Calculating Effectiveness Rates[1] of Tank Car Options

Summary

This paper describes the methodology used to calculate the effectiveness rates of alternative standards for tank cars to be used in high-hazard flammable trains (HHFTs). These calculations were performed in support of the Pipeline and Hazardous Materials Safety Administration's (PHMSA) Notice of Proposed Rule Making (NPRM) *Hazardous materials: Enhanced Tank Car Standards and Operational Controls for High Hazard Flammable Trains*, Docket No. PHMSA-2012-0082 (HM-251). PHMSA is considering three tank car Options, which incorporated design enhancements to protect the shell and heads of tank car tanks from puncture, protect the top and bottom fittings from damage, and protect the tank from thermal tears or ruptures when exposed to pool fire conditions. The methodology described in this technical supplement relies on accident data to calculate the effectiveness rates for the entire design as well as individual design enhancement features. The calculated aggregate effectiveness rates and marginal design feature effectiveness rates, for the three proposed tank car Options are provided in the following table.

Tank Car	Total	Head puncture	Shell puncture	Thermal damage	Top fittings	BOV
Option 1	54	21	17	12	4	<1
Option 2	51.3	21	17	12	1.3	<1
Option 3	41.3	19	9	12	1.3	<1

Introduction

HHFTs pose unique risks in the railroad operating environment. Key considerations include:

- High volume transported in a single train. In a unit train, all of the cars are either loaded or empty. Additionally, unit trains of crude oil and ethanol contain tank cars that are of the same specification.
- Release of flammable liquids in a derailment can have immediate effects (in the form of a pool fire) on the integrity of adjacent cars. In the derailments listed below (Table 3), there were 29 occasions in which a tank car survived the derailment but lost containment (thermal tear) after exposure to pool fire conditions.[2]
- Crude oil and ethanol are the commodities with the top two number of tank car originations in North America and represent a third of the originations of the top 25 commodities by loaded tank car originations over the last three years (see Figure 1).

HHFTs are not an entirely new phenomenon. However, the volume shipped over the last decade is

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[1] Effectiveness rate is a calculated value comparing the predicted volume of lading lost in a derailment between an alternative tank car design and a baseline deign (in this case a non-jacketed DOT 111 tank car).

[2] Alexy, Karl, "Comparative analysis of documented damage to tank cars containing denatured alcohol or crude oil exposed to pool fire conditions," draft paper, Office of Safety, FRA, June 2014.

unprecedented. In 2006, ethanol (typically shipped as Alcohols, n.o.s.) became the commodity with the most tank car originations in North America[3] and held that position until 2013 when crude oil took over the top spot. Figure 1 provides the rail originations of crude oil and ethanol since 2003. DOT is concerned that the historical accident data may not account for all unique risks posed by these trains. Accordingly, a method to quantify changes in risk corresponding to changes in tank car design was established. The method considered the probability of loss of lading, the volume of material released, and the effects of exposure to pool fire conditions.

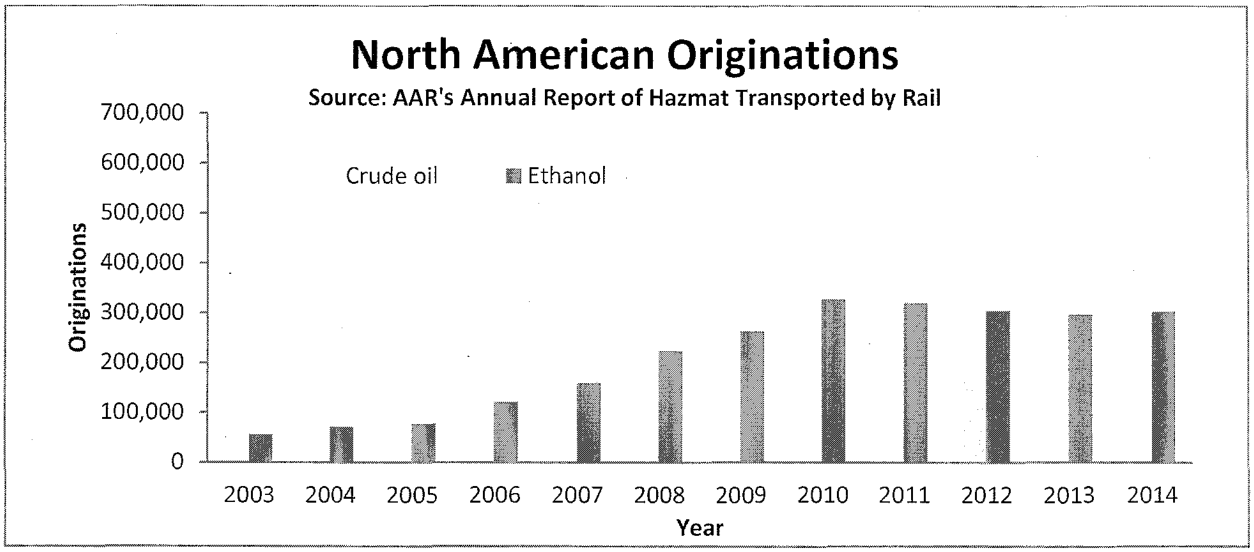

Figure 1: Rail Originations of Crude Oil and Ethanol (the 2014 totals are based on projections: 20% increase in crude oil originations, and an average of the previous 5 years of ethanol originations)

Tank Car Options

Three tank car options are proposed for consideration in HM-251. Table 1 provides a description of the design features for each of the tank car options. All design features are intended to enhance safety. The tank car Options are identical in many ways, but differ with regard to shell and head thickness, top fittings protection, and brake signal propagation system.[4]

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[3] AAR's Annual Report of Hazardous materials Transported by Rail, Calendar Year 2006, October 2007, Report BOE 06-1.

[4] The effectiveness rate of the brake signal propagations system is addressed in a separate paper.

Table 1: Description of alternative tank car standards

Tank Car	Bottom Outlet Handle	GRL (lbs)	Head Shield Type	Pressure Relief Valve	Shell/Head Thickness	Jacket	Tank Material	Top Fittings Protection*	Thermal Protection System	Braking
Option 1:	Bottom outlet handle removed or designed to prevent unintended actuation during a train accident	286k	Full-height, 1/2 inch thick head shield	Reclosing pressure relief device	9/16 inch Minimum	Minimum 11-gauge jacket constructed from A1011 steel or equivalent. The jacket must be weather-tight	TC-128 Grade B, normalized steel	TIH Top fittings protection system and nozzle capable of sustaining, without failure, a rollover accident at a speed of 9 mph	Thermal protection system in accordance with § 179.18	ECP brakes
Option 2:	Bottom outlet handle removed or designed to prevent unintended actuation during a train accident	286k	Full-height, 1/2 inch thick head shield	Reclosing pressure relief device	9/16 inch Minimum	Minimum 11-gauge jacket constructed from A1011 steel or equivalent. The jacket must be weather-tight	TC-128 Grade B, normalized steel	Equipped per AAR Specifications Tank Cars, appendix E paragraph 10.2.1	Thermal protection system in accordance with § 179.18	In trains with DP or EOT devices
Option 3:	Bottom outlet handle removed or designed to prevent unintended actuation during a train accident	286k	Full Height 1/2 inch thick head shield	Reclosing pressure relief device	7/16 inch-Minimum	Minimum 11-gauge jacket constructed from A1011 steel or equivalent. The jacket must be weather-tight	TC-128 Grade B, normalized steel	Equipped per AAR Specifications Tank Cars, appendix E paragraph 10.2.1	Thermal protection system in accordance with § 179.18	In trains with DP or EOT devices

Accident Data

HM-251 proposes tank car standards and operational controls for HHFTs, which are defined in the proposed rule as trains with 20 or more tank cars containing flammable liquids. Since 2006 there have been eleven derailments involving HHFTs in which there was a breach of a tank car and for which a complete set of data, related to the damage to the tank cars involved, is available (see Table 2).[5] These derailments best represent the risks addressed in the NPRM to Docket HM-251.

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[5] DOT originally reviewed all 13 derailments identified in the NPRM, however this paper was based on an analysis of the 11 accidents with a complete data set and that resulted in a breach of the tank cars involved. In LaSalle, Co and Vandergrift there were no breached cars as such there is not point including these incidents.

Table 2: Major Crude Oil/Ethanol Train Accidents involving Crude oil and Ethanol Involving a Breach of the Tank Car (2006 to January 2014)

Location	Date	Number of Tank Cars Derailed	Number of Crude oil/ethanol cars breached	Speed at Derailment (mph)	Material and Type of Train	Product Loss (Gallons)	Fire
New Augusta, MS[6]	Jan 2014	26	3	45	Crude Oil	90,000	No
Casselton, ND	Dec 2013	20	18	42	Crude Oil (unit train)	476,436	Yes
Aliceville, AL	Nov 2013	26	25	39	Crude Oil (unit train)	630,000	Yes
Lac-Megantic,	July 2013	63	59	~65	Crude Oil (unit train)	1,580,000	Yes
Plevna, MT	Aug 2012	17	12	25	Ethanol	245,336	Yes
Columbus, OH	July 2012	3	3	23	Ethanol	53,347	Yes
Tiskilwa, IL	Oct 2011	10	10	34	Ethanol	143,534	Yes
Arcadia, OH	Feb 2011	31	31	46	Ethanol (unit train)	834,840	Yes
Rockford/ Cherry Valley, IL	June 2009	19	13	19	Ethanol (unit train)	232,963	Yes
Painesville, OH	Oct 2007	7	5	48	Ethanol	76,153	Yes
New Brighton, PA	Oct 2006	23	20	37	Ethanol (unit train)	485,278	Yes

Methodology

The effectiveness of each enhanced tank car design feature was calculated in the following manner:

- Five vulnerable areas of damage that have resulted in loss of lading were considered based on documented damage to tank cars involved in the derailments in Table 3; tank head, tank shell, thermal damage (thermal tear and energetic rupture), top fittings, and bottom outlet.
- The volume of lading lost from each tank car and areas of vulnerability are compiled in Table 5, below. The volume of lading loss was provided by the railroads or response contractors. The damage was documented by FRA personnel. These values were used as the baseline effectiveness for tank cars constructed to the current DOT 111 specification requirements.
- The tank car Options proposed in HM-251 include proposed design enhancements intended to minimize the loss of lading from the identified vulnerable areas. The improvement in performance of each of the enhanced design features is estimated as ratios in the performance of each tank car Option relative to the current requirements for the DOT Specification 111 tank car.

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[6] The New Augusta derailment involved DOT Specification 111 cars meeting the CPC-1232 standard.

As an example, Table 4 provides a description of the type of damage sustained by each tank car in the Arcadia, OH accident and estimated volume of product released from each type of damage. Further, Table 4 provides the ratios of expected volume of product that would have released under tank car option 1 as compared to the volume released during the derailment. For each enhanced design feature of the Option 1 tank car, an enhancement ratio[7] is calculated using the following considerations:

- The shell failure ratio (i.e., the ratio of predicted number of cars with shell punctures with Option 1 to that of shell punctures of DOT Specification 111 cars, all other conditions being equal) is based on FRA sponsored research.[8] Following the example provided in Table 3 indicates the enhancement ratio for the Option 1 car is 8.46/14.02 = 0.61). This ratio is used as the multiplier to determine the reduced lading loss volume. The report in foot note 4 was based on simulation of shell puncture and did not consider head puncture. A separate head puncture analysis was used to account for head shields and jackets and stand-off distances.

Table 3: Predicted number of punctured tank cars (interpolated values)

Tank Car	Predicted # of cars punctured at 30 mph derailment speed	Predicted # of cars punctured at 40 mph derailment speed	**Interpolated number at specific derailment speed (Arcadia – 46 mph)**	Predicted # of cars punctured at 50 mph derailment speed
111	7.7	10.9	**14.02**	16.1
Option 1	4.3	6.6	**8.46**	9.7
Option 2	4.3	6.6	**8.46**	9.7
Option 3	5.7	8.3	**10.76**	12.4

- For head failures the ratio of puncture velocity[9] (DOT Specification 111/Option) was used as a multiplier to determine the reduction in lading loss. Puncture velocity is the velocity at which the head of the tank will puncture. The calculated puncture velocity of the head of a DOT 111 specification tank car is 8.6 mph. As an example, from Table 18 of the NPRM the puncture velocity of the head of Option 1 is 18.4 mph. The calculated ratio is (8.6 mph/18.4 mph) or 0.47.

Table 4: Head puncture velocity and enhancement ratio for tank car Options

Tank car	Head puncture velocity	Enhancement ratio
Option 1	18.4 mph	0.47

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[7] The enhancement ratio is the ratio of a performance metric (e.g. head puncture velocity) of the DOT111 tank car to an Option tank car indicated in the NPRM.

[8] Letter Report: Objective Evaluation of Risk Reduction from Tank Car Design and Operations Improvements, Sharma & Associates, Inc. (for FRA Office of Research and Development), July 2014.

[9] Belport, S., Evaluation of the puncture resistance for stainless steel and carbon steel heads, P-93-114 (for the E.I. duPont de Nemours & Company), June 1993.

Tank car	Head puncture velocity	Enhancement ratio
Option 2	18.4 mph	0.47
Option 3	17.8 mph	0.48

  - Thermal protection prevents thermal damage that results in loss of containment. DOT assumes that the other proposed enhanced design features will limit the volume of lading released in the event of a derailment and there will be a commensurate decrease in the occurrence and duration of pool fires. Additionally, DOT assumes pool fires that do occur will last less than 100 minutes (the performance standard for the thermal protection systems). Because all Options are required to be equipped with thermal protection, this is not a factor that will differentiate the Options.
  - Top fittings protection of the Option 1 tank car is assumed to reduce by half the damage to service equipment relative to the DOT Specification 111 tank car. Top fittings protection of tank car options 2 and 3 is assumed to be 1/3 as effective as top fittings protection of tank car option 1.[10]
  - BOV modification prevents lading loss through the BOV. Based on our understanding of the damage to the BOV resulting in release, the proposed BOV modifications would have prevented all of the BOV releases in those derailments listed in Table 3.
- The ratios were multiplied by the actual lading loss in order to calculate the expected volume of lading loss if the cars involved in the baseline incidents were equipped with the enhanced design features proposed for each tank car option.

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[10] The rollover protection standard in the HMR requires top fittings protective structures to withstand a 9 mph rollover, with the speed being defined at the center of the car per 49 CFR 179.102-3..

Top fittings protection requires fittings to be protected against a 2W static load applied vertically and a 1 W static load applied horizontally (the loads are applied separately), where W is the weight of the loaded tank car minus trucks (about 266,000 lb. for a recently manufactured tank car permitted to operate at a gross rail load of 286,000 pounds). This requirement is found in AAR Specification for Tank Cars (M-1002) Appendix E 10.2.

During a recent full-scale, rollover test of a tank car, the fittings protective structure failed significantly at a rollover speed of 9 mph. The design tested was on a car with a with a 5/8" shell and the top fittings protective structure was similar to the bonnet style protective structure used on older style pressure cars, as well current design non-pressure cars (including the CPC-1232).

It is expected that the survival speed of that design is less than 7 mph; in other words the design would have, at best, survived a derailment event that had 60% less energy (based on the square of the difference in velocity) than a 9 mph rollover.

This design has a factor of safety of 1.8 to 2.0 against the static 1W horizontal load, which is the critical and comparable load to the 9 mph rollover standard. In other words, a protective structure that was designed to the top fittings standard with a factor of safety of 1.0, would have an even lower safety factor against a 9 mph derailment, i.e., it is only likely to survive a derailment event that had 33% of the energy (60%/1.8) of a 9 mph rollover.

Additionally, simulations of rollover events at 9 mph suggest that forces in excess of 600 kips are likely to develop during an impact event, which is more than twice the static design load.

From the above, it is surmised that a protective structure that is designed to survive a 9 mph rollover standard is two to three times as likely to survive a derailment event, as compared to a fittings protective structure that is designed to the top fittings (2W, 1W) standard.

- The marginal benefit[11] of the enhanced design features for the option 1 tank car, relative to the DOT Specification 111 tank car, is the difference between the lading loss volume in the DOT Specification 111 and the option 1 tank car
  This marginal benefit, in terms of lading loss, is shown in Table 5 for each type of damage occurring in the Arcadia accident.
- The marginal benefit calculated for each derailment listed in Table 3 and for each enhanced design feature for the Option 1 tank car is shown in Table 6.
- The effectiveness rate was calculated using equation 1 below.

$$E_{i,j} = \frac{(V_{i,DOT111} - V_{i,i})}{V_{total,DOT111}}$$

Where $E_{i,j}$ ss the effectiveness of design enhancement *i* on Option *j*. $V_{i,DOT111}$ is the lading loss from design enhancement j on the DOT111 specification tank car. $V_{i,j}$ is the lading loss from design enhancement *i* on Option *j* tank car. $V_{total,DOT111}$ is the total lading loss from the DOT111 tank car. The aggregate effectiveness rate of all the features for each of the three tank car Options. These values are provided in Table 8.

Table 2: Tank car damage and volume of lading loss from tank car involved in Arcadia, OH derailment

Tank Car	Position	Product Released by Type of Failure (Gallons)						Total Gallons Lost
		Top head puncture	Bottom head Puncture	Shell puncture/fracture	Thermal Tear	Energetic Rupture[12]	Top fittings damage[13]	
ADMX30691	6						1,500	1,500
ADMX30798	7						28,716	28,716
TILX195003	8						Y	0
ADMX30837	9				28,753			28,753
ADMX30874	10		28,726					28,726
ADMX30917	11				28,744			28,744
ADMX29581	12			28,807			Y	28,807
ADMX30680	13			28,762			Y	28,762
ADMX30107	14					28718		28,718
ADMX30175	15						28,680	28,680
ADMX30897	16			28,687			Y	28,687

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[11] The marginal benefit is the difference in lading loss volume between the DIT 111 tank car and an Option tank car from the NPRM.

[12] An event that initiates as a thermal tear but has enough energy to extend the fracture resulting in a separation or near separation of the tank car into multiple sections.

[13] "Y" indicates there was damage to the top fittings however, there was not lading loss directly attributable to the damage.

ADMX30941	17			28,704				28,704
UTLX211623	18					29001	Y	29,001
ADMX30309	19			28,718			Y	28,718
ADMX30187	20			28,715			Y	28,715
ADMX29283	21	14,390	14,390					28,780
ADMX29232	22	14,399	14,399				Y	28,798
ADMX29268	23			28,803				28,803
ADMX30893	24	14,367		14,368				28,735
ADMX31203	25	28,713						28,713
ADMX29876	26		14,357	14,357			Y	28,714
ADMX29964	27			28,718				28,718
ADMX29240	28			28,800				28,800
ADMX30476	29			28,688			Y	28,688
TILX317937	30			28,684				28,684
NATX301502	31			28,638				28,638
ADMX29490	32		28,733					28,733
ADMX31284	33			28,702				28,702
ADMX29793	34	13,370		14,370				28,640
ADMX29420	35					28,752		28,752
TILX198791	36		28,711					28,711
Volume lost from DOT111		85,239	129,316	416,521	57497	86,471	58,896	834,840
Option1/DOT111	**Ratio[14]**	**0.47**	**0.47**	**0.61**	**0.00**	**0.00**	**0.50**	
Volume lost from Option 1		40,062	60,779	254,078	0	0	29,448	
Marginal benefit (Option 1)		45,177	68,537	162,443	57497	86,471	29,448	449,573
	Head Puncture Total		**113,714**	**Loss via thermal damage**		**143,968**		

Table 6: Calculation of marginal benefits of design enhancements (Option 1 to DOT Specification 111) in terms of volume of lading not released

DOT Specification 111 to Option-1	Head Protection[15]	Shell (add'l thickness)	Thermal Protection	Top Fittings Protection	Bottom Outlet Valve
Derailment					
Aliceville	92,309	83,534	20,000	0	0
Arcadia	113,714	162,443	143,968	29,448	0

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[14] A "1" indicates the proposed design enhancement offers no benefits and a "0" indicates the proposed design enhancement prevent similar occurrences.

[15] The volumes in the "Head Protection" column of Table 5 is a sum of volumes in the Top Head Puncture" and Bottom Head Puncture columns of Table 4.

Cherry Valley	99,253	32,063	0	29,054	0
New Brighton	112,361	36,274	50,351	101,137	14,360
Painesville	0	10,154	0	12,692	0
Plevna	15,213	15,261	108,770	7,225	0
Columbus	11,372	0	31,890	0	0
Tiskilwa	23,696	17,652	55,666	0	0
Casselton	51,328	96,321	126,446	0	0
New Augusta	27,189	0	0	0	0
Lac-Megantic	490,216	368,125	40,000	5,000	7,000
Total marginal benefits for all accidents in Table 3	1,036,651	821,827	577,091	184,556	21,360
	21%	17%	12%	4%	0%

Assumptions

The following assumptions were made to complete the calculations.

1. Top head puncture[16] and shell puncture are assumed to lead to loss of all lading, and where both are punctured it is assumed that half the loss is attributed to the top head and the other half to the shell, unless otherwise indicated by the data.
2. Bottom head puncture and shell puncture are assumed to lead to loss of all lading, and where both are punctured it is assumed half the loss is attributed to the bottom head and the other half to the shell, unless otherwise indicated by the data.
3. A puncture in the top half of the head will result in loss of one half of the original lading volume (unless data indicates otherwise).
4. A puncture in the bottom half of the head will result in complete loss of original lading volume (unless data indicates otherwise).
5. Top head puncture and bottom head puncture are assumed to lead to loss of all lading, and where both are punctured it is assumed half the loss is attributed to the top head and the other half to the bottom head, unless otherwise indicated by the data.
6. Thermal tear is assumed to result in a loss of 5,000 gallons of lading unless otherwise specified. Thermal tears occur in tanks that were not breached in the derailment. When a thermal tear occurs it is located in the shell around the vapor space of the tank. In all occasion the material being released from the tank is ignited after the tear occurs. This results in consumption of the flammable liquid. This along with the volume of material lost, if an explosion occurs, immediately following the thermal tear account for an estimated 5,000 gallons.
7. Product loss from shell benefit based on Sharma research (see footnote 3) and calculated as the ratio of predicted number of cars punctured. Sharma's research calculated the probability of puncture of tank cars at derailment speeds of 30, 40 and 50 mile per hour (mph). In order to compare a particular Option to the DOT Specification 111 at the speed of each derailment the predicted number of cars punctured was calculated by linear interpolation.

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[16] The description "top head puncture" is relative to upright tank car. Please note a puncture can occur to a tank head when the tank has rolled onto its side resulting in complete loss of lading.

8. Top head and bottom head puncture improvement is based on the ratio of the puncture velocities calculated using methodologies established in previous research.[17]
9. Thermal protection will prevent thermal tears and energetic ruptures therefore there will be 100% benefit.
10. If shell and service equipment are damaged, all lading loss is attributed to shell.
11. The top fittings protection of Options 1 will reduce by half the volume released as a result of damage to the top fittings relative to the DOT 111 specification tank car.

Validation of Results

In an effort to validate the DOT methodology the effectiveness rates were calculated using the Conditional Probability of Release (CPR).[18] The CPR for four components/features of the tank car, namely, the head, shell, top fittings and bottom fittings, was calculated and used as a surrogate for lading loss. The CPR for the four components of each of the three tank car Options and the DOT Specification 111 were calculated. The calculated CPRs for the four components of the DOT Specification 111 were added to provide a surrogate for the total lading loss and served as the baseline for the evaluation. The effectiveness rate of each component was calculated per Equation 2 below.

$$E_{i,j} = \frac{\left(CPR_{j,DOT111} - CPR_{j,Option}\right)}{CPR_{total,DOT111}}$$

Where $E_{i,j}$ ss the effectiveness of design enhancement *i* on Option *j*. $CPR_{i,DOT111}$ is the calculated CPR from design enhancement j on the DOT111 specification tank car. $CPR_{i,j}$ is the calculated CPR from design enhancement *i* on Option *j* tank car. $CPR_{total,DOT111}$ is the total calculated CPR from the DOT111 tank car (sum of individual CPR values from each feature). The aggregate effectiveness rate of all the features for each of the three tank car Options. The effectiveness rates for each design feature for the Options were summed to determine the overall effectiveness. The results are provided in Table 8, below.

Table 3: Effectiveness rate of tank car specification Options based on Conditional Probability of Release

Option	Head	Shell	Top	Bottom	Total
1	17.3	16.9	29.0	4.0	67.2
2	17.3	16.9	18.5	4.0	56.7
3	16.8	11.2	18.5	4.0	50.5

The relative total effectiveness rate calculated using CPR values are that same as those calculated using the DOT methodology and actual accident data described in this paper, with tank car Option 1 being the most effective and Option 3 the least. Additionally, the effectiveness rates for the head and shell in **Table 8** show reasonable agreement with those in Table 1. The effectiveness rates calculated by the two methods for the top fittings do not align. This is because in the DOT methodology, the lading loss

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[17] Belport, S., Evaluation of the puncture resistance for stainless steel and carbon steel heads, P-93-114 (for the E.I. duPont de Nemours & Company), June 1993.

[18] Treichel, T, et al, safety Performance of Tank Cars in accidents: Probability of Lading Loss (RA 05-02), Railway Supply Institute and the association of America Railroads, 2006. The CPR calculation in this document does not account for thermal damage to tank cars exposed to pool fire conditions.

through damaged top fittings was discounted if there was a breach of the tank shell and therefore is not a significant contributor to the effectiveness. It should be noted that as the puncture resistance is improved as a result of the new tank car standards, the effectiveness rate of the top fittings protection will likely increase.

Conclusion

The methodology described in this technical supplement provided a basis for calculating the effectiveness of the enhanced design features, as well as, an aggregate effectiveness for each proposed tank car Options proposed in the NPRM. By combining well established and new research, with recent, directly applicable derailment data, this method appropriately considers the unique risks associated with the operation of HHFTs. Table 8 provides the calculated effectiveness rates for the three options in the NPRM as well as the current specification jacketed DOT 111 and the DOT 111 built to the CPC1232 AAR standard (non-jacketed). In all cases the effectiveness rates were calculated relative to a current specification non-jacketed DOT 111.

Table 8: Summary of effectiveness rates (%) for Options in NPRM and the CPC-1232 and jacketed DOT 111 tank cars

Tank Car	Total	Head puncture	Shell puncture	Thermal damage	Top fittings	BOV
Option 1	54	21	17	12	4	<1
Option 2	51.3	21	17	12	1.3	<1
Option 3	41.3	19	9	12	1.3	<1
CPC1232 (Non-jacketed)	22	13	9	0	1.3	0
111 (Jacketed)	29	11	8	10	0	0