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Evaluation of Semi-Empirical Analyses for Railroad Tank Car Puncture Velocity, Part I: Correlations with Experimental Data

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13. ABSTRACT (Maximum 200 words)

This report is the first in a two-part series that focuses on methodologies to determine the puncture velocity of tank car shells. In this context, puncture velocity refers to the impact velocity at which a coupler will puncture the tank. In this report, the methodology to calculate puncture velocity is based on a set of semi-empirical equations. Moreover, these semi-empirical equations are evaluated by comparing calculated puncture velocities with results from full-scale, one-fifth scale, and actual tank car impact tests. The semi-empirical equations generally appear to produce reasonable and conservative estimates of puncture velocity when compared with the available experimental data. However, differences between the calculated and observed results become more widespread when the tank is pressurized or when shield protection is present.

The second report in this series explores and describes alternative methodologies to determine puncture velocity of tank cars based on engineering analyses.

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PREFACE

The work described in this report was performed by the John A. Volpe National Transportation Systems Center (Volpe Center) as part of a research program to develop technical information and criteria for evaluating the structural integrity of railroad tank cars. This research is being conducted in support of the Equipment and Operating Practices Research Division of the Office of Research and Development of the Federal Railroad Administration (FRA). The FRA program manager for tank car safety research is Mr. Jose Peña.

This report is the first of two in a series focusing on the puncture resistance of tank car shells from impacts of couplers from other rail cars, broken rails, and other objects. Specifically, methodologies to predict the puncture velocity of a given tank car design are evaluated. Here, the term “puncture velocity” refers to the impact velocity that will cause full penetration of the impacting object into the tank.

In this report, a methodology is described that is based on a set of semi-empirical equations that were originally developed by the Railway Progress Institute - Association of American Railroads Tank Car Safety Research and Test Project, and later modified by the industry to account for head shield protection and jacket insulation in inter-modal tanks. The modified semi-empirical equations are evaluated through comparisons with available experimental data on full-scale and actual tank cars.

The semi-empirical equations generally appear to produce reasonable and conservative estimates of puncture velocity when compared with experimental data. However, differences between the calculated and observed results become more widespread when the tank car is pressurized or when the head shield protection is present. These differences may be attributed to the simplifying assumptions that were applied during the development of the equations. Alternative methodologies to determine the puncture velocity in tank cars will be explored and discussed in the second report in this series.

METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in)	= 2.5 centimeters (cm)
1 foot (ft)	= 30 centimeters (cm)
1 yard (yd)	= 0.9 meter (m)
1 mile (mi)	= 1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2)	= 6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2)	= 0.09 square meter (m^2)
1 square yard (sq yd, yd^2)	= 0.8 square meter (m^2)
1 square mile (sq mi, mi^2)	= 2.6 square kilometers (km^2)
1 acre = 0.4 hectare (he)	= 4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz)	= 28 grams (gm)
1 pound (lb)	= 0.45 kilogram (kg)
1 short ton = 2,000 pounds (lb)	= 0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp)	= 5 milliliters (ml)
1 tablespoon (tbsp)	= 15 milliliters (ml)
1 fluid ounce (fl oz)	= 30 milliliters (ml)
1 cup (c)	= 0.24 liter (l)
1 pint (pt)	= 0.47 liter (l)
1 quart (qt)	= 0.96 liter (l)
1 gallon (gal)	= 3.8 liters (l)
1 cubic foot (cu ft, ft^3)	= 0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3)	= 0.76 cubic meter (m^3)

TEMPERATURE (EXACT)

[(x-32)(5/9)] °F = y °C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm)	= 0.04 inch (in)
1 centimeter (cm)	= 0.4 inch (in)
1 meter (m)	= 3.3 feet (ft)
1 meter (m)	= 1.1 yards (yd)
1 kilometer (km)	= 0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2)	= 0.16 square inch (sq in, in^2)
1 square meter (m^2)	= 1.2 square yards (sq yd, yd^2)
1 square kilometer (km^2)	= 0.4 square mile (sq mi, mi^2)
10,000 square meters (m^2)	= 1 hectare (ha) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gm)	= 0.036 ounce (oz)
1 kilogram (kg)	= 2.2 pounds (lb)
1 tonne (t)	= 1,000 kilograms (kg)
	= 1.1 short tons

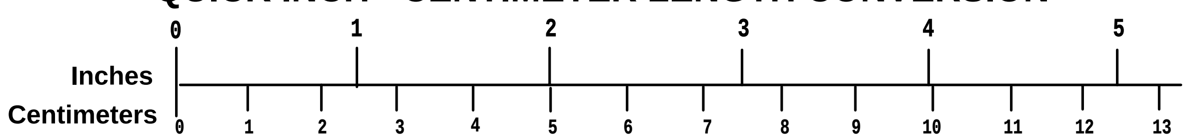
VOLUME (APPROXIMATE)

1 milliliter (ml)	= 0.03 fluid ounce (fl oz)
1 liter (l)	= 2.1 pints (pt)
1 liter (l)	= 1.06 quarts (qt)
1 liter (l)	= 0.26 gallon (gal)
1 cubic meter (m^3)	= 36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3)	= 1.3 cubic yards (cu yd, yd^3)

TEMPERATURE (EXACT)

[(9/5) y + 32] °C = x °F

QUICK INCH - CENTIMETER LENGTH CONVERSION



QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSION

°F	-40°	-22°	-4°	14°	32°	50°	68°	86°	104°	122°	140°	158°	176°	194°	212°
°C	-40°	-30°	-20°	-10°	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°

For more exact and or other conversion factors, see NIST Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50 SD Catalog No. C13 10286

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LIST OF ABBREVIATIONS AND SYMBOLS

AAR	Association of American Railroads
FRA	Federal Railroad Administration
RPI	Railway Progress Institute
RSPA	Research and Special Programs Administration

a	tank head radius
d	indentation
E	Young’s modulus or modulus of elasticity
F	coupler force
g	acceleration due to gravity (386 in/s^2)
h	plate or shell thickness
h_{eff}	effective thickness
h_h	head thickness
h_j	jacket thickness
h_s	shield thickness
K_G	gap factor
m_1	ram car mass
m_2	reaction car mass
p	internal pressure
v_o	impact velocity
v_p	puncture velocity
W_1	ram car weight
W_2	reaction car weight
α	ratio of reaction car weight to ram car weight
Δ	gap distance between shield and tank head
λ	dimensionless internal pressure parameter
τ_u	ultimate shear strength

EXECUTIVE SUMMARY

While current regulations for tank cars require head protection on most pressure cars carrying flammable gases and certain other hazardous materials, they do not prescribe how this head protection performance standard must be met. One option permitted by the current regulations in this regard is the use of a steel plate mounted in front of the tank head to act as a shield. The purpose of head protection is to increase the resistance of the tank-head to puncture from the couplers of other cars, broken rails, and other objects. The industry has now requested a performance standard for head protection based on the ability to predict puncture velocity in lieu of actual testing.

Research is being conducted by the Volpe Center in support of the Federal Railroad Administration (FRA) to examine the structural integrity of tank cars, including methodologies to determine the puncture velocity of a given tank car design. A two-part series of reports have been prepared to describe and evaluate such methodologies.

This report describes a methodology to determine the puncture velocity of tank cars based on a set of semi-empirical equations which were originally developed by the Railway Progress Institute - Association of American Railroads Tank Car Safety Research and Test Project and later modified by the industry to account for head shield protection and jacket insulation in intermodal tanks. Additionally, these semi-empirical equations are evaluated by comparing calculated puncture velocities with results from tank car impact tests. The semi-empirical equations generally appear to produce reasonable and conservative estimates of puncture velocity when compared with experimental data. However, differences between the calculated and observed results become more widespread when the tank is pressurized or when head shield protection is present. These differences may be attributed to the simplifying assumptions that were applied during the development of the equations. For example, Hertz contact is assumed in the formulation to relate maximum impact force and impact velocity, which is an assumption usually associated with problems involving elastic impacts. Alternative methodologies to determine the puncture velocity in tank cars will be explored and discussed in the second report in this series.

Sixty-five test cases involving full-scale and actual tank cars were considered in this report. The outcome predicted by the semi-empirical equations (i.e., puncture or no puncture) agreed with the experimental results in 48 out of these 65 cases. Of the 17 cases where the predicted and actual outcomes disagreed, the semi-empirical equations underestimated the puncture velocity in 15 cases, indicating conservatism when applying the semi-empirical approach. Underestimates may be considered to be on the safe side and of no concern in terms of puncture velocity.

The semi-empirical equations overestimated the actual puncture velocity in two test cases considered in this report. In the first case (Impact number 6 in Table 2 on page 12), the tank was completely filled with liquid (i.e., 0% outage) which represented an anomalous test condition since all other tests in this particular series involving pressurized tanks had an outage of 2%. In the second case where the semi-empirical equations overestimated the actual puncture velocity (Test FS-23 in Table 7 on page 18), the shell thickness was 0.875 inch which represented the largest shell thickness considered in the 65 test cases involving full-scale and actual tank cars.

This test case also involved internal pressurization at 100 psi and thermal insulation with a 0.125-inch steel jacket.

1. INTRODUCTION

Each year, the nation's railroad tank cars make about 1 million shipments with hazardous materials. These materials can be poisonous, corrosive, flammable or pose other health or safety hazards. Approximately 1,000 accidental releases of hazardous materials from tank cars are reported annually to the U.S. Department of Transportation (DOT), Research and Special Programs Administration (RSPA), Office of Hazardous Materials Safety. Most are small spills and leaks but some lead to injuries, property damage, environmental contamination and other consequences of concern.

Two DOT agencies - the Federal Railroad Administration (FRA) and the Research and Special Programs Administration (RSPA) - share responsibility for tank-car safety in the United States. Moreover, these agencies determine which materials must be shipped in tank cars best designed to withstand train crashes and to prevent accidental spills of hazardous materials. In recent years, both the FRA and the railroad industry, through the Railway Progress Institute - Association of American Railroads (RPI-AAR) Tank Car Safety Research and Test Project, have worked cooperatively to develop standards for shipment of hazardous materials in tank cars. These efforts have improved the safety of tank-car operations.

From 1978 to 1984, regulations were changed to require tank car head protection on most pressure cars carrying flammable gases and certain other hazardous materials. The purpose of tank car head protection is to increase the resistance of the tank head to puncture from the couplers of other cars, broken rails, and other objects. Current regulations, however, do not prescribe how this tank car head protection performance standard must be met but do permit, as an option, the use of steel plates mounted in front of the tank heads which act as head shield protection. The industry has now requested a performance standard for tank car head protection based on the ability to predict puncture velocity in lieu of actual testing.

Studies on tank car puncture were conducted by the RPI-AAR Tank Car Safety Research and Test Project in the 1970s. These studies were funded partially by the FRA. Data were collected during impact tests on tank-like structures of varying scales. As part of that study, semi-empirical equations were developed to calculate the velocity at which the tank car shell would puncture (referred to as the puncture velocity). More recently, the DuPont Company modified these semi-empirical equations to include the effect of head protection and thermal insulation for intermodal tanks (Belport, 1993). Subsequently, the FRA requested technical support from the Volpe National Transportation Systems Center (Volpe Center) to evaluate the applicability of the semi-empirical equations to actual tank cars.

This report is the first in a two-part series on the evaluation of semi-empirical equations to calculate the puncture velocity of tank car shells. In this report, results from the semi-empirical equations are correlated with data obtained from tank car impact tests. The sources of these experimental data include:

- RPI-AAR tank-car study report (Phillips and Olsen, 1972)
- Chlorine tank car report (Coltman and Hazel, 1992)
- Aluminum tank car report (Larson, 1992)

A second report in this series will describe comparisons between the semi-empirical equations and engineering analyses which was conducted to provide a theoretical basis for calculating the puncture velocity of tank car shells.

The semi-empirical equations to calculate puncture velocity are described in Section 2. Correlations between the calculated puncture velocity from these equations and actual test data are presented in Section 3.

2. SEMI-EMPIRICAL EQUATIONS TO CALCULATE PUNCTURE VELOCITY

The semi-empirical equations to calculate puncture velocity are discussed in this section. These equations were originally developed by the RPI-AAR Tank Car Safety Project for bare tank heads (Shang and Everett, 1972), and later modified by the DuPont Company to account for shield protection and thermal insulation.

In deriving the equations to predict puncture velocity, the energy transmitted by wave propagation is considered small compared to the initial kinetic energy and the energy dissipated during deformation, and is therefore neglected. In such cases, local indentations or penetrations are strongly coupled to the overall deformation of the structure. More-over, the process is considered as isothermal so that temperature and other thermodynamic effects are also neglected.

The derivation of equations to predict puncture velocity consists of three parts: (1) maximum impact force as a function of indentation, (2) indentation as a function of impact velocity, and (3) a failure criterion.

(1) Maximum impact force as a function of indentation.
The maximum force due to a coupler impacting the head of a tank is related to the indentation or dent size by the following equation:

$$F(d) = 35 \times 10^6 d^{3/2} \left(\frac{h}{2a}\right)^3 \left(\frac{p+15}{15}\right)^{0.6} \tag{1}$$

where F is the maximum impact force (in units of kips), d is the indentation (in inches), h is the shell thickness (in inch), a is the radius of the tank head (in inches), and p is the internal pressure (in psi). The exponent of 3/2 for d indicates that a Hertzian relationship between the contact force and the indentation was assumed in the formulation. The Hertz contact assumption implies that the problems of elastic contact and elastic impact are treated identically in this formulation. The assumption of Hertz contact may be valid for low-velocity impacts, but may be questionable for impacts involving large plastic deformations or those resulting in puncture or other types of failure.

(2) Indentation as a function of impact velocity.
The semi-empirical equation for indentation or dent size is a linear function of impact velocity:

$$d(v) = 8.8 \times 10^{-5} \left(\frac{2a}{h}\right)^2 a^{1/16} \left(\frac{W_1 v}{g}\right) \left[1 - 0.23\left(\frac{p}{40}\right)^{0.5}\right] \tag{2}$$

where d is the indentation relative to its undeformed condition (in inches), v is the impact velocity (in miles per hour), W_1 is the weight of the impacting car (in kips), and g is the acceleration due to gravity (386 in/s^2). Also, a is the ratio between the weights of the tank car and the ram car or W_2/W_1.

(3) Failure criterion.
Failure is assumed to occur when the maximum stress exceeds or is equal to the ultimate shear strength. For this purpose, the transverse shear component of stress is calculated for a flat circular plate subjected to a concentrated load offset from the center to represent a "knuckle" impact. An infinite series solution for this configuration is available in the open literature (for example, refer to page 290 of Timoshenko and Woinowsky-Krieger, 1959). The RPI-AAR formulation is based upon the first five terms of the infinite series solution which is:

$$t = 1.81\frac{F}{ah} \tag{3}$$

where F is the coupler force and a is the radius of the circular plate. Mathematically, the failure criterion can be expressed as:

$$1.81\frac{F}{ah} \geq t_u \tag{4}$$

where t_u is the ultimate shear strength of the head material. In general, mechanical properties for a given material are reported in terms of yield strength, ultimate tensile strength, and percent elongation. Assuming that triaxial stresses are related to uniaxial test data by the von Mises equivalent stress, the ultimate shear strength is equal to 57.7% of the ultimate tensile strength.

2.1 Puncture Velocity for a Bare Head

An equation to calculate the maximum coupler force as a function of impact velocity can be derived by combining equations (1) and (2):

$$F(v) = 0.00383a^{3/32}(W_1 v)^{3/2}\, l(p) \tag{5}$$

where $l(p)$ is a dimensionless function of internal pressure defined as:

$$l(p) = \left[1 - 0.23\left(\frac{p}{40}\right)^{0.5}\right]^{3/2}\left(\frac{p+15}{15}\right)^{0.6} \tag{6}$$

The numerical value of l is always greater than or equal to 1. For example, a value of 1.0 corresponds to the case of no internal pressure; a value of 1.72 to a pressure of 100 psi.

An expression to calculate the puncture velocity (i.e., the velocity at which puncture of the tank may be expected) can be derived by substituting the equation for maximum coupler force into the failure criterion. In other words, combining equations (4) and (5), and then solving for the velocity gives:

$$v_p = \frac{27.6}{W_1 a^{1/16}} \left[\frac{t_u a h}{l(p)} \right]^{2/3} \tag{7}$$

In this equation, v_p is the puncture velocity in miles per hour (mph).

2.2 Puncture Velocity for a Tank Car Head with Head Shield and/or Jacket

Test results indicate that there is a small reduction in impact velocity between head shield and tank car head impacts, suggesting that the head shield has a negligible energy absorption capability. Apparently the primary benefit of a head shield is to increase the overall material thickness. In calculating the puncture velocity, the apparent increase in material thickness is represented by an effective thickness parameter defined as

$$h_{eff} = \left[h_h^{1.33} + h_s^{1.33} + h_j^{1.33} \right]^{1/1.33} \tag{8}$$

where h_h is the tank car head thickness, h_s is the head shield thickness, and h_j is the jacket thickness. The exponent of 1.33 is an empirical constant.

A small but measurable reduction in impact velocity has been observed when a coupler hits a head shield and then when it hits the tank car head because, in general, the head shield is placed with a gap distance between it and the tank head. This reduction in impact velocity can be estimated by applying the principle of energy conservation which is stated mathematically as:

$$e_1 + \frac{1}{2} m v_1^2 = e_2 + \frac{1}{2} m v_2^2 \tag{9}$$

where e_1 and e_2 are initial and final energy states, m is the mass of the ram car, v_1 is the ram-car velocity before shield impact, and v_2 is the ram-car velocity after shield impact but before head impact. In equation (9), e_1 is assumed to be zero and $e_2 = F_S \cdot \Delta$ where F_S is the coupler force acting on the shield and D is the gap distance between the shield and the tank head.[1] The maximum coupler force acting on the head shield can be calculated using equation (5). Substituting these values into equation (9) and solving for v_2, the ram-car velocity (in miles per hour) after head shield impact but before tank car head impact is:

[1] This formulation assumes that the shield has small energy absorption capability.

$$v_2 = v_1 \sqrt{1 - \frac{2F\Delta g}{(17.6 v_1)^2 W_1}} \tag{10}$$

where g is the acceleration due to gravity (386 in/s^2). The conversion factor of 17.6 in/s = 1 mph has also been included in equation (10). A so-called gap factor can be defined as:

$$K_G = \frac{1}{\sqrt{1 - \frac{2F\Delta g}{(17.6 v_{pb})^2 W_1}}} \tag{11}$$

where v_{pb} is the puncture velocity for a bare tank car head (in mph) with effective thickness as defined in equation (8), or

$$v_{pb} = \frac{27.6}{W_1 a^{1/16}} \left[\frac{t_u a h_{eff}}{l(p)} \right]^{2/3} \tag{12}$$

Then, the puncture velocity for a tank car head with head shield protection and/or jacket insulation can be calculated from:

$$v_p = K_G \cdot v_{pb} \tag{13}$$

where K_G is the gap factor defined by equation (11) and v_{pb} is defined by equation (12).

A secondary benefit of the head shield is that it prevents puncture by blunting the corner edges of the coupler making puncture less likely. This effect has not been taken into account explicitly in these equations.

3. CORRELATION OF RESULTS FROM SEMI-EMPIRICAL EQUATIONS WITH TEST DATA

The semi-empirical equations were evaluated by comparing results from these equations with test data from various sources. The first source of data is the RPI-AAR Tank Car Head Study (Phillips and Olsen, 1972) which included 42 full-scale tests on riveted head tank cars (34 on bare head tank cars, 6 with head shield protection, and 2 with an insulating jacket), 33 one-fifth scale tests (29 on bare head tank cars and 4 with head shield protection), and 3 tests on DOT112A340W tank cars (2 on bare heads and 1 with head shield protection). Measurements on the maximum impact force and indentation size for varying impact velocities were recorded during some of these tests.

Figure 1 compares impact forces measured in the first phase of the RPI-AAR tank car head study on riveted tank cars (Phillips and Olsen, 1972) with those calculated from equation (1). Two sets of data are plotted in the figure: data for non-pressurized tank cars and data for pressurized tank cars. The straight line shown on the plot represents perfect correlation. Data points falling below the straight line represent cases where the calculated impact forces overestimated the actual test results. Conversely, points above the line represent cases where the calculated impact forces underestimated those from the actual test. The figure indicates that agreement between the calculated and measured impact forces is better at relatively low force levels (less than 200 kips) than at higher force levels. In other words, equation (1) is more accurate at predicting impact forces at relatively low impact velocities than at higher velocities. A quantitative measure of the overall scatter observed in the plot can be estimated by calculating a statistic known as the correlation coefficient. When all the data points plotted in Figure 1 are included in this calculation, the correlation coefficient is 0.858. For comparison, the correlation coefficient for a perfect correlation is equal to one. The correlation coefficient corresponding to the data for non-pressurized tank cars is equal to 0.972, and for pressurized cars the correlation coefficient is 0.627. These values for the correlation coefficient indicate that the semi-empirical equation for impact force is more accurate for non-pressurized tanks than it is for pressurized tanks.

Figure 2 compares measured indentation from the first phase of the RPI-AAR tests (Phillips and Olsen, 1972) with dent sizes calculated from equation (2). Similarly, the figure shows two sets of data corresponding to non-pressurized and pressurized tank cars. The correlation coefficient for the scatter illustrated in Figure 2 is equal to 0.895 for non-pressurized tank cars, and 0.739 for the pressurized tank cars. The correlation coefficient for all the data points plotted in Figure 2 is 0.833. As in the case of the equation for predicting maximum impact force, the equation to calculate indentation is relatively more accurate for non-pressurized tank cars than for pressurized tank cars.

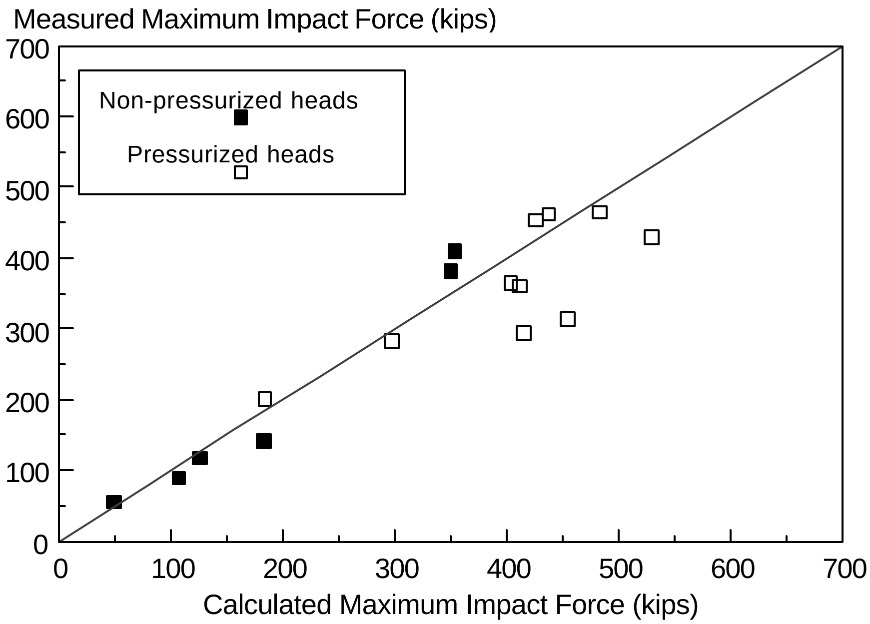

Figure 1. Comparison between Calculated and Measured Impact Forces

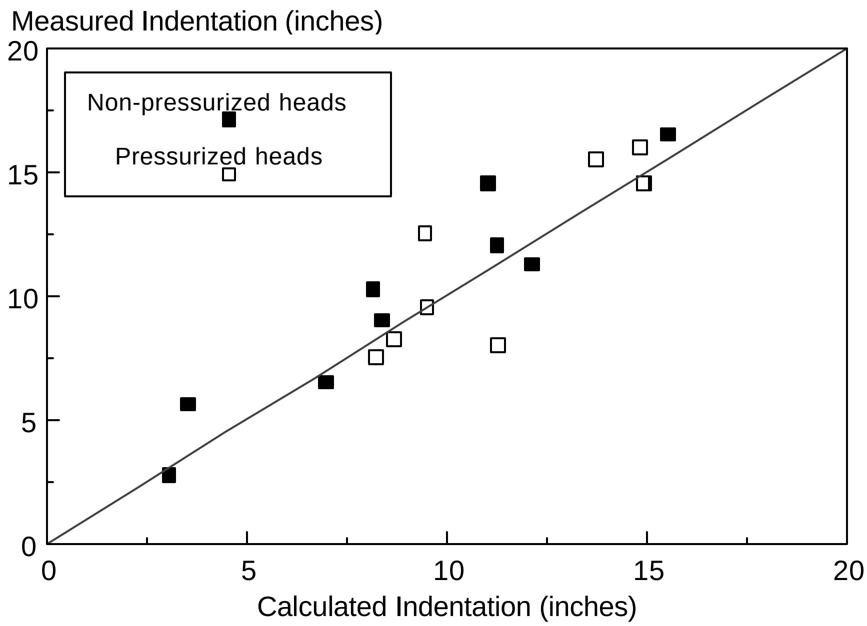

Figure 2. Comparison between Calculated and Measured Indentation

The term “puncture velocity” refers to a threshold value for a given tank car design; an impact velocity below the threshold is considered safe from puncture and a velocity higher than the puncture velocity is expected to cause full penetration of the coupler by piercing the tank. As such, the puncture velocity is difficult to quantify precisely by testing only. An impact test will result in either a dent without puncture or full penetration (puncture), but gives no additional information in regard to the threshold. Consequently, direct comparisons between actual and calculated puncture velocities cannot always be shown in graphical form. For this reason, the comparison between test results and predicted puncture velocities from the semi-empirical equations is presented in tabular form. Specifically, the tables in this section will: (1) summarize the test variables in a given test series, and (2) show the correlations between calculated puncture velocity and the experimental data.

Table 1 summarizes the test data for 25 full-scale impact experiments involving bare tank car heads. Some experiments were repeated with identical test variables except impact velocity. In all these tests, the ram car weighed 128,900 lb. Also, the material of the tank car head was AAR M-115 steel which has an ultimate tensile strength between 55 and 65 ksi. Assuming that triaxial stresses are related to uniaxial test data by von Mises equivalent stress, the ultimate shear strength is related to the ultimate tensile strength by:

$$t_u = \frac{1}{\sqrt{3}} s_u = 0.577 s_u \tag{14}$$

The last column in Table 1 lists the puncture velocity calculated using equation (7) and assuming that the ultimate shear strength is 38 ksi (i.e., 0.577×65 ksi). Puncture is predicted if the maximum impact speed is greater than the calculated puncture velocity. The calculated puncture velocity and the experimental results were consistent in 11 out of 12 cases when the tank car was not pressurized, and 8 out of 13 cases when the tank car was pressurized internally. Two experiments resulted in a slight fracture of the tank car head without full penetration of the coupler (both tests were recorded as “no puncture” events). The semi-empirical equations predicted puncture in one case which was pressurized (impact test no. 17 in Table 1), but no puncture in the other case which was not pressurized (impact test no. 18). The outage was 2% in all the tests except impact test numbers 20, 21, and 25 in which the outage was 100%.

Table 1. Full-Scale Impact Tests on Riveted Cars
RPI-AAR Data, First Series

Impact No.	Test Car Weight (kips)	Test Car Diameter (inch)	Head Thickness (inch)	Internal Pressure (psig)	Impact Velocity (mph)	Punctured (Test Result)	Calculated Puncture Velocity (mph)
1	96.6	78	0.5000	0	4.3	no	17.9
2	“	“	“	“	5.0	no	“
3	“	“	“	“	6.2	no	“
22	“	“	“	“	16.0	no	“
4	107.3	80	0.4375	0	7.2	no	16.5
5	“	“	“	“	8.4	no	“
6	128.9	88	0.4375	0	10.2	no	17.4
7	“	“	“	“	12.9	no	“
8	128.2	88	0.4375	20	8.7	no	14.8
9	“	“	“	“	9.5	no	“
10	108.4	80	0.4375	40	11.0	no	12.7
11	“	“	“	“	12.7	no	“
12	107.5	83	0.4375	40	14.0	no	13.1 (x)
13	“	“	“	“	14.0	no	“ (x)
14	130.0	88	0.4375	40	16.0	YES	13.4
15	128.8	88	0.4375	20	14.9	no	14.8 (x)
16	127.0	88	0.4375	20	15.0	no	14.8 (x)
17	127.4	88	0.4375	30	15.7	no (see Note 6)	14.0 (x)
18	107.6	83	0.4375	20	15.7	no (see Note 6)	14.4 (x)
19	107.3	80	0.4375	0	16.0	no	16.5
20	40.9	83	0.4375	0	8.5	no	18.0
21	“	“	“	“	11.2	no	“
23	108.4	80	0.4375	20	16.1	YES	16.3 (x)
24	108.4	80	0.4375	10	16.1	YES	14.0
25	48.0	88	0.4375	0	16.1	YES	15.2

NOTES:

(1) Source of the test data is the Final Phase 5 Report on Tank Car Head Study (RA-05-1-17), Table C-I on page C-7.

(2) **All tests were performed on bare heads.** That is, no shield protection or thermal insulation was present in these tests.

(3) In all test cases, the ram car weight was 128.9 kips.

(4) The head material was AAR M-115 steel (ultimate tensile strength between 55 to 65 ksi). In the calculation of puncture velocity, the ultimate shear strength was assumed to be 38 ksi.

(5) The outage was 2% in all tests except tests 20, 21, and 25 in which the outage was 100%.

(6) Puncture is predicted if the maximum impact speed is GREATER than the calculated puncture velocity.

(7) Test result was recorded as a “no puncture” test, but slight fractures were observed.

(8) The symbol (x) indicates disagreement between the predicted and experimental event (i.e., “puncture” or “no puncture”).

Table 2 lists the test parameters and the calculated puncture velocities for a second test series comprising nine full-scale experiments conducted in the RPI-AAR Tank Car Head Study (Phillips and Olsen, 1972). In this test series, the tank car head thickness was 0.5 inch and the ram car weighed 128,900 lb. The predicted outcome (i.e., whether puncture occurred or not) was consistent with the experimentally observed result in all but two cases. Pressurized tank cars were involved in the two cases where the predictions and experiments disagreed. In one of the anomalous cases (impact test no. 6), the outage was 0% which in itself was an anomaly since the outage in all other tests involving pressurized tank cars was 2%.

Eight tests on full-scale riveted tank car heads were conducted during the RPI-AAR Tank Car Head Study. Six tests were conducted on tank cars with a head shield of 0.5 inch thickness, and two tests were conducted on a conventionally insulated tank car which had 4 inches of fiberglass and steel jacket of 0.125 inch thickness. Table 3 lists the variables for each of these tests. Although the tank car head material (AAR M-115 steel) and the head shield material (A-36 steel) were different designations, the ultimate shear strength for both was assumed to be the same (38 ksi) in the calculation of puncture velocity. In the case of the jacketed and insulated tank car, the jacket material was assumed to have the same ultimate shear strength as the head. The table indicates agreement between the calculated and experimental results for puncture in four out of six cases involving head shield protection and none out of two cases for the jacketed and insulated tank cars.

The RPI-AAR Tank Car Head Study also included experiments using one-fifth scale-model tanks. These scale-model experiments were performed as a cost-saving measure since more scale-model tests could be performed than full-scale tests at the same cost. Table 4 lists the test data for the one-fifth scale-model tests without head shield protection. The calculated puncture velocity falls within the bounds of the test results in two out of eight cases. The test results corresponding to a full-scale thickness of 5/8 (0.625) inch and tank car heads made from TC-128B material are shown in Figure 3 (see page 16). Differences between the predicted and observed results are evident except when the internal pressure was 50 psi. Table 5 lists the variables in the one-fifth scale-model tests with head shield protection. Calculations suggested that puncture would occur in all the listed cases but no punctures were observed in any of the tests, indicating that the calculations are conservative. On the other hand, the results from Table 4 may also suggest that the usefulness of the one-fifth scale-model data may be questionable without further examinations.[2]

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[2] Discrepancies between scaled and full-scale test data were encountered in impacts test involving chlorine tank cars (Coltman and Hazel, 1992).

Table 2. Full-Scale Impact Tests on Riveted Tank Cars
RPI-AAR Data, Second Series

Impact No.	Test Car Weight (kips)	Outage	Internal Pressure (psig)	Impact Velocity (mph)	Punctured (Test Result)	Calculated Puncture Velocity (mph) (see Note 4)
1	48.5	100%	0	8.8	no	17.8 to 20.1
2	“	“	“	8.9	no	“
3	45.4	100%	0	6.0	no	17.9 to 20.2
4	“	“	“	11.5	no	“
5	125.2	2%	40	6.2	no	13.0 to 14.6
6	127.0	0%	40	10.5	YES	13.0 to 14.6 (x)
7	128.5	2%	40	10.5	no	13.0 to 14.6
8	128.6	2%	40	14.0	YES	13.0 to 14.6 (x)
9	128.5	2%	40	12.5	no (see Note 6)	13.0 to 14.6

NOTES:
(1) Source of the test data is the Final Phase 5 Report on Tank Car Head Study (RA-05-1-17), Table C-II on page C-17.
(2) **All tests were performed on bare tank car heads.** That is, no head shield protection or thermal insulation was present in these tests.
(3) In all test cases, the ram car weight was 128.9 kips, the tank car diameter was 87.5 inches, and the tank car head thickness was 0.5 inch.
(4) The tank car head material was AAR M-115 steel (ultimate tensile strength between 55 to 65 ksi). In the calculation of puncture velocity, the ultimate shear strength was assumed to be 32 and 38 ksi corresponding to the two values listed for calculated puncture velocity.
(5) Puncture is predicted if the maximum impact speed is GREATER than the calculated puncture velocity.
(6) Test result was recorded as a “no puncture” test, but slight fractures were observed.
(7) The symbol (x) indicates disagreement between the predicted and experimental event (i.e., “puncture” or “no puncture”).

Table 3. Full-Scale Impact Tests on Riveted Tank Cars with Head Shield Protection or Jacket Insulation RPI-AAR Data, Second Series

Impact No.	Test Car Weight (kips)	Shield or Jacket Thickness (inch)	Measured Impact Speed (mph)	Punctured (Test Result)	Calculated Puncture Velocity (mph)
10	127.1	0.5	12.5	no	16.5
11	129.9	0.5	14.0	no	16.4
12	127.7	0.5	16.1	no	16.5
13	128.8	0.5	17.0	no	16.5 (x)
14	128.2	0.5	16.5	no	16.5
15	127.3	0.5	17.0	no	16.5 (x)
16	128.3	0.125	17.1	YES	13.0 (x)
17	127.8	0.125	14.5	no (see Note 5)	13.0 (x)

NOTES:

(1) Source of the test data is the Final Phase 5 Report on Tank Car Head Study (RA-05-1-17), Table C-II on page C-17.

(2) In all test cases, the ram car weight was 128.9 kips, the test car diameter was 87.5 inches, the internal pressure was 40 psig, the tank car head thickness was 0.5 inch, and the distance between the head shield (or jacket) and the tank car head (gap distance, *D*) was 4 inches. Head shield protection was present in impact tests 10 through 15 (head shield thickness of 0.5 inch). Four-inch fiberglass insulation and a steel jacket of 0.125 inch thickness were present in impact tests 16 and 17.

(3) The tank car head material was AAR M-115 steel. The head shield material was A-36 steel. In the calculation of puncture velocity, the ultimate shear strength was assumed to be 38 ksi for both materials.

(4) Puncture is predicted if the maximum impact speed is GREATER than the calculated puncture velocity.

(5) Test result was recorded as a “no puncture” test, but slight fractures were observed.

(6) In all tests list in this table, the outage was 2%.

(7) The symbol (x) indicates disagreement between the predicted and experimental event (i.e., “puncture” or “no puncture”).

Table 4. One-Fifth Scale Tank Car Head Impact Tests without Head Shield Protection
RPI-AAR Data

Impact No.	Tank Car Head Material	Tank Car Head Thickness (inch)	Internal Pressure (psig)	Maximum Impact Speed Resulting in No Puncture (mph)	Minimum Impact Speed Resulting in Puncture (mph)	Calculated Puncture Velocity (mph)
33-35,40,46,54	TC-128-B	0.625	0	13.0	14.0	10.8
37-39	TC-128-B	0.625	50	7.8	8.3	**8.1**
19-21,36	TC-128-B	0.625	100	6.6	6.9	7.5
56-58	TC-128-B	1	0	13.9	15.0	**14.8**
41-43,55	TC-128-B	1	100	9.8	10.2	10.3
44-45,47	TC-128-B	0.8125	100	7.9	8.3	9.0
48-50	A-285-C	1	100	8.3	8.8	8.9
51-53	A-515-70	0.8125	100	7.0	7.4	8.7

NOTES:

(1) Source of the test data is the Final Phase 5 Report on Tank Car Head Study (RA-05-1-17), Tables E-I and E-II on pages E-6 and E-7.

(2) **All tests were performed on bare tank car heads.** The value of the tank car head thickness was extrapolated from 1/5-scale to full-scale.

(3) In all test cases, the ram car weight was 357.8 kips, the test car weight was 358.0 kips, and the test car diameter was 118.5 inches.

(4) In the calculation of puncture velocity, the ultimate shear strength was assumed to be 45 ksi for AAR TC-128-B steel (average reported UTS = 76.2 ksi), 36 ksi for ASTM A-285-C steel (average UTS = 62.6 ksi), and 43 ksi for ASTM A-515-70 steel (average UTS = 71.7 ksi). The assumed values of ultimate shear strength are roughly 60% of the ultimate tensile strength.

(5) Bolded numbers in the column for "Calculated Puncture Velocity" refer to agreement with experimental observations.

Table 5. One-Fifth Scale Tank Car Head Impact Tests with Head Shield Protection
RPI-AAR Data

Impact No.	Ram Car Weight (kips)	Tank Car Head Thickness (inches)	Head Shield Thickness (inches)	Internal Pressure (psig)	Measured Impact Speed (mph)	Punctured (Test Result)	Calculated Puncture Velocity (mph)
71	357.8	0.625	0.5	100	14.0	no	12.8
72	“	“	“	“	15.9	no	“
73	“	“	“	“	17.5	no	“
74	451.5	0.625	0.5	100	17.8	no	11.1

NOTES:

(1) Source of the test data is the Final Phase 5 Report on Tank Car Head Study (RA-05-1-17), Tables E-I and E-II on pages E-6 and E-7.

(2) In each test case, the gap distance was 4 inches.

(3) In all test cases, the test car weight was 358.0 kips and the test car diameter was 118.5 inches.

(4) The tank car head material was AAR TC-128-B steel (average UTS =76.2 ksi). The head shield material was ASTM A-606 steel (average UTS = 75.9 ksi). In the calculation for puncture velocity, the ultimate shear strength of the head and shield material are assumed to be the same and equal to 45 ksi (which corresponds approximately to 60% of the UTS).

(5) Puncture is predicted if the maximum impact speed is GREATER than the calculated puncture velocity.

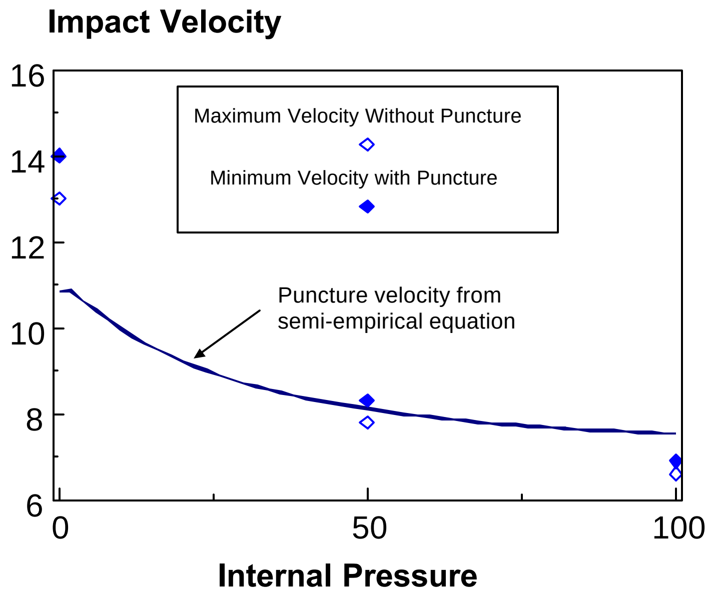

Figure 3. Comparison between Calculated Puncture Velocity and One-Fifth Scale Data for TC-128B Tank Car Head Material with 0.625-inch Thickness

The RPI-AAR Tank Car Head Study (Phillips and Olsen, 1972) also included three tests on DOT112A340W tank cars: two with bare tank car heads and one with head shield protection. The variables for these three tests are listed in Table 6. In the case of no head shield protection, the predicted puncture velocity of 10.0 mph agreed with the test results where no puncture was observed at 9.3 mph while puncture occurred at 12.7 mph. In the test with head shield protection, the calculated puncture velocity was 15.9 mph while the test conducted at 15 mph did not result in puncture, confirming the calculated result.

Impact tests on chlorine tank cars (Coltman and Hazel, 1992) provided another source of data to compare with the semi-empirical equations. Table 7 shows data for nine full-scale tests (three with head shield protection, and six with steel jackets). The calculated puncture velocity for each case involving head shield protection is 20.5 mph, but one experiment conducted at 23.4 mph did not result in puncture. Again, this result indicates conservatism regarding the semi-empirical equations. Conversely, in the case of a steel jacket with 0.875-inch thickness, the calculation overestimated the actual puncture velocity; the threshold was computed to be 16.9 mph, but puncture occurred in a test conducted at 15.1 mph. In the case of steel jacket with 0.813-inch thickness, the puncture velocity was calculated to be 16.2 mph and no puncture was observed in a test conducted at an impact velocity of 15.1 mph which corroborates the calculated result.

Table 6. RPI-AAR Impact Tests on DOT112A340W Tank Cars

(a) No Head Shield Protection

Impact No.	Test Car Weight (kips)	Head Shield Thickness (inch)	Measured Impact Speed (mph)	Punctured (Test Result)	Calculated Puncture Velocity (mph)
1	127.1	-	9.3	no	10.0
2	“	-	12.7	YES	“

(b) With Head Shield Protection

Impact No.	Test Car Weight (kips)	Head Shield Thickness (inch)	Maximum Impact Speed (mph)	Punctured (Test Result)	Calculated Puncture Velocity (mph)
3	129.9	0.5 (1/2)	15.5	no	15.9

NOTES:

(1) Source of the test data is the Final Phase 5 Report on Tank Car Head Study (RA-05-1-17), Table F-I on pages F-5.

(2) Impact test numbers 1 and 2 were performed on bare tank car heads. In all test cases, the tank car head thickness was 0.6875 (11/16) inch.

(3) For impact test number 3, the gap distance was 4 inches.

(4) In all test cases, the ram car weight was 348.9 kips, the test car diameter was 119.0 inches, and the internal pressure was 100 psig.

(5) The tank car head material was AAR TC-128-B steel. The minimum requirement for the ultimate tensile strength of this material is 81 ksi. The head shield material was ASTM A-515-70 steel. In the calculation of puncture velocity, the ultimate shear strength was assumed to be 60 ksi for both materials (which corresponds roughly to 75% of the minimum requirement UTS for TC-128-B steel).

(6) Puncture is predicted if the maximum impact speed is GREATER than the calculated puncture velocity.

Table 7. Full-Scale Impact Tests

(a) 112/114 Tank Cars (with Head Shield Protection)

Test	Ram Car Weight (kips)	Reaction Car Weight (kips)	Tank Car Head Thickness (inch)	Tank Car Head Diameter (inches)	Head Shield Thickness (inch)	Insulation Thickness (inch)	Maximum Impact Speed (mph)	Punctured (Test Result)	Calculated Puncture Velocity (mph)
FS-11	261.25	263.55	0.688 (11/16)	120	0.5 (1/2)	0.5 (1/2)	16.0	no	20.5
F2-12	“	“	“	“	“	“	19.0	no	“ (x)
FS-13	“	“	“	“	“	“	23.4	no	“

(b) 105 Tank Cars (with Steel Jacket)

Test	Ram Car Weight (kips)	Reaction Car Weight (kips)	Tank Car Head Thickness (inch)	Tank Car Head Diameter (inches)	Jacket Thickness (inch)	Insulation Thickness (inch)	Maximum Impact Speed (mph)	Punctured (Test Result)	Calculated Puncture Velocity (mph)
FS-21	268.25	268.45	0.875 (7/8)	102	0.125 (1/8)	4	13.0	no	16.9
FS-23	“	“	“	“	“	“	15.1	YES	“ (x)
FS-22	“	“	“	“	“	“	17.0	YES	“
FS-25	268.25	268.45	0.813 (13/16)	102	0.125 (1/8)	4	13.8	no	16.2
FS-24	“	“	“	“	“	“	14.3	no	“
FS-26	“	“	“	“	“	“	15.1	no	“

NOTES:
(1) Source: M. Coltman and M. Hazel, “Chlorine Tank Car Puncture Resistance Evaluation,” DOT/FRA/ORD-92/11, July 1992.
(2) Insulation thickness was considered equivalent to the “gap distance” in the calculation of puncture velocity. For the 112 tank cars, an additional 4-inch gap between the head shield and insulation was assumed.
(3) The 105 tank cars had steel jackets, but no head shield. The 112 tank cars had shield protection, but no jacket.
(4) In all tests, the internal pressure was 100 psi.
(5) For calculating the puncture velocity, the ultimate shear strength is assumed to be 60 ksi.
(6) Puncture is predicted if the maximum velocity is GREATER than the calculated puncture velocity.
(7) The symbol (x) indicates disagreement between the predicted and experimental event (i.e., “puncture” or “no puncture”).

Table 8 shows data from the same test program (Coltman and Hazel, 1992) using actual tank cars; one DOT112J340W tank car and four DOT105A500W cars. These tank cars have different head diameters as well as different thicknesses for the shell, head shield, and thermal protection system insulation jacket. In the single test on the DOT112J340W tank car, the calculated puncture velocity of 20.1 mph was confirmed by the test result (no puncture was observed in a test conducted at 18.5 mph). In the tests on the DOT105A500W tank cars, the calculated puncture velocity of 16.8 mph underestimated the actual threshold value (a test conducted at 17.5 mph did not puncture). The latter result could suggest that the semi-empirical equations produce conservative estimates of puncture velocity.

Impact tests have also been conducted on aluminum DOT111A60ALW1 tank cars (Larson, 1992). Six experiments were conducted in this test series (three with a bare head and three with head shield protection). Table 9(a) lists the data for the tests conducted on bare heads where the impact velocity was the only variable. The calculated puncture velocity for these tests was found to be 6.1 mph, which appears to overestimate the actual puncture velocity because a test conducted at 5.0 mph resulted in fracture (but not full penetration of the coupler).

In order to calculate puncture velocity for the test cases involving head shield protection, the semi-empirical equations were modified to account for different materials in the head shield and the tank head. In these tests, the head shields were made from steel and the tank shells from aluminum. The modification to account for different materials in the head shield and the tank is similar to that derived for effective thickness. By mathematical analogy, an effective ultimate shear strength t_{eff} is defined as:

$$t_{eff} = \left[t_{SU}^{q} + t_{HU}^{q} \right]^{1/q} \tag{15}$$

where t_{SU} is the ultimate shear strength of the head shield material, t_{HU} is the ultimate shear strength of the tank head material, and q is treated as an empirical constant. The ultimate shear strength of 5052 aluminum is assumed to be 14.4 ksi, and that of AAR TC-128 is 47 ksi (both values correspond to 0.577 times the ultimate tensile strength of these respective materials). In the present calculations, q in equation (15) is assumed to be 3.

Table 8. Impact Tests on Actual Tank Cars

(a) DOT112J340W

Test	Ram Car Weight (kips)	Reaction Car Weight (kips)	Tank Car Head Thickness (inch)	Tank Car Head Diameter (inches)	Head Shield Thickness (inch)	Insulation Thickness (inch)	Maximum Impact Speed (mph)	Punctured (Test Result)	Calculated Puncture Velocity (mph)
112-1	265.16	333.0	0.688 (11/16)	120	0.5 (1/2)	0.5 (1/2)	18.5	no	20.1

(b) DOT105A500W

Test	Ram Car Weight (kips)	Reaction Car Weight (kips)	Tank Car Head Thickness (inch)	Tank Car Head Diameter (inches)	Head Shield Thickness (inch)	Insulation Thickness (inch)	Maximum Impact Speed (mph)	Punctured (Test Result)	Calculated Puncture Velocity (mph)
105-1	261.16	257.35	0.844 (27/32)	102	0.125 (1/8)	4	14.9	(see Note 4)	16.8
105-2	“	“	“	“	“	“	15.5	no	“
105-3	“	“	“	“	“	“	16.6	no	“
105-4	“	“	“	“	“	“	17.5	no	“ (x)

NOTES:

(1) Source: M. Coltman and M. Hazel, “Chlorine Tank Car Puncture Resistance Evaluation,” DOT/FRA/ORD-92/11, July 1992.
(2) Insulation thickness was considered equivalent to the “gap distance” in the calculation of puncture velocity. For the 112 tank cars, an additional 4-inch gap between the head shield and insulation was assumed.
(3) The 105 tank cars had steel jackets, but no head shield. The 112 tank cars had head shield protection, but no jacket.
(4) In test 105-1, “failure” occurred at the stub sill reinforcement rather than by puncture. In the subsequent tests on 105 tank cars, the reinforcement was removed.
(5) For all tank cars in these tests, the internal pressure was 100 psi.
(6) For calculating the puncture velocity, the ultimate shear strength was assumed to be 60 ksi.
(7) Puncture is predicted if the maximum velocity is GREATER than the calculated puncture velocity.
(8) The symbol (x) indicates disagreement between the predicted and experimental event (i.e., “puncture” or “no puncture”).

Table 9. Impact Tests on Aluminum/Cold Temperature Tank Cars

(a) DOT111A60ALW1 (Bare Head)

Test	Ram Car Weight (kips)	Reaction Car Weight (kips)	Tank Car Head Thickness (inch)	Tank Car Head Diameter (inches)	Internal Pressure (psig)	Impact Speed (mph)	Punctured (Test Result)	Calculated Puncture Velocity (mph)
FA-13	263.0	263.0	0.625 (5/8)	102	4	3.0	no	6.1
FA-12	“	“	“	“	“	5.0	YES (see Note 4)	“ (x)
FA-11	“	“	“	“	“	8.0	YES	“

(b) DOT111A60ALW1 with Head Shield Protection

Test	Ram Car Weight (kips)	Reaction Car Weight (kips)	Tank Car Head Thickness (inch)	Tank Car Head Diameter (inches)	Internal Pressure (psig)	Head Shield Thickness (inch)	Maximum Impact Speed (mph)	Punctured (Test Result)	Calculated Puncture Velocity (mph)
FA-21	263.0	263.0	0.625 (5/8)	102	4	0.5 (1/2)	17.8	YES	19.4 (x)
FA-22	“	“	“	“	“	“	15.1	no	“
FA-31	263.0	263.0	0.625 (5/8)	102	4	0.625 (5/8)	17.5	no (see Note 5)	20.7

NOTES:

(1) Source: W.G. Larson, “Aluminum/Cold Temperature Tank Car Puncture Resistance Tests: Data Report,” DOT/FRA/ORD-92/29, August 1992.

(2) In these tests, the bare tank car head was made from 5052 aluminum alloy. The head shield material was AAR TC-128.

(3) For calculating the puncture velocity, the ultimate shear strength for aluminum was assumed to be 14.4 ksi, and 46.8 ksi for steel.

(4) According to the report, the coupler did not penetrate entirely into the tank car head, but shear cracks were clearly visible, indicating a slight puncture and suggesting that the impact velocity was near the puncture threshold velocity.

(5) This test was considered invalid because the couplers on the reaction and ram cars did not fully couple which may have interfered with the ram penetration force.

(6) Puncture is predicted if the maximum velocity is GREATER than the calculated puncture velocity.

(7) The symbol (x) indicates disagreement between the predicted and experimental event (i.e., “puncture” or “no puncture”).

Table 9(b) lists the variables for three impact tests on aluminum tank cars protected with steel head shields. Two tests were conducted under identical conditions except the initial impact velocity. The puncture velocity for these tests was calculated to be 19.4 mph, which appears to overestimate the actual puncture velocity because a test at 17.8 mph resulted in puncture. The third test in this series involved a shield with increased thickness (0.625 inches versus 0.5 inches in the previous two tests). Consequently, a higher puncture velocity (20.6 mph) was calculated which was supported by the test result; no puncture as observed for a 17.5-mph impact.[3]

[3] The test result at 17.5 mph must be qualified (see Note 5 at the bottom of Table 9).

4. DISCUSSION AND SUMMARY

Failures from couplers impacting tank car heads have been characterized by: (1) plug formation, (2) petal formation or dishing, (3) ductile hole enlargement, and (4) fragmentation.[4] The semi-empirical equations do not make a distinction between these different failure modes. In addition, in some tank car designs, failures often occur at the reinforcing pad rather than at the location of coupler impact, but the semi-empirical equations do not account for this possibility.

Although these equations have the capability to account for the effect of internal pressurization, they do not account for the effect of the liquid contained in the tank. For example, the results from impact tests 5 and 6 in Table 2 suggest that outage has a significant effect on the puncture velocity, but outage is not considered in the semi-empirical equations.

As presented in Section 2, the semi-empirical equations do not have the capability to account for different materials in the tank car head and the head shield. For example, the case of an aluminum tank car head protected by a steel head shield cannot be handled directly by the equations without modification. Such a modification was described in Section 3, but does not have a theoretical basis other than by mathematical analogy to the effective thickness parameter.

The failure criterion for the semi-empirical equations is based on the transverse shear stress component for a flat plate subjected to a concentrated load. The load may be applied at the center of the plate or off-center. Physically, this component of stress is reasonable to apply as a failure criterion since the failure modes associated with tank car puncture are invariably shear-type failures. However, in the RPI-AAR formulation, the mathematical expression for this stress component was derived by taking only the first five terms in the infinite series solution. Further examinations conducted in the present study have revealed that the number of terms required to match the infinite series solution for transverse shear to within a given accuracy depends on the distance the load is applied from the center of the plate. For example, if the load is applied at an offset distance 0.2 times the radius of the plate, 10 terms are needed to achieve 2 decimal-place accuracy. If the load is applied at an offset distance of 0.3 times the plate radius, 20 terms are required for the same level of accuracy. The failure criterion for tank car punctures will be discussed in greater detail in the next report in this series.

Notwithstanding the foregoing discussion, the predictions from the semi-empirical equations for puncture velocity are generally within reasonable agreement with experimental data. But the agreement between predictions and experimental data becomes worse when head shield protection is present and when the tank is internally pressurized. In cases involving head shield protection, the calculated puncture velocity appears to be conservative (lower than observed test results).

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[4] For example, see Shang and Everett, 1972.

Neglecting the one-fifth scale data, 65 test cases involving full-scale and actual tank cars were considered in this report. The outcome predicted by the semi-empirical equations (i.e., puncture or no puncture) agreed with the experimental results in 48 out of these 65 cases. Of the 17 cases where the predicted and actual outcomes were different, the semi-empirical equations overestimated the puncture velocity in two cases. In other words, in almost all cases where the predicted and actual outcomes disagreed, the semi-empirical equation underestimated the actual puncture velocity, indicating conservatism when applying the semi-empirical approach. Underestimates may be considered to be on the safe side and of no concern in terms of puncture velocity.

The semi-empirical equations overestimated the actual puncture velocity in two tests cases considered in this report. In the first case (Impact number 6 in Table 2 on page 12), the tank car was completely filled with liquid (i.e., 0% outage) which represented an anomalous test condition since all other tests in this particular series involving pressurized tank cars had an outage of 2%. In the second case where the semi-empirical equations overestimated the actual puncture velocity (Test FS-23 in Table 7 on page 18), the shell thickness was 0.875 inch which represents the largest shell thickness considered in the 54 test cases involving full-scale and actual tank cars. This test case also involved internal pressurization at 100 psi and thermal insulation with a 0.125-inch jacket.

Agreement between calculated puncture velocity and test results may be improved by either (1) adjusting or modifying the semi-empirical equations to match the available test data, or (2) deriving alternative formulations based on engineering principles. These options will be described in the second report of this series.

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