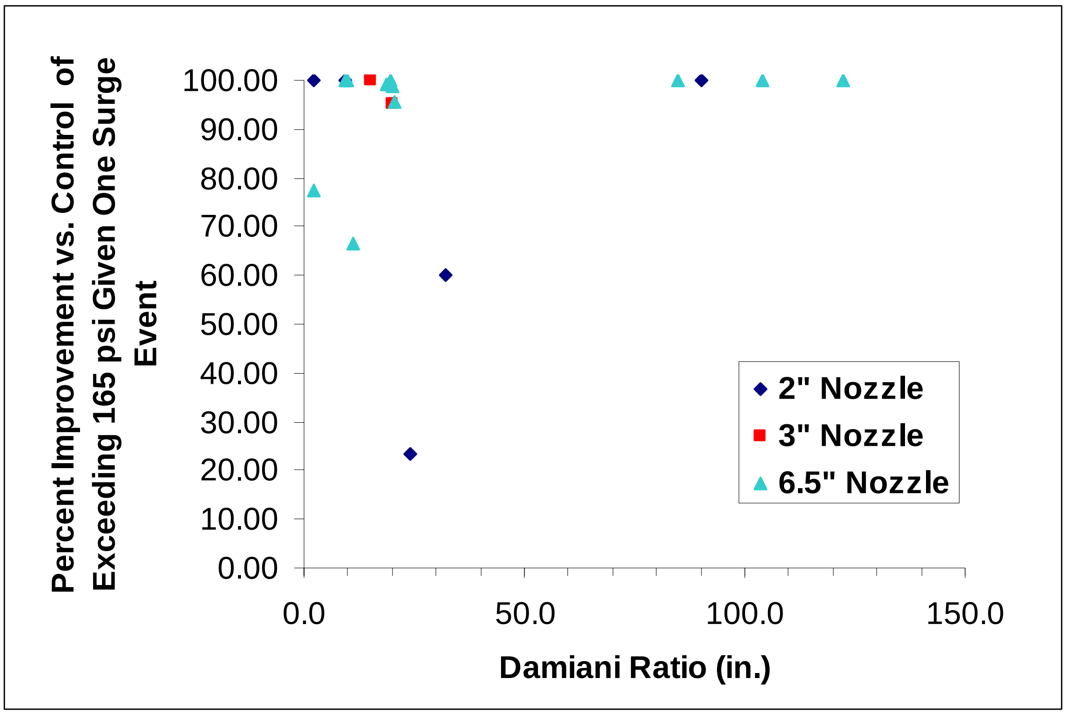

Figure 12. Relationship between Damiani Ratio and Estimated Improvement over No SPRD (Control)

7.0 DISCUSSION AND CONCLUSIONS

The 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.

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APPENDIX

DIAGRAMS OF SURGE PRESSURE REDUCTION DEVICES (SPRDs)

No diagrams are included for these two devices:

1. Half-pipe baffle, transverse:
   - Similar to the longitudinal halfpipe baffle, except that it is installed perpendicular to the tank shell's long dimension, and the openings at either end of the baffle face the shell sides.
2. 1-Inch Orifice Plate:
   - This is a one inch diameter hole in a plate bolted onto the top of the nozzle.

The RSI-AAR Railroad Tank Car Safety Research & Test Project thanks ACF Industries, E.I. DuPont de Nemours Corporation, GATX Corporation, Hydro-Damp, Inc., Midland Manufacturing, Salco Products and Union Tank Car Company for providing these diagrams and allowing their inclusion in this report.

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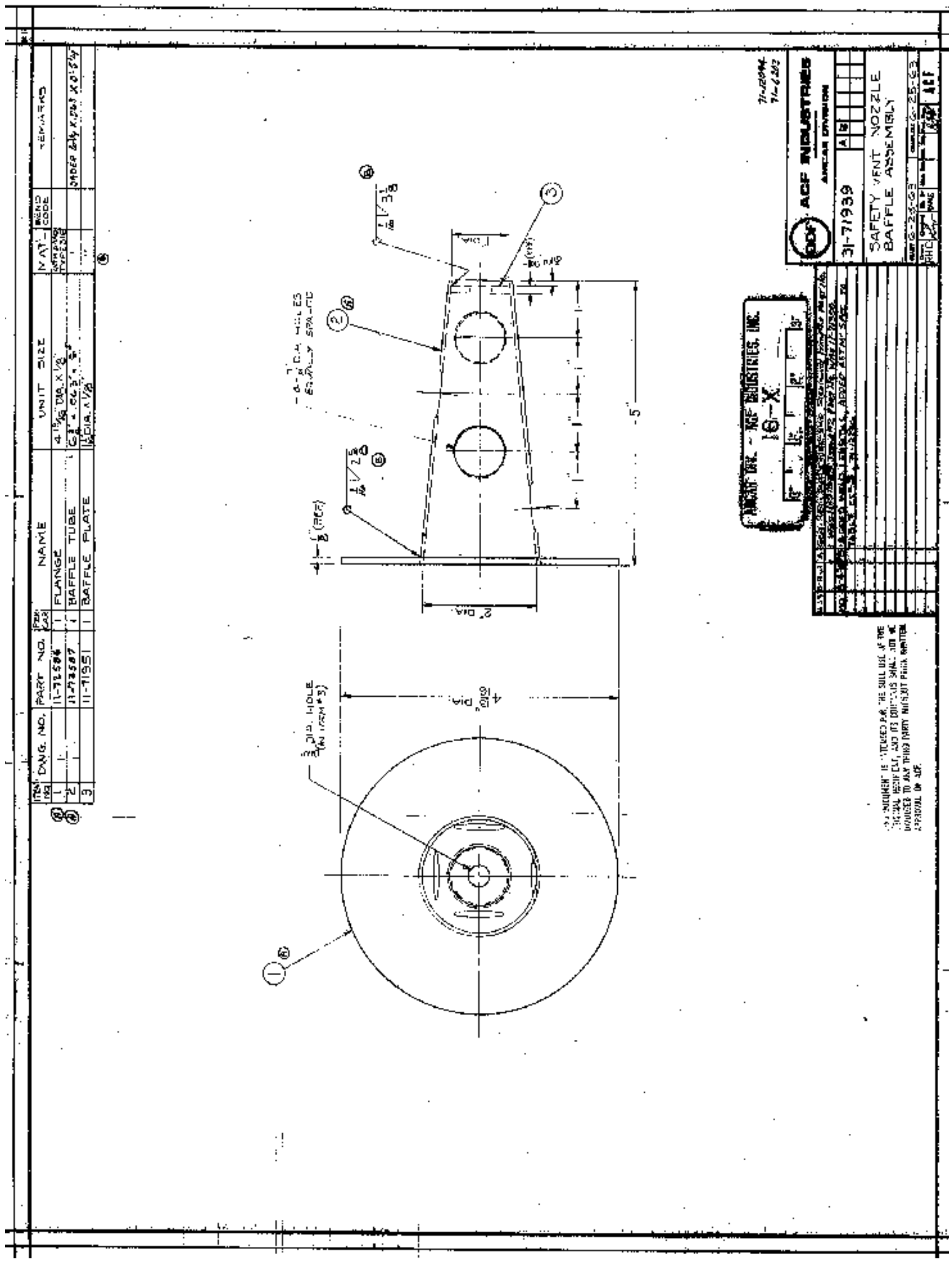
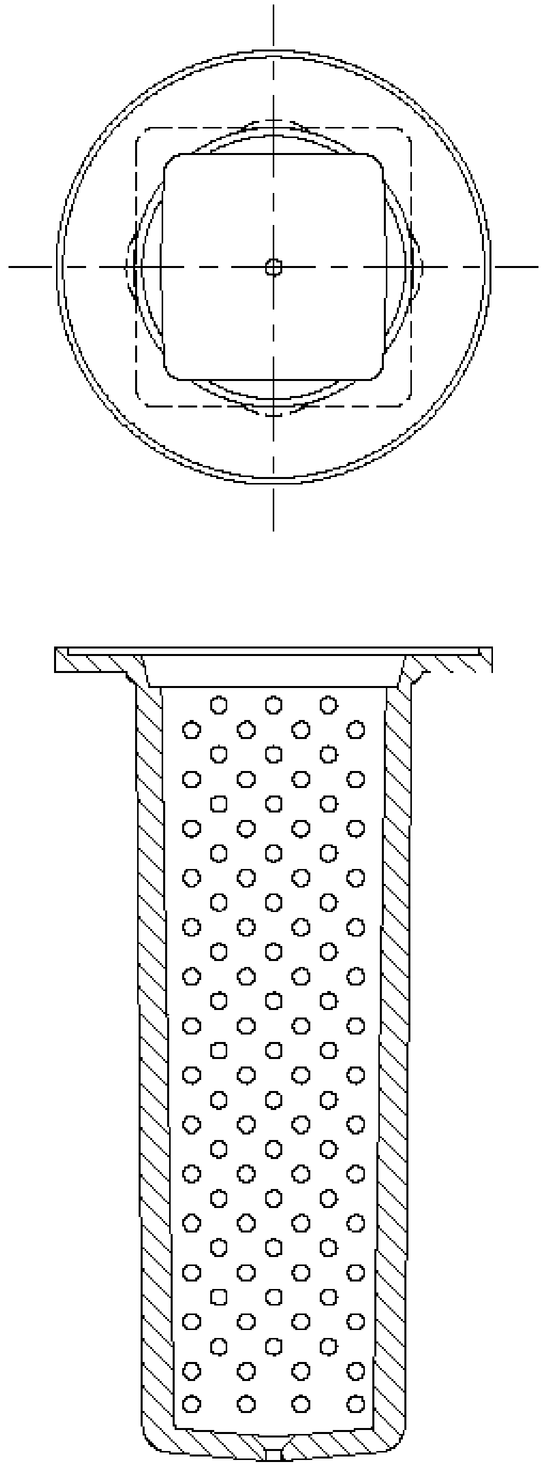
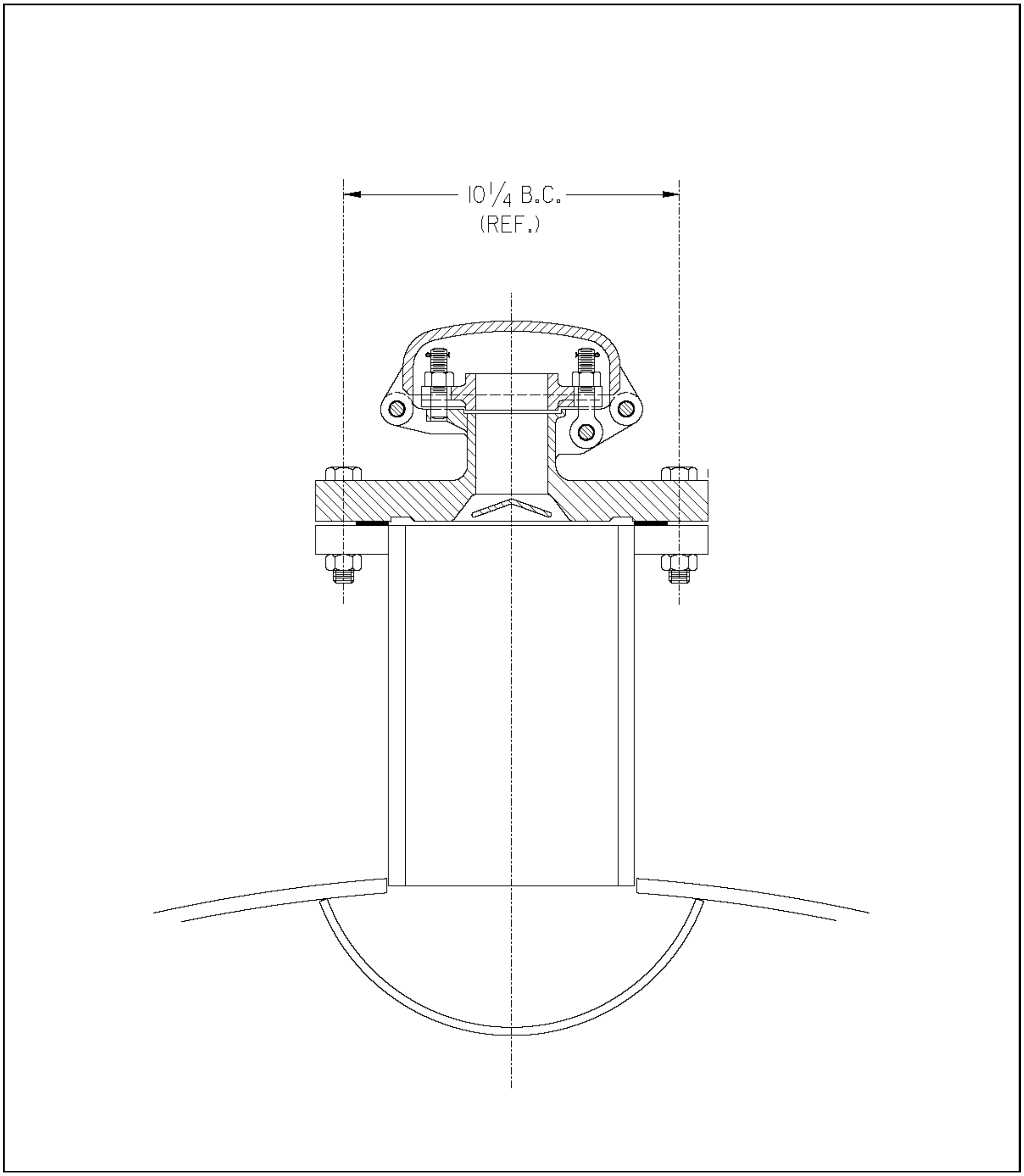


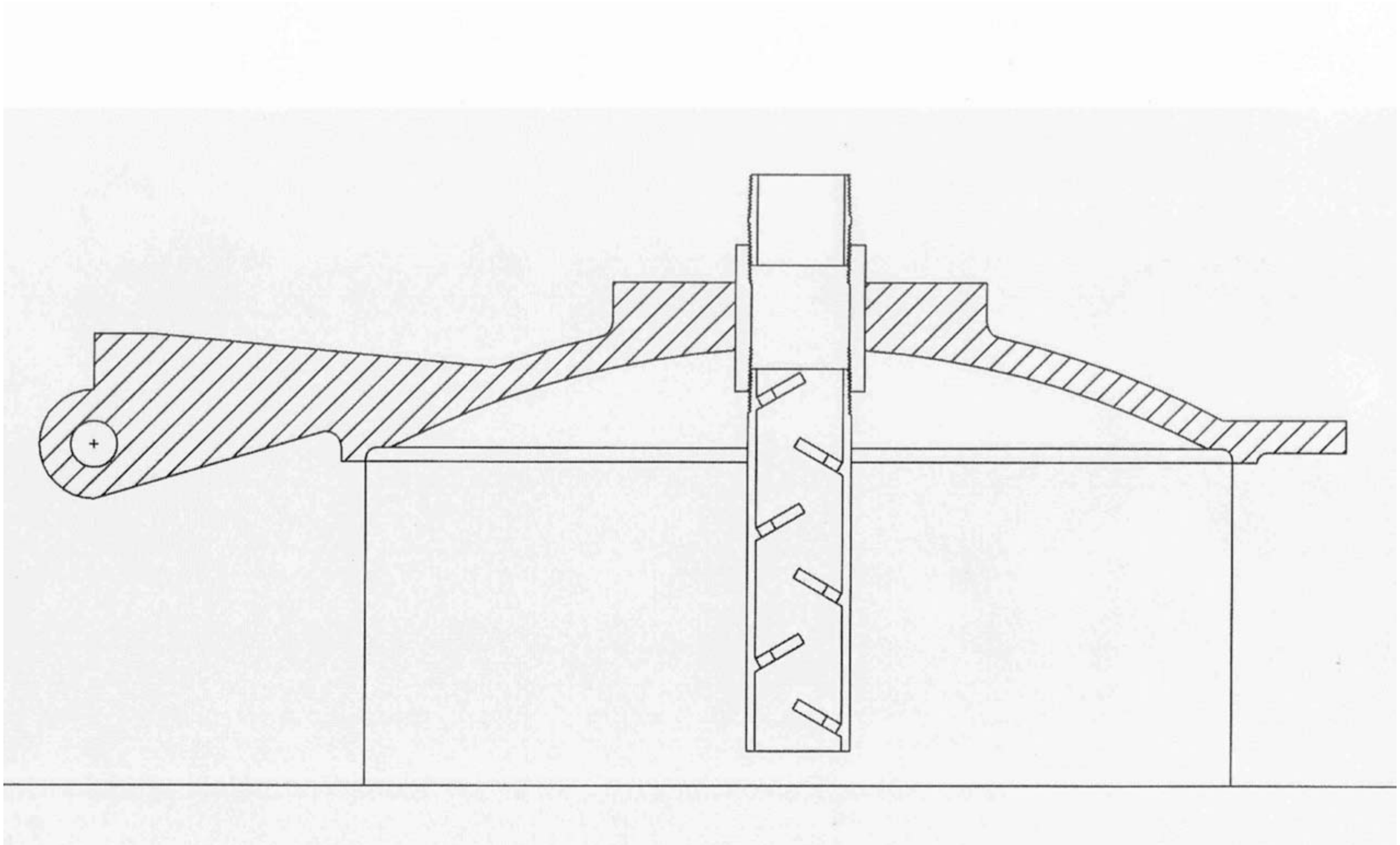
Device: ACF Inverted Cone



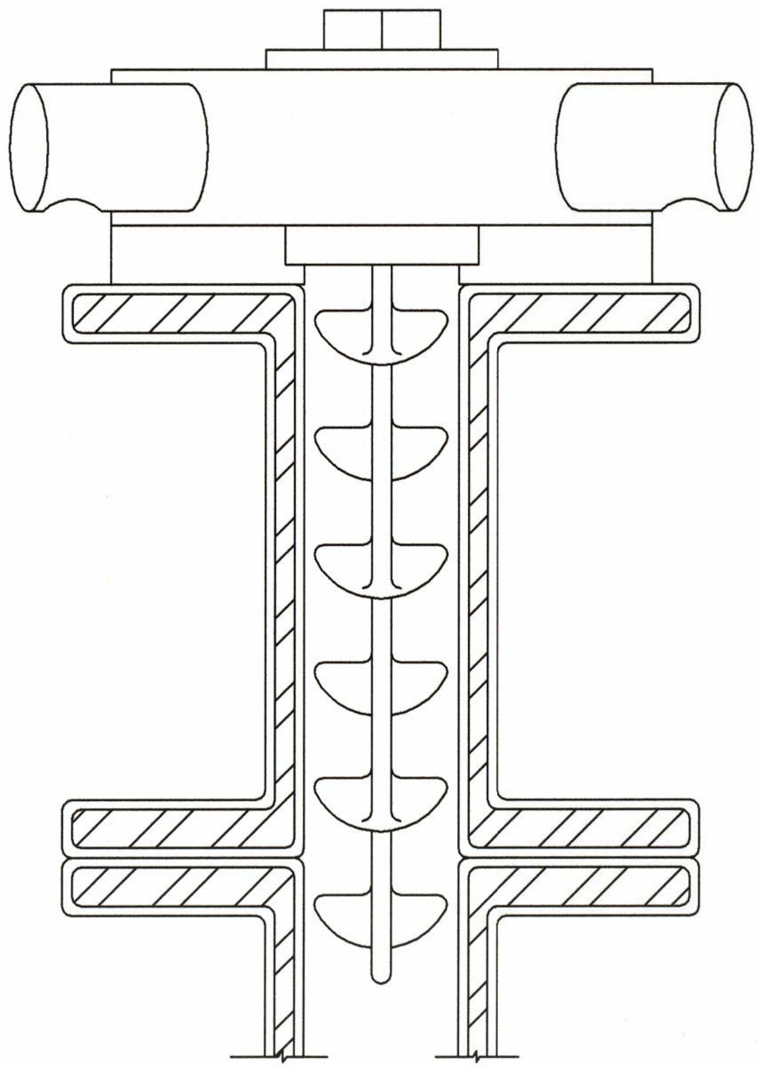
Device: GA/Salco Sieve



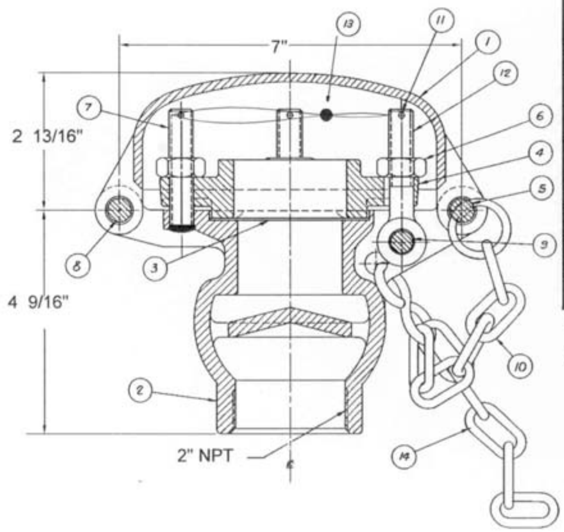
Device: Half-pipe Baffle, Longitudinal



Device: Hydro-Damp Style 20, Mounted Internally



Device: Hydro-Damp Style 70



ITEM NO.	QTY.	PART NAME	A-424		A-426		A-428		A-428-ML	
			MATERIAL	PART NO.	MATERIAL	PART NO.	MATERIAL	PART NO.	MATERIAL	PART NO.
1	1	TOP	MALL. IRON	425-1-MI	MALL. IRON	425-1-MI	STAINLESS	429-1-SS	STAINLESS	429-1-SS
2	1	BASE	STEEL	424-2-CS	STAINLESS	426-2-SS	STAINLESS	426-2-SS	MONEL[4]	426-2-ML
3	1	DISC[2]	STAINLESS	425-3-SS	STAINLESS	425-3-SS	STAINLESS	425-3-SS	STAINLESS	425-3-SS
4	1	RETAINER	DUCTILE IRON	425-4-DI	DUCTILE IRON	425-4-DI	STAINLESS	429-4-SS	STAINLESS	429-4-SS
5	1	SWING PIN	SS/STEEL	425-5-XS	SS/STEEL	425-5-XS	STAINLESS	429-5-SS	STAINLESS	429-5-SS
6	4	NUT	STEEL[1][3]	425-6-CS	STEEL[1]	425-6-CS	STAINLESS	429-6-SS	STAINLESS	429-6-SS
7	3	STUD	STEEL[1][3]	425-7-CS	STEEL[1]	425-7-CS	STAINLESS	429-7-SS	STAINLESS	429-7-N60
8	1	HINGE PIN	STEEL	425-8-CS	STEEL	425-8-CS	STAINLESS	429-8-SS	STAINLESS	429-8-SS
9	1	EYE BOLT PIN	STEEL	425-9-CS	STEEL	425-9-CS	STAINLESS	429-9-SS	STAINLESS	429-9-SS
10	1	CHAIN	STEEL	24-3-CS	STEEL	24-3-CS	STEEL[1]	24-3-CS	STEEL[1]	24-3-CS
11	4	COTTER PIN	STAINLESS	425-11-SS	STAINLESS	425-11-SS	STAINLESS	425-11-SS	STAINLESS	425-11-SS
12	1	EYE BOLT	STEEL[1][3]	425-12-CS	STEEL[1]	425-12-CS	STAINLESS	429-12-SS	STAINLESS	429-12-N60
13	1	SEAL[2]	SS/LEAD	425-13-XS	SS/LEAD	425-13-XS	SS/LEAD	425-13-XS	SS/LEAD	425-13-XS
14	1	TANK CHAIN[2]	STEEL[1][3]	425-14-CS	STEEL[1]	425-14-CS	STEEL[1]	425-14-CS	STEEL[1]	425-14-CS

NOTE: 1 Alternate material available. **2** Not furnished unless requested. **3.** For stainless hardware use suffix -SH. **4.** Electropolished

2" DISC HOLDER WITH BAFFLE - THREADED

RUPTURE DISC DEVICES

Device: Midland !-424

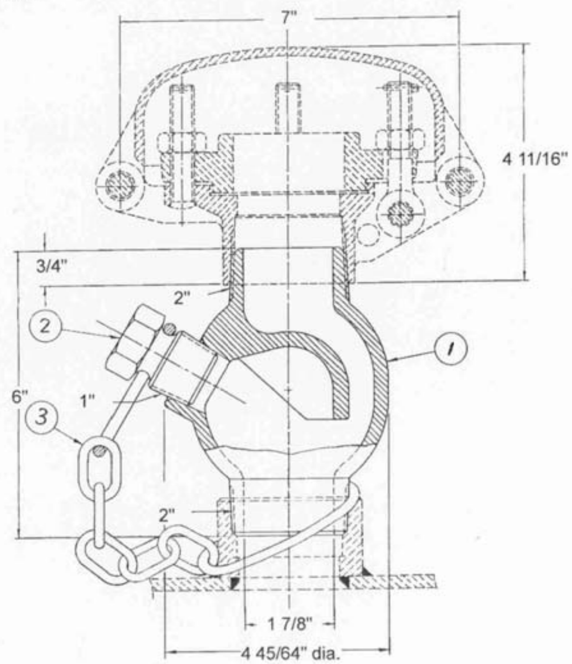
RUPTURE DISC DEVICES

2" AIR CONNECTION - THREADED

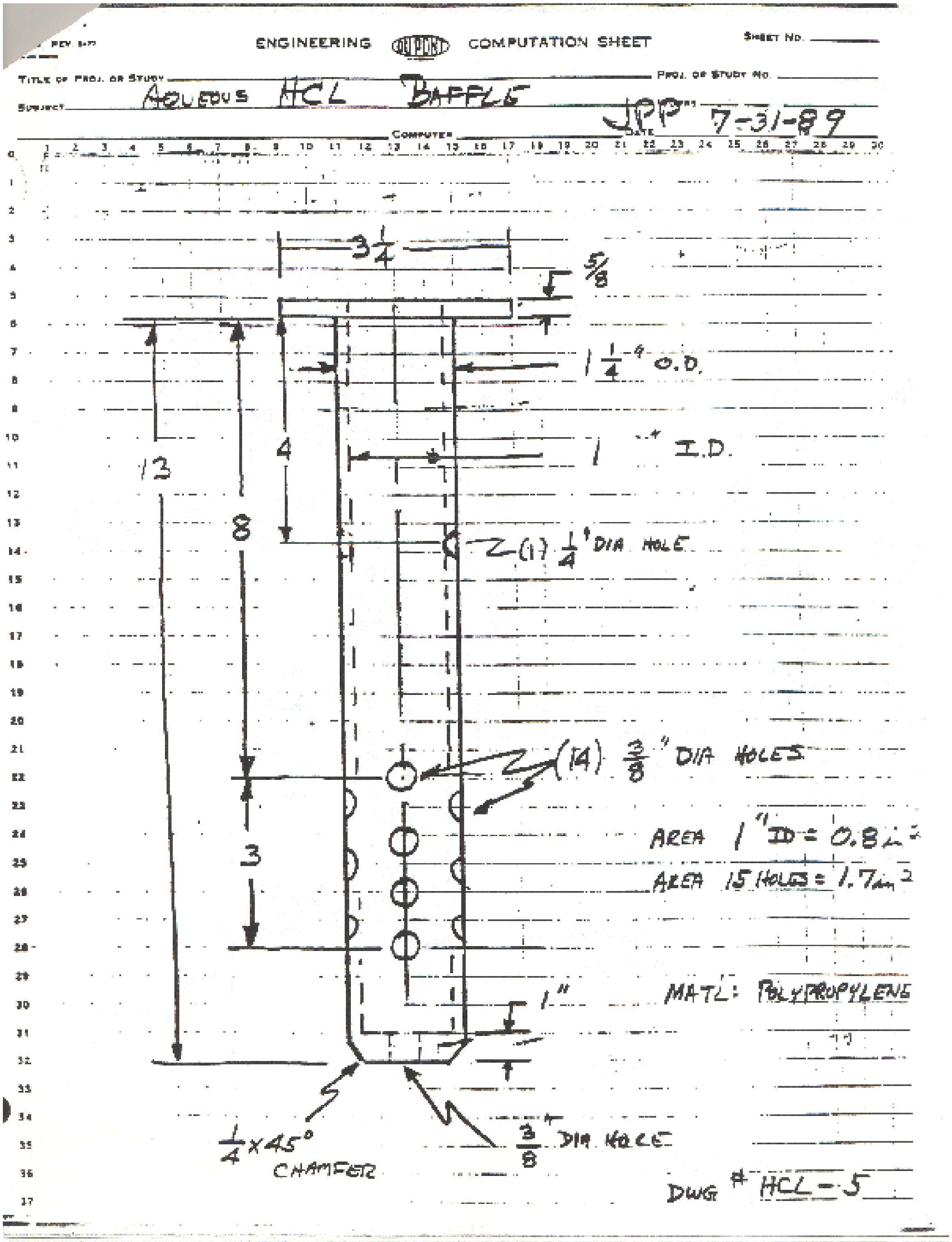
A-425-15-CS, A-425-15-XS, A-425-15-SS, A-425-15-MO

ITEM NO.	QTY.	PART NAME	A-425-15-CS		A-425-15-XS		A-425-15-SS		A-425-15-MO	
			MATERIAL	PART NO.	MATERIAL	PART NO.	MATERIAL	PART NO.	MATERIAL	PART NO.
1	1	BODY	STEEL	425-15-CS	STEEL/SS INSERT	425-15-XS	STAINLESS	425-15-SS	316 STAINLESS	425-15-MO
2	1	PLUG(2)	STEEL	24-CS	STEEL	24-CS	NITRONIC 60	24-N60	NITRONIC 60	24-N60
3	1	CHAIN ASSEMBLY	STEEL	24-10-CS	STEEL	24-10-CS	STEEL(1)	24-10-CS	STEEL(1)	24-10-CS

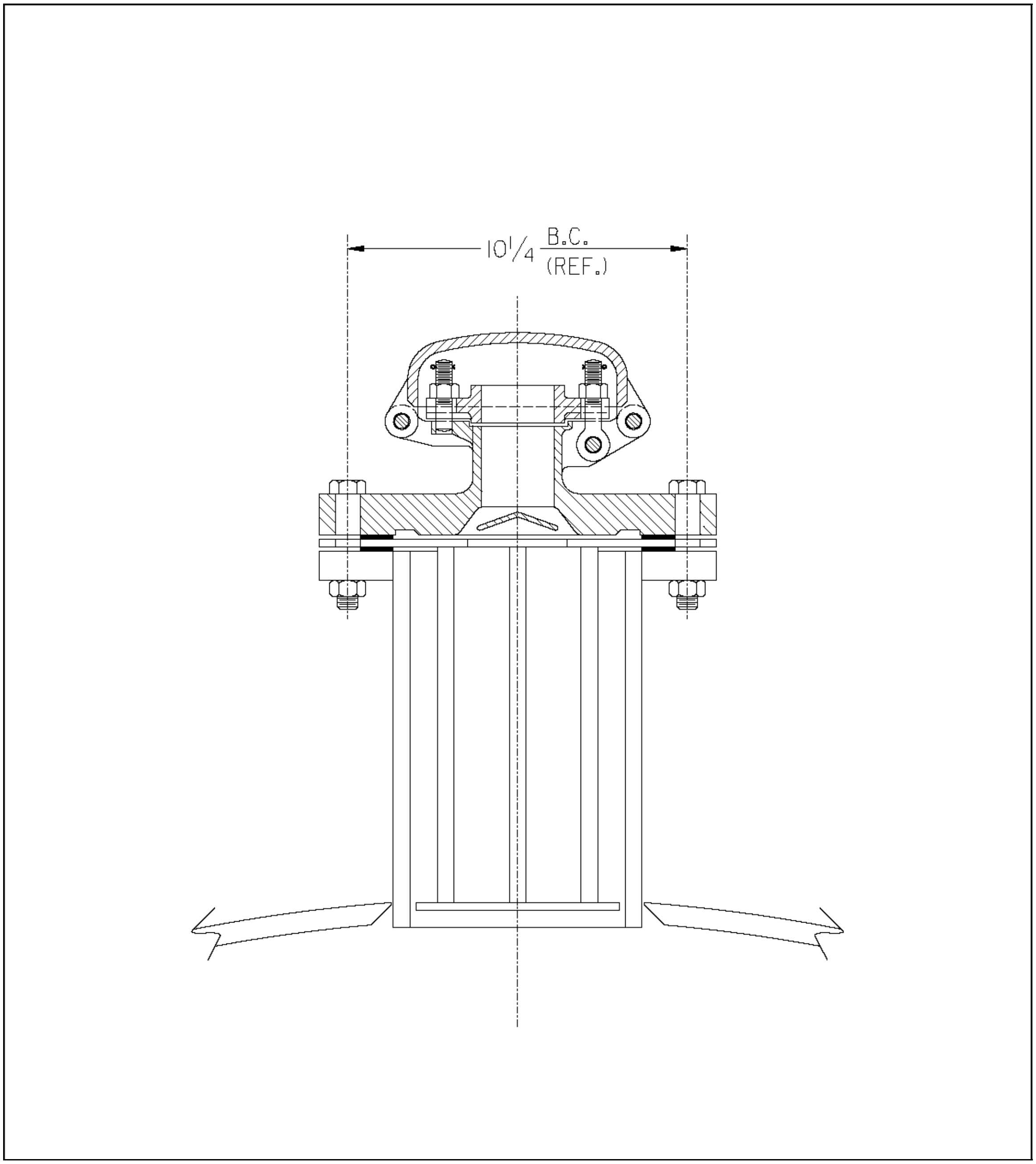
NOTE: 1. Alternate material available. **2**. Order 1" nipple 3" long (part number 425-154) and cap 1" NPT (part number 34) separately if required instead of plug (part number 24) and specify materials.



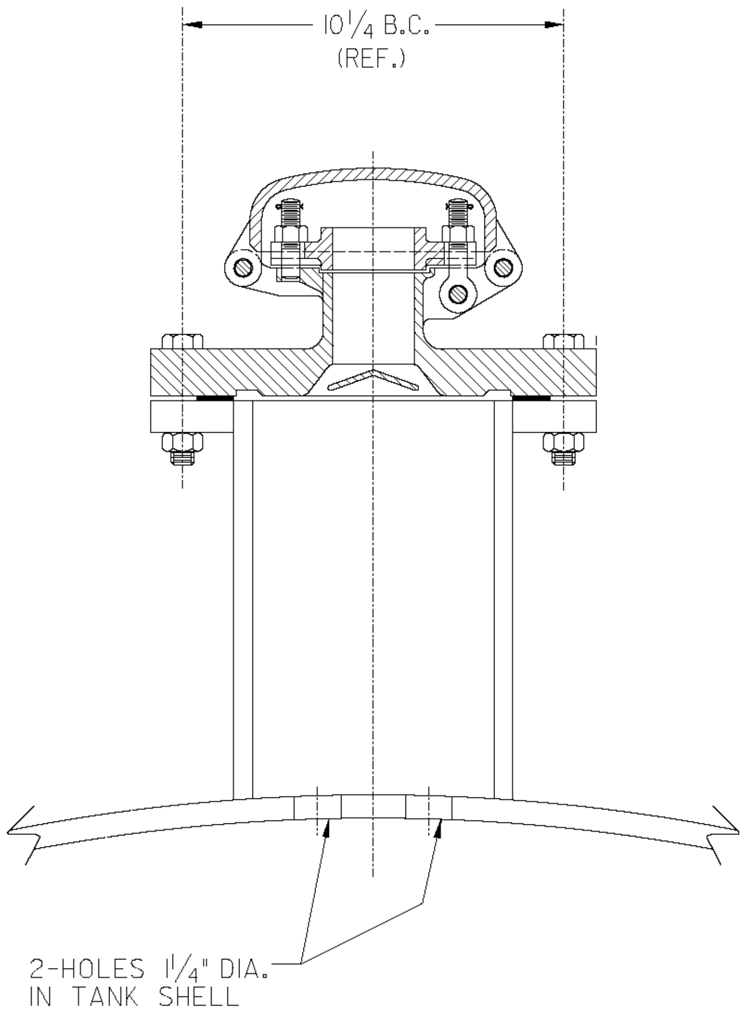
Device: Midland 525



Device: Perforated Pipe



Device: Union Tank "Long" Milkstool



Device: Union Tank Surge Chamber

Railway Supply Institute

ASSOCIATION OF AMERICAN RAILROADS