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Reducing Hazardous Materials Releases from Railroad Tank Car Safety Vents

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The leading cause of hazardous materials releases in railroad transportation over the 5 years prior to this research was burst frangible disks on tank cars. These burst disks occur as a result of pressure surges in the tank car safety vent during transportation. More than a dozen different surge pressure reduction devices (SPRDs) have been developed to protect the frangible disk from these surges. A statistical analysis of tank cars in service indicated that cars equipped with SPRDs experienced a lower rate of leakage due to burst frangible disks than similar cars without SPRDs. This analysis, however, did not provide sufficient resolution to determine the relative effectiveness of the different SPRD designs. A series of controlled experiments was conducted to determine the surge reduction effectiveness and the flow performance of different SPRDs. These tests showed that there were significant differences in the performance of the various surge pressure reduction devices in both surge reduction and flow rate. The results of these tests will help tank car builders, owners, and operators improve the safety performance of tank cars by installing SPRDs that will reduce non-accident-caused releases of hazardous materials and still function adequately to relieve pressure when necessary. The results also will provide a basis for setting SPRD performance and testing requirements and identify promising design elements for new SPRDs.

Since 1982, the railroad industry has reduced its rate of accident-caused releases of hazardous materials by an order of magnitude (Figure 1). This impressive accomplishment has been achieved by the prevention of derailments through improved design and maintenance of track and vehicles, and through enhancements in tank car design and components that make the cars more resistant to damage in the event that they are involved in an accident (*2*). Prevention of railroad accidents involving hazardous materials continues to be of importance to the railroad industry because of these accidents' potential for serious safety and environmental effects. Consequently, research on further reducing the likelihood of derailments and improving the damage resistance of tank cars is ongoing.

However, this improvement in railroad safety also has enabled the industry to shift some of its attention toward another aspect of hazardous materials transportation safety: reducing releases not caused by railroad accidents. These types of releases usually are associated with leaks from various valves and fittings on tank cars and are due to an entirely different set of causes than accident-caused releases. These nonaccident releases (NARs) generally result in much smaller spills than those from accidents, but in recent years they have outnumbered accident-caused releases by nearly 20:1. Their greater frequency makes them both a nuisance and a safety concern to the railroads. NARs sometimes cause injuries and on occasion can result in large hazardous materials releases with costly environmental consequences (*3*).

The problem of NARs is not unique to the railroad industry; they are the primary cause of hazardous materials releases for both highway and inland waterway transport as well (Figure 2). There are jurisdictional differences regarding regulatory oversight and consequent differences in reporting criteria between land and waterborne transportation (the Research & Special Programs Administration and the U.S. Coast Guard, respectively). Nevertheless, the overall pattern is clear—nonaccident releases are a major issue for all three transport modes and all have programs underway to address the issue (Barkan, Goolsby, Harvison, and Williams, unpublished).

REDUCTION OF NARS IN RAILROAD TRANSPORTATION

Over the past decade, the railroad industry has pursued a two-pronged approach addressing both operational and hardware-related causes of NARs. Although most railroad NARs occur in transportation, they frequently are due to the inadequate securement of tank car fittings at the loading or unloading rack. Either the condition of these fittings is not detected when the car is offered for transportation or the improperly secured fitting loosens while the car is in transit, resulting in a leak. An operational approach to correcting these types of releases has been implemented through the North American Non-Accident Release Reduction Program, a joint effort of the railroads, tank car companies, and chemical industry. The program was launched in Canada in 1991 and expanded to the United States in 1995 (*4*). Statistics on leaking tank cars are collected by the Association of American Railroads (AAR) Bureau of Explosives (BOE). These data are used to determine how frequently tank cars originating from various locations develop leaks. If a particular location originates more than a threshold level of leaking cars, management personnel at that facility are provided detailed information on the nature of the leaks. Informational and training assistance also is offered to help improve securement practices used at the facility.

The other approach has been to study tank car fittings themselves to determine if the designs can be improved to reduce the likelihood of spills. Analysis of AAR BOE statistics shows that over the 5 years prior to this study, the most frequent cause of railroad transportation NARs was from tank car safety vents (Figure 3). This type of pressure relief device is used primarily on cars transporting corrosive materials. The purpose of the safety vent is to provide pressure relief, primarily in the event of a thermally induced overpressure situation that could occur in an accident in which a car is engulfed in fire. Modeling results (*5, 6*) suggest that such an event is highly unlikely. This

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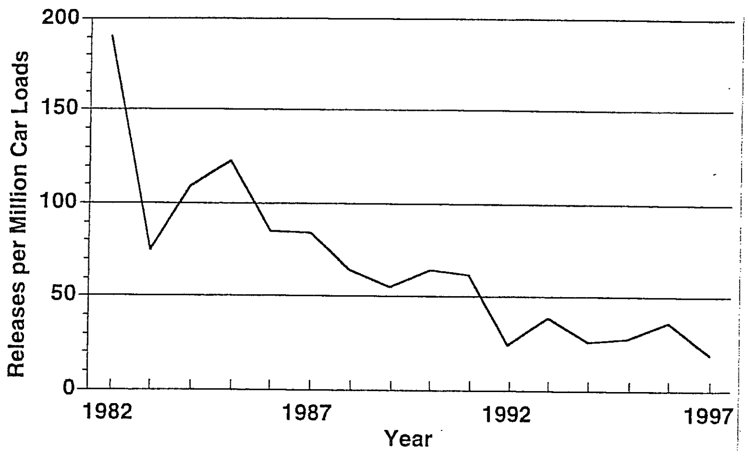

FIGURE 1 Accident-caused releases per million hazardous materials carloads (*1*).

is corroborated by empirical results from an analysis of more than 30 years of data from the Railway Progress Institute–Association of American Railroads: Railroad Tank Car Safety Research and Test Project. There is no recorded incident of a frangible disk functioning in an accident due to thermal overpressure of a tank car transporting corrosive materials. Presumably this is due to the generally low-vapor pressure of these materials.

Safety vents differ from safety valves in that they employ a frangible disk instead of a recloseable valve. Frangible disks burst when they are exposed to their rated burst pressure and must be replaced each time they have broken (Figure 4). If burst frangible disks occurred only in the overpressure condition in which they are intended to function (described above), they would not pose an NAR problem. However, they fail much more frequently as a result of momentary surges in pressure that occur due to liquid sloshing within the tank car during transport. This sloshing can create something akin to "water hammer" in the safety-vent nozzle. If the resultant, momentary surge in pressure in the nozzle exceeds the rated pressure of the disk, it will rupture. After the disk bursts, the lading will be exposed to the atmosphere until the break is detected and the disk replaced. Due to the safety vent's location on top of the tank car, the broken disk may remain undetected for many miles, allowing fumes to escape and liquid to spill out whenever the car is sufficiently accelerated or decelerated. Safety vents are used primarily on cars transporting corrosive materials because the use of valves would require that they be made of more costly corrosion-resistant alloys. Furthermore, even if valves are used, they still would be subject to the same transportation-induced overpressure events that cause disks to fail (this would be partially mitigated if the valve's start-to-discharge pressure was increased as an added factor of safety). The use of valves thus would reduce the incidence of these releases, but it probably would not eliminate them.

The safety vent has been in use since early in the 20th century when acids and other corrosive materials first began to be transported in railroad tank cars. One might be tempted to ask why the industry has endured such a frequent source of hazardous materials release. We think that the explanation lies in a change in the design of tank cars that substantially increased the incidence of burst frangible disks in the 1960s.

During the first half of the century, tank cars used for low-pressure, liquid products employed an expansion dome mounted on top of the horizontal cylindrical tank (since 1930 this type of tank car has been classified as the 103). In the mid-1950s it was realized that the expansion dome was not necessary and its elimination would enable a larger diameter and consequently more efficient tank car (*7*). This new "domeless" tank car was classified as the 111 (Figure 5), and by the early 1960s, the majority of new tank cars were being constructed to this design (*9*).

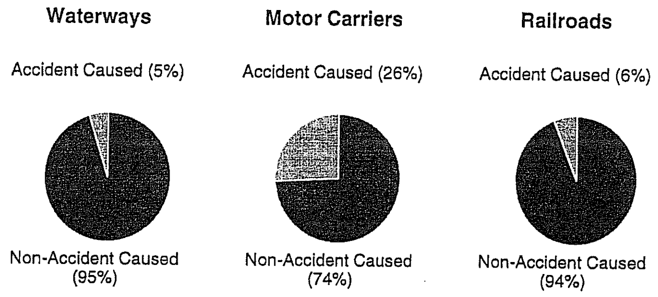

FIGURE 2 Modal comparison of the percentage of non-accident- to accident-caused releases of hazardous materials, 1996 (unpublished data from American Waterways Organization, National Tank Truck Carriers, and Association of American Railroads).

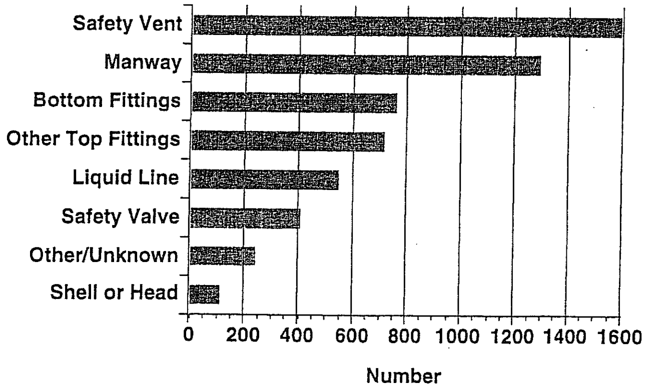

FIGURE 3 Sources of non-accident-caused releases from railroad tank cars, 1992–1996 (AAR BOE data).

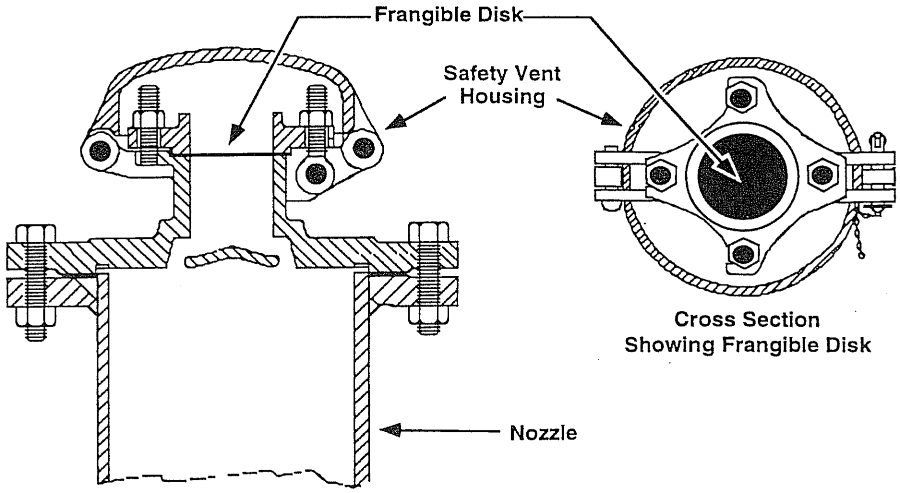

FIGURE 4 Diagram of a typical railroad tank car safety vent showing the frangible disk and the nozzle.

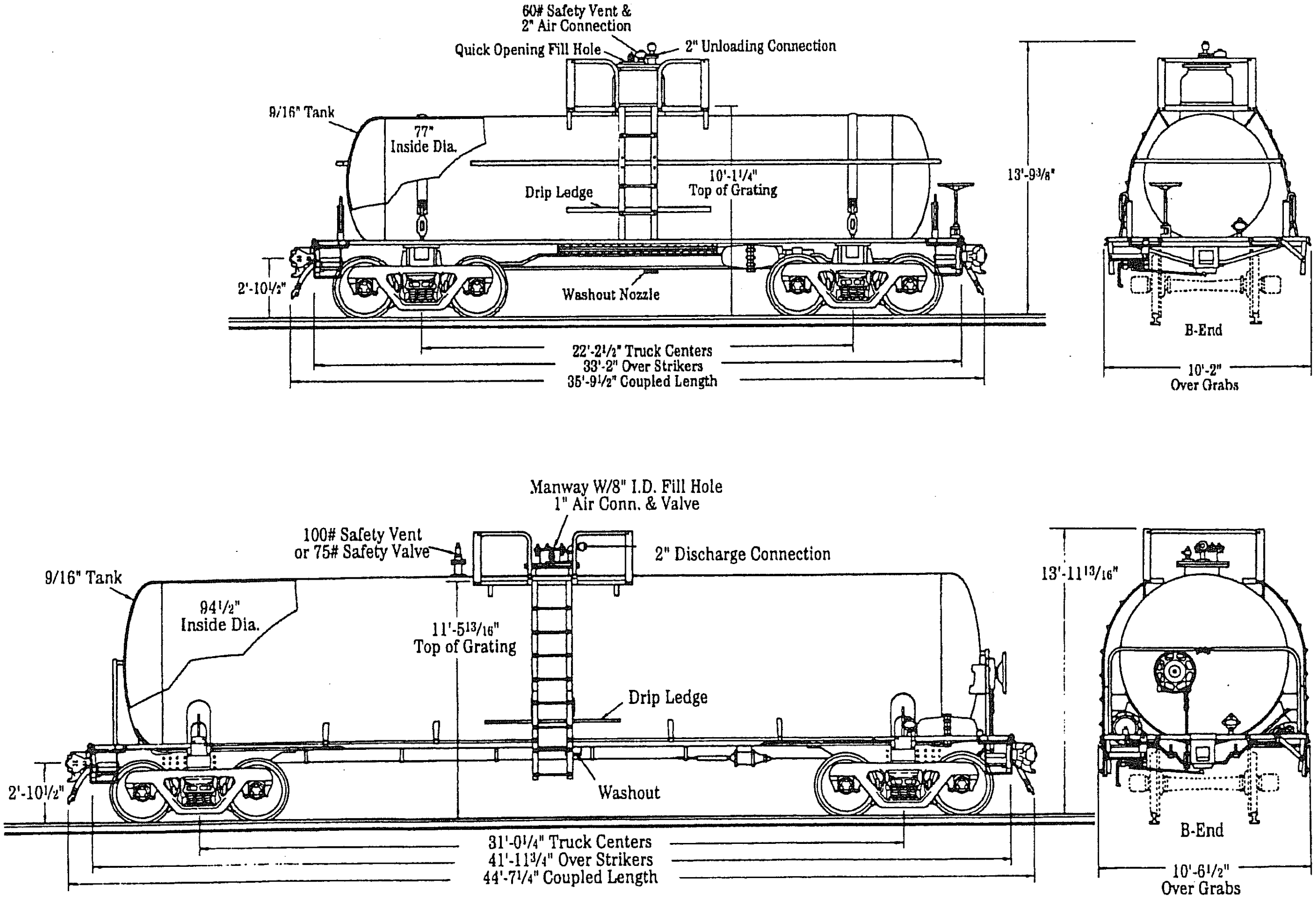

FIGURE 5 Diagram of type-103 (*top*) and type-111 (*bottom*) tank cars showing the presence and absence of the expansion dome, respectively (*8*). Note the location of the safety vent on the expansion dome of the 103 and directly on the shell of the 111 (1 in. = 25.4 mm).

On the type-103 tank cars, the safety vent was mounted on top of the expansion dome. In this position it probably was somewhat isolated from the liquid sloshing that occurred in transport. On the type-111 cars the safety vent was mounted either directly on the tank shell or on the "manway" cover (a plate attached to a short, approximately 508-mm-diameter vertical cylinder mounted on top of the tank shell). In both cases, the safety vent is in much closer proximity to waves in the liquid within the tank that are caused by rapid accelerations and decelerations that can occur in transit. The inertia of these waves causes liquid to travel up into the safety-vent nozzle, resulting in momentary compression of the air trapped within the nozzle until the wave has passed. If this compression event exceeds the rated burst pressure of the frangible disk, it will burst.

Until recently, the most commonly used disk burst pressure was 689 kPa (100 psi). In recognition of the problem of burst frangible disks, the AAR Tank Car Committee supported the U.S. Department of Transportation's (DOT) increase in the required pressure rating of frangible disks from 20 percent to 33 percent of a tank car's burst pressure (Code of Federal Regulations, or CFR, 179.15). As an example, a typical 111A-100W1 tank car that formerly had employed a 689-kPa (100-psi) disk now is required to have an 1138-kPa (165-psi) disk instead (*4*).

As the problem became evident to the railroad tank car community in the mid-1960s, there were various attempts to correct it. Tank car companies conducted research and developed various types of surge pressure reduction devices (SPRDs) that were mounted in or below the safety-vent nozzle. They generally employed baffles or other approaches to slow down the flow of liquid up into the safety vent. The intent was to reduce the rapid inertial flow of liquid up into the nozzle and thereby attenuate the surge in pressure (Union Tank Car Company, 1966 unpublished data, and General American Tank Car Co., 1967, 1969 unpublished data). Safety-vent manufacturers, chemical companies, and other after-market suppliers of the tank car industry also developed various types of SPRDs. By the early 1990s there were more than a dozen different SPRD designs in use. Tests by chemical companies and the Federal Railroad Administration on some of these devices indicated their effectiveness (Cyanamid, 1986 unpublished data, and DuPont, 1993 unpublished data; *10*) under controlled conditions. However, there were no objective data on the effectiveness of the devices in operating service and no requirement that they be used. Consequently, in cooperation with the owners and operators of tank cars equipped with safety vents and SPRDs, AAR undertook a study to obtain the data necessary to evaluate SPRD performance in reducing NARs from tank car safety vents.

METHODS

Field Study of SPRD Effectiveness

Tank car owners and operators were asked to provide AAR with the identity (car reporting mark and number) of groups of similar cars equipped with safety vents. These owners also identified the cars within these groups that were or were not equipped with SPRDs, and for those that were equipped, they identified which type of SPRD was on each car and when it had been installed. Using AAR's TRAIN 2 database on car movements, we determined the number of shipments each car had made over a specified period of time. For the corresponding period of time for each car, we used the BOE hazardous materials release database to determine the number of burst-frangible-disk NARs reported. These two groups of data enabled us to estimate the per-shipment rate of burst-frangible-disk NARs for tank cars equipped with most of the different types of SPRDs and to compare that rate to similar cars in similar service that were not equipped. These results showed that, overall, SPRDs reduced the incidence of these releases by more than 50 percent (Figure 6). These results led the AAR Tank Car Committee to require that new tank cars with safety vents be equipped with SPRDs (*11*).

What this investigation did not reveal was the relative effectiveness of SPRDs. This was because we could not be sure that the cars equipped with different SPRDs all had been exposed to the same operating environment. Therefore, we could not draw firm conclusions about the relative effectiveness of different SPRDs in preventing burst frangible disks. If car builders were going to equip their cars with SPRDs, they wanted to use the most effective designs. Even more critical was the question of retrofit of existing cars. Cars not currently equipped with SPRDs could justifiably be retrofitted—but, as with new cars, which type was best? And most critical of all, was there a need to retrofit cars that already had an SPRD? The answer to the latter question was fundamentally dependent on the relative performance of the different SPRDs. If there was sufficient heterogeneity in the performance of different SPRDs, then replacement of the less effective types with the more effective types might be justified. The Tank Car Committee and DOT also were interested in the effect of an SPRD on flow rate through the safety-vent nozzle, since this is the primary reason for its presence on the car. Answering these questions would require controlled experiments. To address these questions, AAR, the Chlorine Institute, the Federal Railroad Administration, and the Railway Progress Institute cooperated on two series of tests (*12*). The first was a series of full-scale tank car impact tests designed to enable the objective comparison of the effect of different SPRDs on the surge pressure in the safety-vent nozzle. The second was flow testing to assess the effect of SPRDs on pressure relief capacity.

Impact Testing of SPRD Effectiveness

Test Car, Instrumentation, and Laboratory

The impact tests were conducted at the ACF Industries laboratory in St. Charles, Missouri. The test car was a 100-ton, 20,884-gallon, DOT-111A-100W1, general-service tank car loaded with water. Most tank car safety-vent nozzles are either 50.8, 76.2, or 165.1 mm

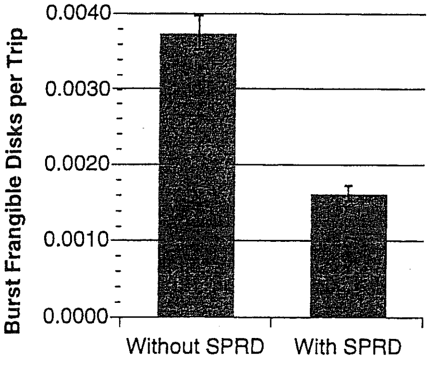

FIGURE 6 Comparison of the per-shipment rate of burst frangible disks on tank cars with and without SPRDs installed (the error bars indicate one standard deviation above and below the mean).

(2, 3, or 6½ in.) in diameter, and different SPRDs are designed specifically for these different sizes. The test tank car was equipped with a nozzle diameter of 165.1 mm (6½ in.). In our tests we simulated the internal geometry of the smaller-diameter nozzles by the installation of inserts with the appropriate inside diameter for each particular SPRD.

In place of a frangible disk, the safety vent on the test car was fitted with a steel disk equipped with a pressure transducer. This enabled us to obtain a continuous measurement of the pressure exerted at the location of the frangible disk and to compare the effects of the various SPRDs. Pressure transducers also were mounted at various other locations on the tank and the data recorded.

We could control the impact speed and the resultant coupler force with a high degree of reliability. This was accomplished by spotting the struck car (stationary until impact) at exactly the same location in each test, and by the design of the ramp that enabled precise positioning of the striking car (moving prior to impact) at a specified location on the ramp each time. The variability in impact speed was further reduced by the fact that the ramp was located within a heated building, thereby eliminating most of the effect of varying meteorological conditions such as wind, temperature, and moisture that can affect impact speed. Both the struck car and the striking car were instrumented to continuously monitor the speed of the striking car as it rolled down the ramp and the coupler force on both cars at impact.

Summary of Pilot Test Results

A pilot test was conducted to answer several questions regarding the design of the primary test and to see if we could replicate certain key results of previous research (*10*; DuPont, 1993 unpublished data). We also wanted to learn the effect on surge pressures of the test car being the struck car versus the striking car. We corroborated previous results that had shown that surge pressure was a positive function of impact speed and a negative function of outage (the percentage of tank volume not filled with liquid) (*10*). We also corroborated the results that the pressures on the top of the tank and in safety vents on the tank declined with distance from the struck end of the car (*10*) and that differences in draft gear also affect safety-vent surge pressure (DuPont, 1993 unpublished data).

We learned that higher but more variable pressure surges were generated in the safety-vent nozzle when the test car was the striking car than when it was the struck car. These data allowed us to develop estimates of the variance in surge pressure that we would see in the primary test, thereby enabling us to determine the sample size we would need to gain a specified confidence interval in our results. Taken together, these results enabled us to plan the primary test more efficiently.

Effect of SPRDs on Attenuation of Surge Pressure

Our objective was to maximize the surge pressures in the test nozzle while holding impact force constant. To ensure consistency in the test conditions, we controlled coupler force at approximately 4 448 240 N (1,000,000 lb), which corresponded to impacts of approximately 10.94 to 11.59 km/h (6.8 to 7.2 mph). This is in the upper range of normal operating service. In order to obtain reliably high surge pressures in the safety-vent nozzle, we used 0.5 percent outage and mounted the test nozzle about midway between the center of the car and the struck end.

In each test, the test car rolled down a ramp from a predetermined location and struck the standing car. We conducted these tests for 21 different SPRD setups (Table 1). These included a control for each nozzle diameter and a test of each of the SPRD-nozzle combinations known to be in use. For each of the three nozzle diameters, we established an experimental baseline, or control, by conducting 30 impacts with no SPRD in place. For each SPRD, at least 10 impacts were conducted.

TABLE 1 Impact Test Matrix for SPRDs and Nozzle Diameter

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

1 in. = 25.4 mm

During each impact we recorded the pressure at the frangible disk location for several seconds following impact. Three representative time histories for the pressure in the 165.1-mm (6½-in.) nozzle are presented in Figure 7. Manufacturers of frangible disks provided information that disks required at least 1 millisecond of pressure in excess of the rated pressure of a disk for it to burst. Therefore, in our statistical summary of the results, we defined the peak pressure as the highest pressure sustained for at least 1 millisecond.

Results

Figure 8 shows average peak surge pressures for the 50.8-mm, 76.2-mm, and 165.1-mm (2-in., 3-in., and 6½-in.) nozzles. The results for each nozzle diameter without an SPRD are in the first column, labeled "CONTROL." Each of the other columns represents the average peak pressure measured with the indicated SPRD configuration. The stars indicate the highest peak pressure observed and the error bars indicate one standard deviation above and below the mean. The highest peak pressure provides an indication of the possible range. However, these test results do not reflect the full range of possible field conditions such as the effect of outage, impact speed, nozzle position, and draft gear, described above.

Flow Testing of SPRDs

We conducted the flow tests at the Colorado Engineering Experiment Station, Inc. (CEESI), in Nunn, Colorado. We used the same SPRD configurations, safety vent, and nozzle diameters as in the impact tests, with two exceptions. We did not flow-test the half-pipe baffle

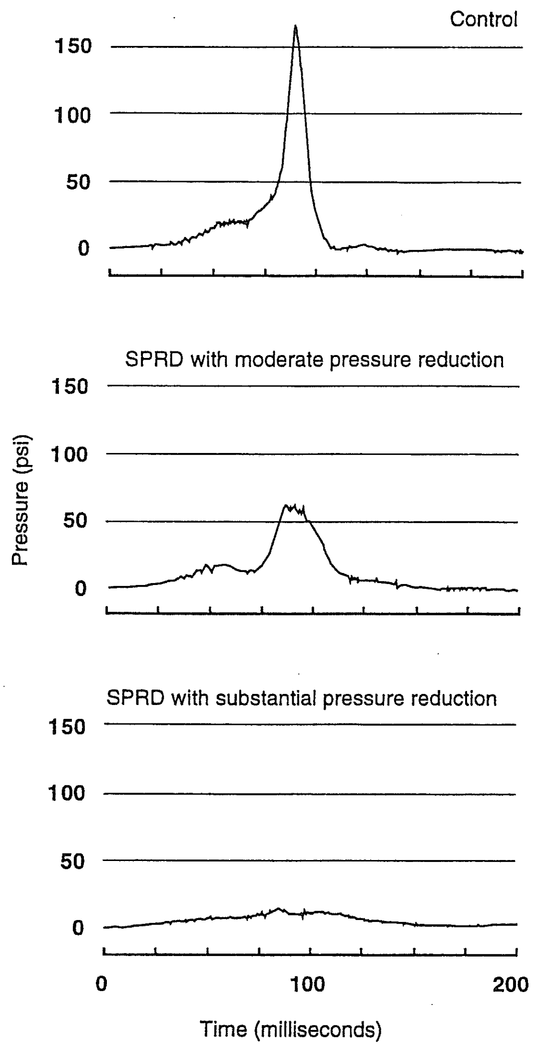

FIGURE 7 Representative time histories of the pressure in the 165.1-mm (6½-in.) safety-vent nozzle under three different test conditions (impact occurred at time = 0) (1 psi = 6.9 kPa).

because this SPRD is mounted below the nozzle and the flow area is substantially larger than the inlet to the safety-vent nozzle itself. Consequently, we assumed that the effect of the half pipe on flow is negligible. Also, the combination of Midland A-424 and A-425-15-CS was flow-tested on the 50.8-mm (2-in.) nozzle as opposed to the 165.1-mm (6½-in.) nozzle.

We conducted the flow tests of the SPRDs in accordance with standard procedures for flow-testing tank car pressure-relief vents and valves (*11*). The performance of each system was tested for pressures of 689.48 kPa (100 psi) and 1 137.64 kPa (165 psi) by determining flow at 110 percent of both pressures—758.43 kPa (110 psi) and 1 251.40 kPa (181.5 psi), respectively. Flow also was determined at two intermediate pressures, 930.80 kPa (135 psi) and 1 103.17 kPa (160 psi), to investigate the pressure-flow relationship in more detail.

The flow-test results for the controls and the SPRDs are presented in Table 2. The relationship between pressure and flow was linear (regression $R^2 > 0.998$ in all cases), and the percent reduction in flow caused by any one SPRD relative to the control for the same nozzle diameter was constant regardless of pressure. Table 2 shows the flow at 1 251.40 kPa (181.5 psi), the percent reduction in flow relative to the corresponding control, and the discharge coefficient C_d (the ratio of the actual flow to the flow through an ideal conduit with the same orifice area) for each configuration.

DISCUSSION OF RESULTS

The results of the impact testing show that all the SPRDs reduce the pressure surges in tank car safety-vent nozzles but that there is a wide range in their effects. Based on their design, the different SPRDs appear to work in one of three ways by:

1. Metering the flow into a relatively large "protected" volume above the device, but not substantially changing the direction of flow;
2. Metering and changing the direction of flow, and without a large "protected" volume above the device; or
3. Changing the direction and preventing direct upward flow, but not substantially metering flow.

SPRDs of Type 1 above, in which the ratio $V:a$ is maximized, appear to be most effective at attenuating surge pressure, where V is the protected volume of the space between the opening into the SPRD and the frangible disk, and a is the area of the opening into the SPRD.

The relationship $V:a$ 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 disk. Since the inertial effect on the ris-

TABLE 2 Effect of SPRDs on Flow

2-Inch Nozzle	Flow Rate (scfm)*	Percent Drop	Estimated Cd
CONTROL	10,125	n/a	0.87
Midland A-425-15-CS	7,027	30.6%	0.65
Midland A-424	6,553	35.3%	0.61
A425-15-CS & A-424	5,768	43.0%	0.54
Hydro-Damp 70	4,186	58.7%	0.66
1-inch orifice plate	2,464	75.7%	0.86
Perforated pipe	2,318	77.1%	0.36
3-Inch Nozzle			
CONTROL	11,412	n/a	0.97
GA/Salco sieve	6,135	46.2%	0.67
ACF inverted cone	6,032	47.1%	0.66
6½-Inch Nozzle			
CONTROL	11,456	n/a	0.98
Union Tank milkstool	8,842	22.8%	0.64
Midland milkstool	8,812	23.1%	0.72
Midland A-425-15-CS	7,337	36.0%	0.68
Midland A-424	6,818	40.5%	0.64
Surge chamber	6,764	41.0%	0.75
GA/Salco sieve	6,221	45.7%	0.67
Hydro-Damp 20 (internal)	2,792	75.6%	0.53
Hydro-Damp 20 (external)	2,300	79.9%	0.44

1 in. = 25.4 mm

* scfm = standard cubic feet per minute. These flow rates were measured at a gauge pressure of 181.5 psi at ambient temperature and barometric pressure and were adjusted to a standard temperature of 519.68°R (=60°F) and a standard barometric pressure of 14.696 psi.

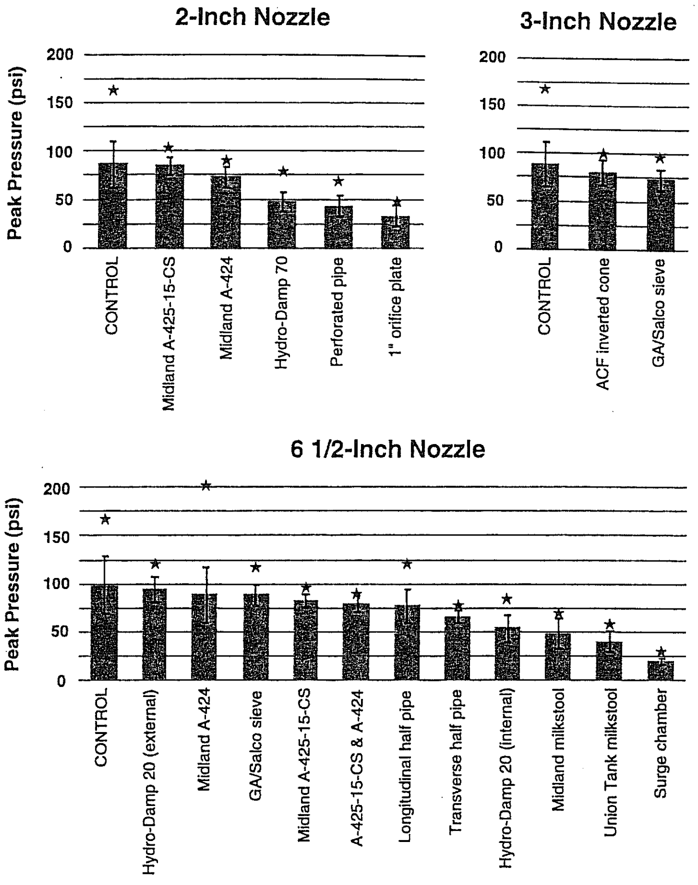

FIGURE 8 Histograms showing the effect of SPRDs on peak pressure in 2-in., 3-in., and 6½-in. safety-vent nozzles (1 in. = 25.4 mm; 1 psi = 6.9 kPa). (The error bars indicate one standard deviation above and below the mean; * indicates the highest peak pressure observed for the specified condition.)

ing 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.

We observed a significant inverse relationship ($R^2 = 0.726$) between the SPRDs' Damiani ratio and average peak surge pressure (Figure 9). SPRDs with large Damiani ratios have been used extensively on cars with 165.1-mm (6½-in.) nozzles. This is because these nozzles' large volume enabled a favorable Damiani ratio. The 25.4-mm (1-in.) orifice plate also has a large Damiani ratio and demonstrated a substantial pressure reduction when used in the 50.8-mm (2-in.) nozzle. However, prior to 1996, it could not be used without an exemption from DOT because it violated the regulatory minimum orifice size for safety vents, which specified that the opening be equivalent to a circular opening of 44.45 mm (1¾ in) in diameter.

In 1996, DOT published new rules that incorporated a performance-based flow capacity requirement (C.F.R. §179.15). In 2000, the AAR Tank Car Committee adopted a proposal jointly developed by industry and DOT representatives that established testing criteria for flow performance of safety-vent nozzles. These new requirements should enable greater use of SPRDs with favorable Damiani ratios on safety-vent nozzles less than 165.1 mm (6½ in.) in diameter.

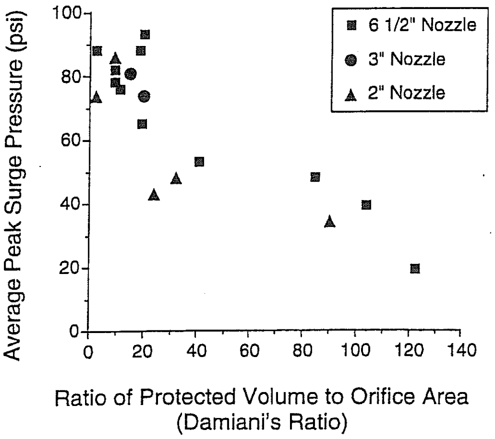

FIGURE 9 The relationship between Damiani's ratio (the protected volume above the most restrictive orifice divided by the orifice area) and the average peak surge pressure observed in the safety-vent nozzle ($r^2 = 0.726$) (1 in. = 25.4 mm; 1 psi = 6.9 kPa).

CONCLUSIONS

The field service results and impact testing show that SPRDs are an effective means of preventing NARs due to burst frangible disks. The AAR Tank Car Committee requirement that SPRDs be installed on new tank cars has probably contributed to the decline in safety-vent NARs observed in recent years (*4*). Another factor that certainly has helped is the increase in the required burst pressure for frangible disks in tank cars. Because of their higher rating, these frangible disks are more tolerant of pressure surges.

The flow testing results indicate that there is a strong correlation between the minimum cross-sectional area in the SPRD and a reduction in flow, with more restrictive minimum cross-sectional areas causing a greater reduction in flow.

SPRDs whose design maximizes Damiani's ratio appear to be the most effective at attenuating surge pressures. A wider use of the most effective SPRDs in combination with higher-rated disks offers the prospect of almost complete elimination of this cause of NAR.

ACKNOWLEDGMENTS

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