Advanced Tank Car Collaborative Research Program (ATCCRP)

Executive Summary and Conclusions

December 2016

Report Submitted to:
American Chemistry Council
Association of American Railroads
The Chlorine Institute
The Fertilizer Institute
Railway Supply Institute
Transport Canada
U.S. Department of Transportation - Federal Railroad Administration
U.S. Department of Homeland Security - Transportation Security Administration

Advanced Tank Car Collaborative Research Program Executive Committee

Executive Summary and Conclusions

Over the last decade, there has been significant ongoing research to develop strategies for improving railroad tank cars so they can maintain tank integrity for more severe accident conditions. Beginning in 2006 and continuing through 2009, Dow Chemical Company, Union Pacific Railroad, and Union Tank Car Company assembled a joint project team to drive forward a holistic process for the development of a next generation rail tank car. This work was performed under the Next Generation Railroad Tank Car (NGRTC) Program and completed in cooperation with U.S. Department of Transportation, Federal Railroad Administration (DOT – FRA), Transport Canada (TC), and U.S. Department of Homeland Security Transportation Security Administration (DHS - TSA) and addressed safety, security, emergency response and operational challenges. The NGRTC program developed a database of both full-scale impact testing on tank cars and tank heads as well as a significant database on characterization of tank car materials and laboratory scale component tests (e.g. panel punch tests). An additional effort in the NGRTC Program was the development and validation of detailed finite element tank impact models and tank car steel constitutive and failure models which can be used to accurately predict the puncture resistance under different impact conditions [1].

Subsequent to the NGRTC Program, the Advanced Tank Car Collaborative Research Program (ATCCRP) was initiated to coordinate research efforts to enhance the safety and security of rail tank car shipments of toxic inhalation hazard (TIH) materials. The ATCCRP builds on the prior and ongoing research conducted by the NGRTC Project, the Chlorine Institute (CI) tank car safety research [2-4], and the RSI-AAR Tank Car Safety Research and Test Project [5, 6]. The ATCCRP is a joint effort comprised of the following groups: shippers of tank cars carrying toxic inhalation hazard (TIH) materials [represented by the American Chemistry Council (ACC), CI, and the Fertilizer Institute (TFI)]; railroads that transport hazardous materials [represented by the Association of American Railroads (AAR)]; and rail tank car builders and lessors [represented by the Railway Supply Institute (RSI)]. In addition, Memoranda of Cooperation (MOC) were developed to formalize cooperation agreements between ATCCRP participants and the DOT - FRA, TC, DHS - TSA and the DHS Science and Technology Directorate (DHS - S&T).

Some of the significant conclusions resulting from the ATCCRP and supporting tank car safety research efforts are:

1. We have vastly improved our understanding of tank impact and puncture behaviors and developed a wealth of new experimental data and analytical results to support ongoing and future tank car safety efforts.

2. No new high technology design or material that produced significant new protection levels (e.g. composites, crushable foams, advanced engineered energy absorbing

sandwich panels) has been identified. Traditional tank car designs with monolithic layers of good quality steel are relatively efficient structures for resisting the impact threats in the railroad safety environment.

3. The HM-246 interim specification cars provide a significant level of improvement over the legacy designs. The HM-246 interim specification car puncture energy improvements were on average 90%, 100%, and 45% for the anhydrous ammonia (AA), ethylene oxide (EO), and chlorine (Cl) cars respectively. Empirically-derived probabilities of lading release for interim specification cars were 51% to 61% lower than those of legacy cars.

4. The only option identified for possible improvements in puncture protection over the HM-246 interim specification car designs are potential optimized sandwich designs, requiring alternative steels in the jacket (outer tank) for enhanced puncture protection. This conclusion is based on puncture analyses performed for various tank design configurations. Functional tank car designs for these sandwich cars were not developed in the research and the protection levels have not been proven by testing.

1.1 Background

An objective at the beginning of the Next Generation Rail Tank Car (NGRTC) program (2006-2009) was to develop, if possible, an advanced tank car design that could withstand 5-10 times higher impact energies than the baseline designs. To achieve this, the NGRTC program investigated both the puncture behavior of existing tank car designs and advanced tank car protection concepts. These advanced concepts included crushable structures and energy absorbing concepts developed for various applications (e.g. automotive, ship structures, aerospace). Example concepts included multi-layer sandwich structures with crushable foams or engineered metal cores. Although these advanced systems were shown to have potential for large area blunt impact loads, they performed poorly for smaller impactors (e.g. a broken rail) that could sequentially puncture the layers and prevent the system from resisting significant impact force or dissipate significant energy. As a result, an outcome of the NGRTC program was that systems that primarily relied on one or two larger monolithic layers that can independently (or collaboratively) resist significant forces for small impactors were considered to be the most promising designs. Traditional tank car designs were found to be relatively efficient for resisting impacts and punctures for a given structural weight. The NGRTC program also concluded that the goal of a 5-10 times increase impact energy was probably not achievable with any realistic tank design.

The Advanced Tank Car Collaborative Research Program has a similar purpose and scope: to further improve the safety and security of rail tank cars carrying TIH materials. The ATCCRP was organized by first collecting a wide range of technical white papers (TWP) on potential technologies that could improve the safety and security of tank cars. These topics included the following (note: some numbers are missing because similar topics were combined):

TWP-1: Effect of Pressure on Puncture Resistance – Chlorine and Anhydrous Ammonia

TWP-3: Reducing Dispersion Effects by Lading Temperature Reduction

TWP-4: Sandwich Tank Car Design

TWP-5: Composite Materials for Protection Systems

TWP-6: Structural Foams and Adhesives

TWP-9: Coupler Modifications

TWP-10: Correlating Material Properties to Puncture Resistance

TWP-11: Relating Conditional-Probability-of-Release to Modeling and Tests

TWP-13: Other TIH Materials

TWP-14: Analysis of Different Impactor Threats and Impact Conditions

TWP-15: Development of Performance-Based Testing Requirements for Railroad Tank Cars

TWP-16: Application Study for Perforated Armor Plating

TWP-17: Revising and Updating Conditional Release Probability Estimates

TWP-18: Forensic Analyses and Elimination of Real-World Failures

TWP-19: Improvements in Tank Car Weld Safety

TWP-20: Investigation of Impactors in Past Accidents

TWP-21: Demonstrate Approval Protocols on Candidate Technologies

TWP-22: Development of Advanced Head Protection Concepts

Note that the initial topics through TWP-14 were developed at the start of the ATCCRP efforts and additional TWPs were added at later times as they were identified and proposed.

The ATCCRP participant organizations reviewed and ranked the merits of the TWPs including anticipated commercial feasibility; estimated costs; and proposed schedules. Each organization identified the five TWP projects they believed were most important and likely to provide meaningful results. A system was worked out and used to identify inter-dependencies between projects and rate the proposed TWP research against the following ATCCRP objectives:

- Improved puncture resistance;
- Reduce releases at top fittings;
- Mitigate potential security threats;
- Provide a basis for possible use in establishing regulatory standards and protocols for performance tests;
- Enhance security, situational awareness, and tools for emergency responders.

The ATCCRP Committee decided to perform the following projects:

- TWP-14 (Analysis of Different Impactor Threats and Impact Conditions)
- TWP-11 (Relating Conditional Probability of Release to Modeling and Tests) was initiated as a smaller Phase I proof of concept effort.
- TWP-17 (Update and Expansion of Report RA-05-02 on Lading Loss Probabilities) as a predecessor to the TWP-11 effort.
- TWP-10 (Correlating Material Properties to Puncture Resistance)
- TWP-5 (Composite Materials for Protection Systems) Phase I modeling effort was initiated as a proof of concept.
- TWP-4 (Sandwich Car Design)
- TWP-15 (Development of Performance-Based Testing Requirements for Railroad Tank Cars) was performed as an initial effort where impact tests were performed under FRA sponsorship to establish the baseline side impact response of DOT-111 and DOT-112 tank cars.
- TWP-22 (Development of Advanced Head Protection Concepts)

1.2 Summaries of the ATCCRP Projects

More detailed summaries of the findings leading to the conclusions given above are provided below.

TWP-14 - Analysis of Different Impactor Threats and Impact Conditions

The TWP-14 project was important since the NGRTC program had used a primary impactor threat of a 6x6 inch square punch with a ½ inch radius around the edges of the impact face. This impactor was chosen at the time to balance the design between concepts that work for energy dissipation in blunt object impacts and protection systems that resist penetration of sharp or small puncture threats. However, the distribution of the effective sizes of impactors and the size of the most critical impactor leading to punctures in real world derailments and accidents is not known.

Analyses of different impactor sizes and impact conditions were needed to improve the understanding of how the idealized conditions previously analyzed relate to the chaotic impact conditions and wide range of potential impactors that exist in derailments.

The approach used in the research and development program was to apply a tank impact and puncture prediction capability using detailed finite element analyses (FEA). The FEA capability was developed and validated previously in the NGRTC program. In this study, the analyses were applied to investigate the tank puncture behaviors for a wide range of impact conditions. In the initial phase of this program, different sizes and shapes of impactors were investigated. The impactors used included square, rectangular, and round impact face geometries. A new parameter was developed to characterize the effective size of the impactor. This impactor characteristic size is the square root of the area of the impactor face. The impactor characteristic size parameter provided a good correlation for the different impactor sizes and shapes analyzed with a strong linear correlation of the puncture force with the characteristic size of the impactor.

To investigate the effects of the impactor orientation, a series of analyses was performed with a 12x12 inch square impactor with a 0.1-inch edge radius. The analyses were performed with various levels of pitch, yaw, and combined rotations to produce increasingly concentrated loadings along the impactor edges or corner. The analyses showed that the rotated orientations reduced the puncture forces from that of the 12-inch characteristic size to that of approximately a 4.5-to5 inch effective characteristic impactor size when rotated to a 45-degree edge impact and as small as a 3-inch impactor for the corner impact. Corresponding analyses where the tank was rotated to produce oblique impacts produced similar reductions in puncture forces and puncture energies. As a result, we see that a large blunt impactor can have the puncture potential of a much smaller impactor when impacting under non-ideal (offset, oblique, or rotated) impact conditions.

An additional result of the TWP-14 project was to characterize the puncture resistance of various tank designs for a wide range of impact conditions. In addition to the analyses performed on the baseline 105J500W chlorine (Cl) tank car, a series of other tank car types were analyzed. The evaluations were performed for the 105J600I Cl tank car (HM-246 interim specification car), the 112J340W and 112J500I anhydrous ammonia (AA) tank cars, and 105J300W, 105J400W, and 105J500I ethylene oxide (EO) tank cars. A full set of normal and 45-degree oblique side impacts were performed with a range of different size and shape impactors for each of the Cl, EO, and AA tank car designs considered. For comparison of the various designs, the calculated puncture energies all of the various designs were normalized to those of the 105J500W Cl tank car. The comparison for these normalized results is provided in Figure 1.

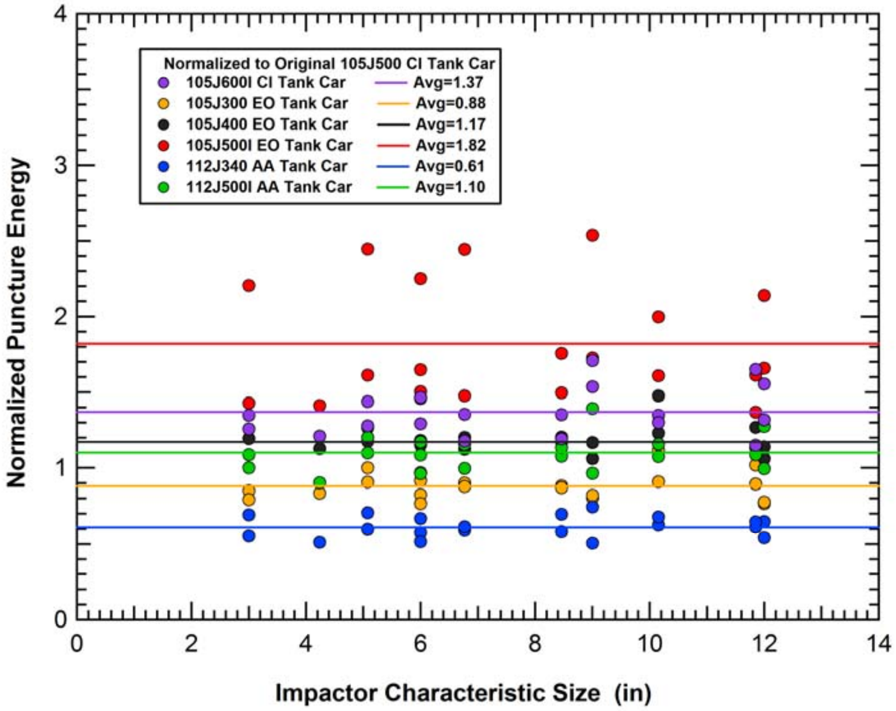


Figure 1. Comparison of relative puncture performance of various tank designs.

In this comparison, the puncture energies for the 105J500W EO tank car design are considerably higher than for any of the other tank car design. The EO tanks have relatively high puncture energies as a result of the lower tank pressures and larger diameter tanks. The 105J500W, 105J400W, and 105J300W EO tank cars have puncture energies on average 82% higher, 17% higher, and 12% lower, respectively, than the 105J500W Cl tank car. The puncture energies for the 105J600W Cl tank car were on average 37% higher than the 105J500W Cl tank car. The 112J500W and 112J340W AA tank cars are on average 10% above and 39% below the 105J500W Cl tank car, respectively.

TWP-10 - Correlating Material Properties to Puncture Resistance

The TWP-10 project was performed to assess a range of alternate tank car materials that could possibly improve puncture resistance. It built on the past material characterization efforts of the NGRTC Project (e.g. A1011, A516-70), and the Chlorine Institute sponsored program to characterize other high strength low alloy (HSLA) candidate steel materials (A710, HPS-70, and HPS-100). In the TWP-10 project, this past data is combined with additional testing and analysis to evaluate the impact and puncture resistance performance of candidate materials that could be used in tank car structure (both shell and jacket). The objective is that, by understanding the appropriate form of models for material damage and failure, analysts can predict structural performance and link the failure behavior to basic material properties. Such well-founded modeling will allow design optimization and selection of the most appropriate material for the tank structures.

The research program included detailed characterizations of various steel material samples (including a number of different TC128B variants). These detailed material characterizations included assessing tensile stress-strain properties as well as mechanical behavior of notched samples. As part of the research, detailed constitutive and damage models were developed for each material and the models were used to simulate the corresponding tests.

In addition to the direct material characterization, a series of puncture analyses were performed for various candidate materials to identify the material characteristics that most strongly control puncture resistance. Candidate materials with a wide range of mechanical properties were used in a suite of puncture analyses under various side impact conditions using a Cl tank car geometry (following the TWP-14 methodology). This effort used a set of candidate steels with significantly different properties from TC128B as shown in Figure 2. Note that these candidate steels were selected based on their mechanical properties and availability of test data and not necessarily for their suitability for use in railroad tank car service (e.g. weldability, fatigue resistance, cost). The idea is that once the desirable mechanical properties were identified, the selection of a tank car material that optimizes the desirable properties could be identified.

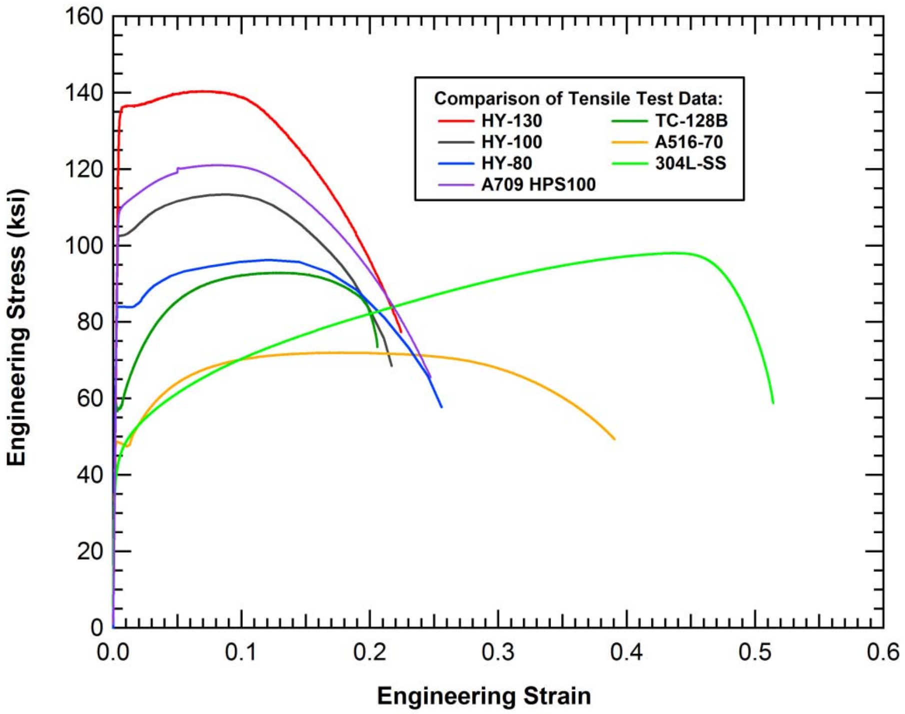


Figure 2. Candidate tank car steels with a range of mechanical properties.

The summaries of the normalized puncture energies for the impact analyses performed on the candidate steels are summarized in Figure 3. The 304L stainless produces the highest average normalized puncture energy (55% improvement over TC128B) but only a 17% improvement in average normalized puncture force which is less than three other materials (HY-100, A709 HPS100, and HY-130).

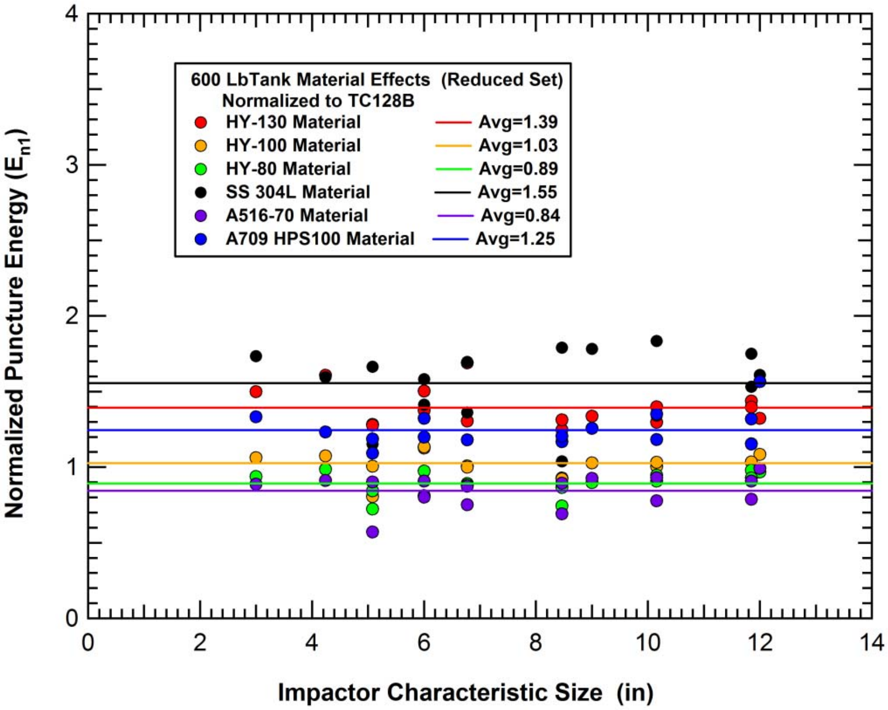


Figure 3. Relative puncture energy performance for candidate tank car steels.

The material properties were investigated in different combinations in an attempt to understand the material characteristics that contribute most significantly to the puncture resistance. The goal was to relate puncture behavior (as determined from the full-scale numerical simulations) to the stress-strain properties of the materials (strength and ductility). Three models are proposed in this work that included linear combinations of ultimate strength, yield strength and ductility. All three models provide excellent predictions of the observed puncture behavior (within 10% of the TC128B-normalized puncture energy). The proposed models were determined empirically by least square fitting of the puncture data when combined with the different input variables. The resulting models provide a basis to predict the effect of differing strength properties of other candidate materials on the puncture behavior of a rail tank car. However, material selection is not simply based upon stress-strain curve properties. There are other issues involved (such as weldability, corrosion and fatigue resistance, toughness, material cost etc.) that clearly are not captured by these models.

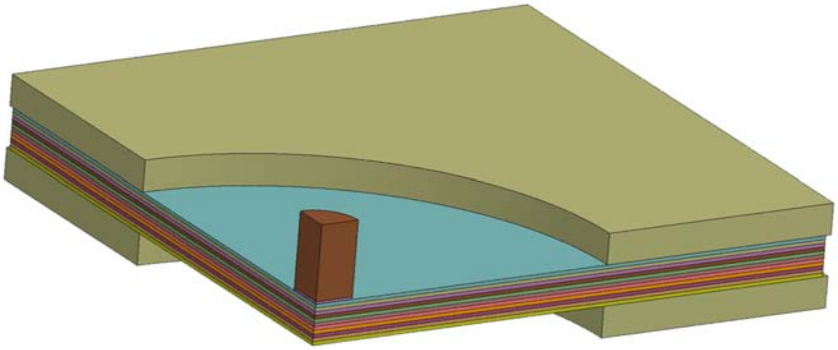
Although these models are purely empirical, an examination of the numerical puncture force response clearly indicates the compelling role of the ultimate strength of the material in predicting puncture force levels. In addition, the force-deflection characteristics of the simulations exhibit reasonable correlation to the yield strength of the material. The trends observed indicate that an increase in ultimate strength leads to higher puncture energy; conversely, an increase in yield strength leads to a lower puncture energy. Thus a material that has a relatively low yield and high ultimate strength is most efficient at resisting punctures (e.g. 304L stainless steel). Note that these results for the stainless steel were based on simpler constitutive models developed from tensile test data only. A more detailed material characterization of the stainless steel is ongoing.

These material puncture models provide a viable method to compare and contrast different candidate materials for tank car structure. Without this tool, expensive and time-consuming laboratory tests and full-scale simulations would be required to evaluate different candidate materials. Moreover these models can be used to help the industry determine the possible impact of different material modifications that impact mechanical properties. Given these tools, puncture enhancement of different candidate materials can be predicted to aid in material selection decisions and cost-benefit analyses. Applying these models to various proposed candidate tank car steels indicate that most new materials will net at best a modest improvement in puncture performance.

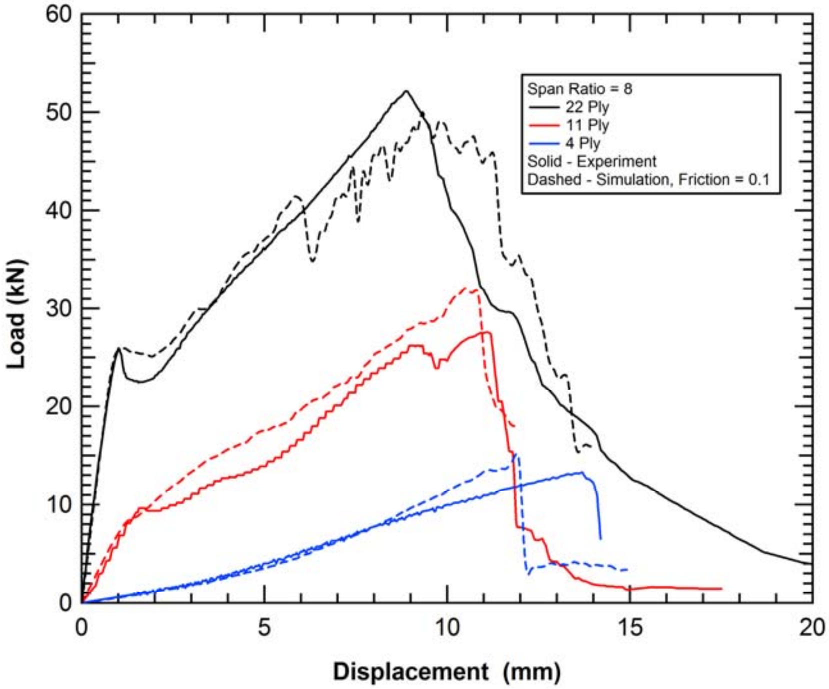
TWP-5 - Composite Materials for Protection Systems

The TWP-5 project was performed as a Phase I modeling effort as a proof of concept. In the project, the *MAT_COMPOSITE_MSC_DMG model [7] was calibrated for an S-2 Glass fiber composite and puncture analyses were performed on a few tank car concepts to assess the potential performance of composite systems. The S-2 glass system was selected both based on the availability of the test data and having a good balance of properties (cost, availability, puncture resistance) for tank car application. The composite damage model was selected as the only available model that has all of the damage mechanics necessary for the dynamic puncture analysis of thick composite systems (delamination, punch shear mechanisms through thickness, etc.).

The validation of the damage model was performed using punch data on S-2 glass/epoxy available in the open literature [e.g., 10-13] as shown in Figure 4. These are laboratory-scale tests of different panel thicknesses. The resulting model was applied to tank impact simulations. An example simulation is shown in Figure 5 where equivalent weight composite and steel jackets were evaluated. In this case, a 0.386-inch-thick TC128B steel jacket is compared to a 1.44-inch-thick S-2 glass composite jacket. Although the composite is much thicker and has high strength, the relative stiff elastic response results in the jacket reaching the failure point early in the deformation process (shown in Figure 5a). As a result, it did not appear that the composite systems could provide significant puncture protection performance improvements for the types of impact threats commonly experienced in tank car impacts and derailments.

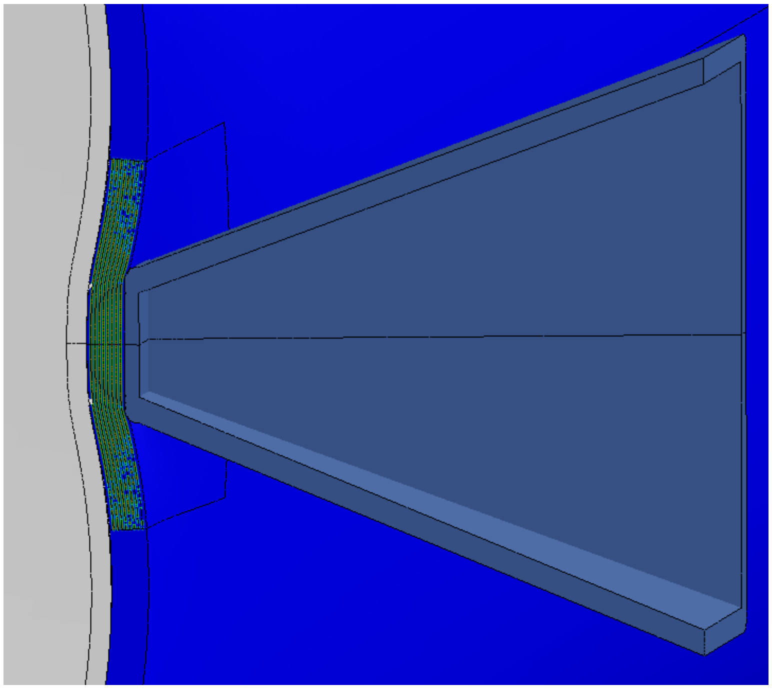


(a) Model of the panel punch test configuration

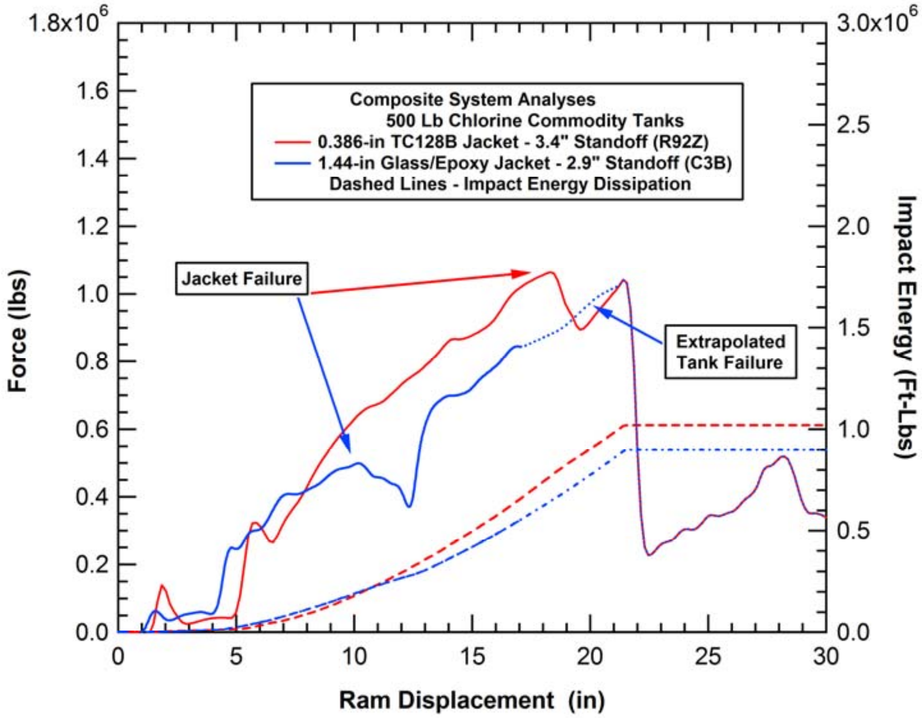


(b) Model and test correlation

Figure 4. Composite damage model validation for the panel punch tests.



(a) Calculated deflections at composite jacket failure



(b) Comparison of the composite and steel jacket behaviors

Figure 5. Calculated performance of equivalent weight steel and composite jackets.

TWP-4 - Sandwich Car Design

The TWP-4 project (Sandwich Car Design) was identified as the best option for the advanced "car design platform" for the ATCCRP work. The sandwich car in this application was primarily considered to be a double tank or "tank-within-a-tank" concept here since the NGRTC program had found difficulties in getting improved puncture resistance in sandwich panels with crushable foam or engineered metal cores between the outer sandwich plates. For example, if the composite materials had been identified as providing enhanced puncture resistance, they could easily be incorporated in the outer tank structures of a sandwich design.

A primary effort of the TWP-4 project was to evaluate the puncture performance of candidate tank car configurations in a suite of puncture analyses under various impact conditions (following the TWP-14 methodology). The designs featured baseline, retrofit, and sandwich tank design concepts for AA, EO, and Cl tank cars. Note that the effort was only to perform impact and puncture analyses on the tank systems and did not develop workable sandwich tank designs including inner tank supports, standoffs, bolsters and sills, or manway and top fittings.

An example of the approach for side impacts on AA tank car designs are shown in Figure 6. Note that the puncture energies in this example are normalized by the functional fit to the baseline 112J340W tank analyses rather than to the individual 112J340W results for each impact scenario to reduce scatter. The 112J500I tank design (HM-246 interim specification car) has on average 90% greater puncture energy than the baseline 112J340W AA tank. Alternatively, the 340 psi sandwich design with a 0.412-inch-thick TC128B jacket has similar puncture energy to the baseline 112J500I tank for square impactors. This is despite having approximately 6% less combined jacket thickness (1.03" compared to 1.10"). The sandwich 340 psi design shows increased puncture energy for large round impactors, and no improvement for the small round or the square impactors.

A comparison of baseline and retrofit EO side impacts is shown in Figure 7. The baseline 105J500I tank design (HM-246 interim specification car) has on average double the puncture energy of the baseline 105J300W EO tank. The baseline 105J500I and sandwich 300 psi designs have the same combined tank/jacket thickness (1.037"). Moving material from the tank to the jacket (baseline 105J500I to retrofit or sandwich 300 psi design) improved performance, especially for large impactors. The sandwich 300 psi design has on average 15% higher puncture energy than the 105J500I EO tank.

A comparison of baseline, retrofit, and sandwich Cl tank side impacts is shown in Figure 8. The 105J600I tank (HM-246 interim specification car) has on average 45% greater puncture energy than the baseline 105J500W Cl tank. The sandwich 300 psi design performed on average 10% better than the baseline 105J600I design. The greatest improvement is for small impactors. The retrofit 500 psi design performed on average 5% better than the baseline 105J600I design. This is consistent with the approximately 5% greater total thickness (1.152" compared to 1.10"). Moving material from the tank to the jacket improved performance, but the benefit was not large.

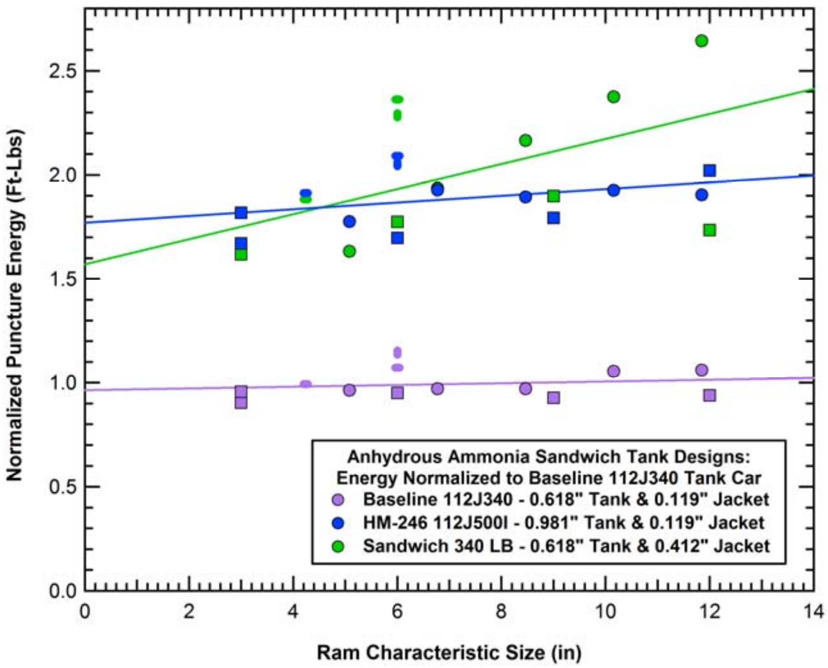


Figure 6. Relative side-impact puncture energies for AA tank designs

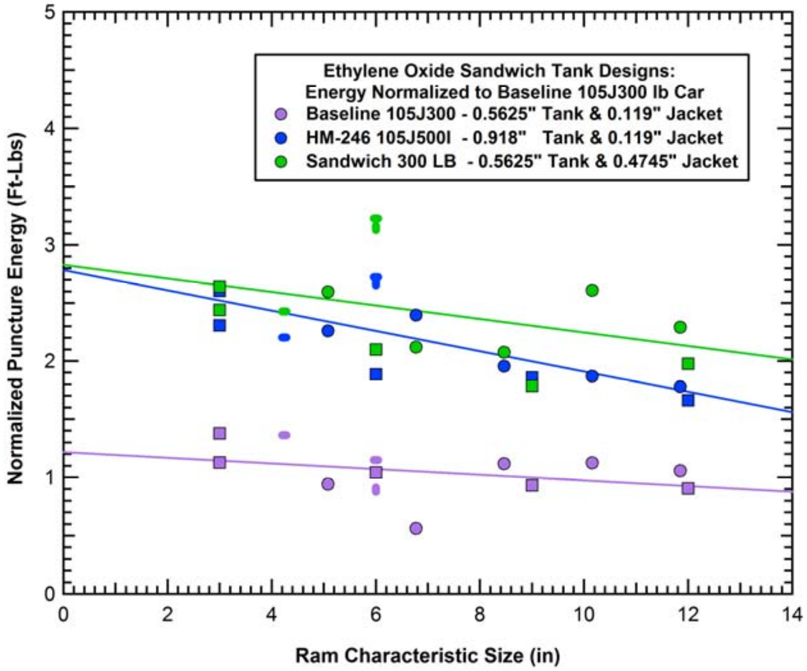


Figure 7. Relative side-impact puncture energies for EO tank designs

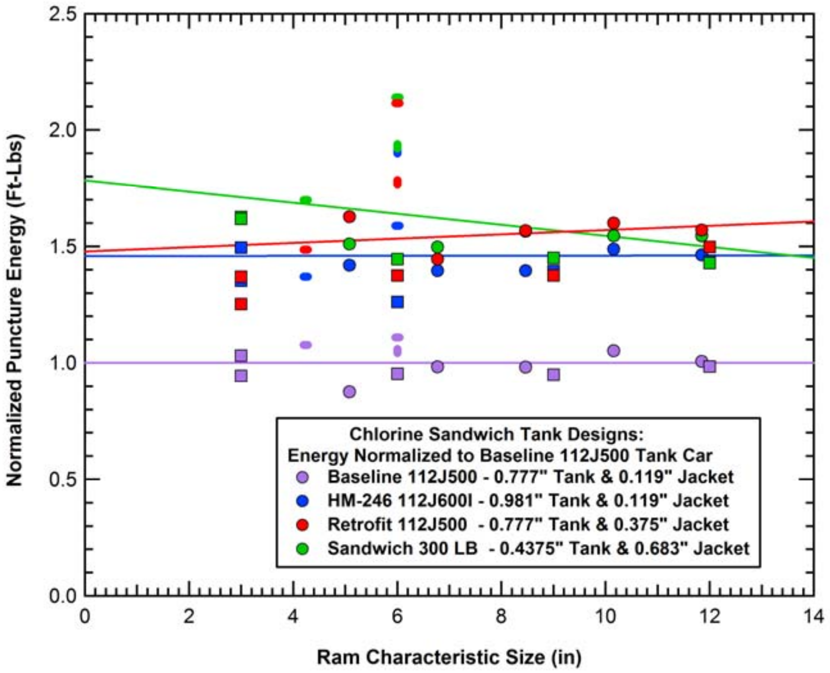


Figure 8. Relative side impact puncture energies for Cl tank designs

The primary conclusion of these comparisons of the various baseline, retrofit, and sandwich design concepts was that there were significant puncture improvements realized from the baseline legacy design to the improved HM-246 interim designs. These improvements were on average 90%, 100%, and 45% for the AA, EO, and Cl respectively. Comparison of the puncture performance of double tank sandwich concept to the HM-246 interim designs (using equivalent total thickness of the tank and jacket) resulted in much smaller incremental improvements than achieved by the interim specification cars over the baseline legacy tank designs.

The one significant advantage of a double tank sandwich construction was that it could be more easily adapted to use the alternate candidate materials identified in TWP 10. A change in the steel for the commodity tank beyond the list of currently approved steels would require a significant effort to ensure reliability, durability, corrosion resistance, and safety at levels equal to or greater than existing steels. However, replacing the steel in the outer jacket would be much simpler under current approved design guidelines and could easily gain approval by the AAR Tank Car Committee.

A secondary effort of the TWP-4 project was to evaluate the puncture performance of candidate sandwich tank car configurations using the steels identified under TWP-10 as having the highest puncture protection potential for the outer jacket material. The two materials evaluated are the highest strength material that resulted in the largest tank puncture forces (HY-130) and the material with the highest puncture energy resistance (304L stainless steel).

A comparison of sandwich AA tank side impacts with different jacket materials is shown in Figure 9. In this case, the puncture performance (energy) is normalized by the fit to the 112J500I tank design (HM-246 interim specification car). The double tank 340 psi sandwich designs with either the TC128B or high strength steel (HY-130) jackets provide little benefit for this tank design. The 304L SS variation works well with on average approximately a 50% increase in puncture energy. Although there is improvement for all but the smallest (3-inch) impactor sizes, the greatest improvements are seen with large impactors.

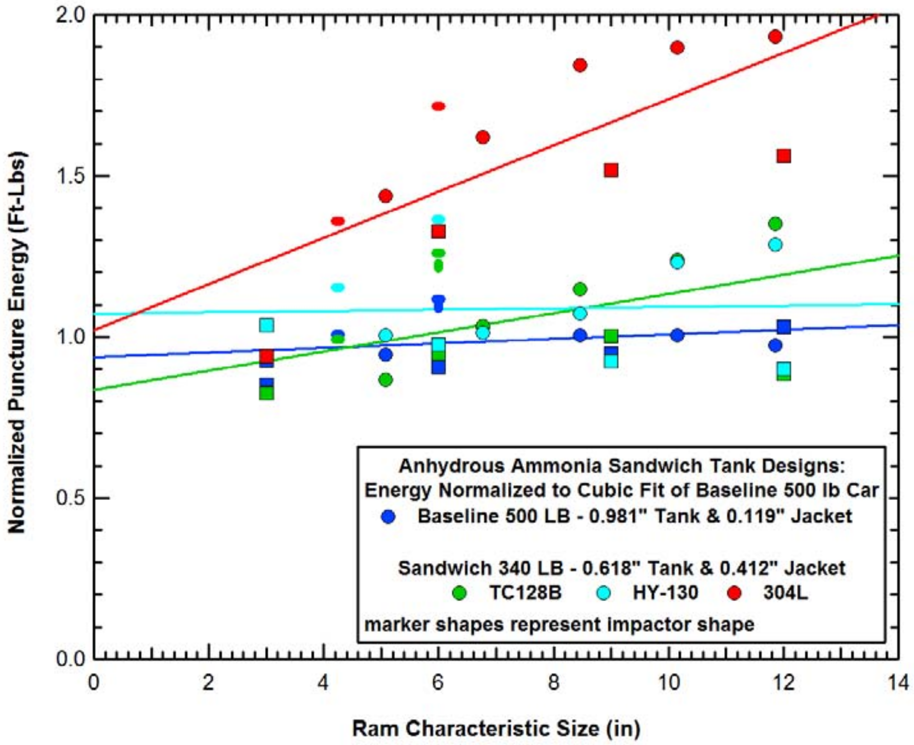


Figure 9. Relative side-impact puncture energies for AA jacket materials

A comparison of sandwich EO tank side impacts with different jacket materials is shown in Figure 10 using the 105J500I design (HM-246 interim specification car) as the baseline to normalize the puncture energy. The jacket material was varied for the sandwich 300 psi EO tank. The standard sandwich design had a TC128B jacket. HY-130 and 304L stainless steel variations were tested. Both variations provide approximately 40-50% improvement in puncture energy for small impactors. However, the high strength HY-130 performance is not maintained for large impactors. The sandwich design with the 304L SS variation works well for all impactor sizes for the EO Sandwich tank.

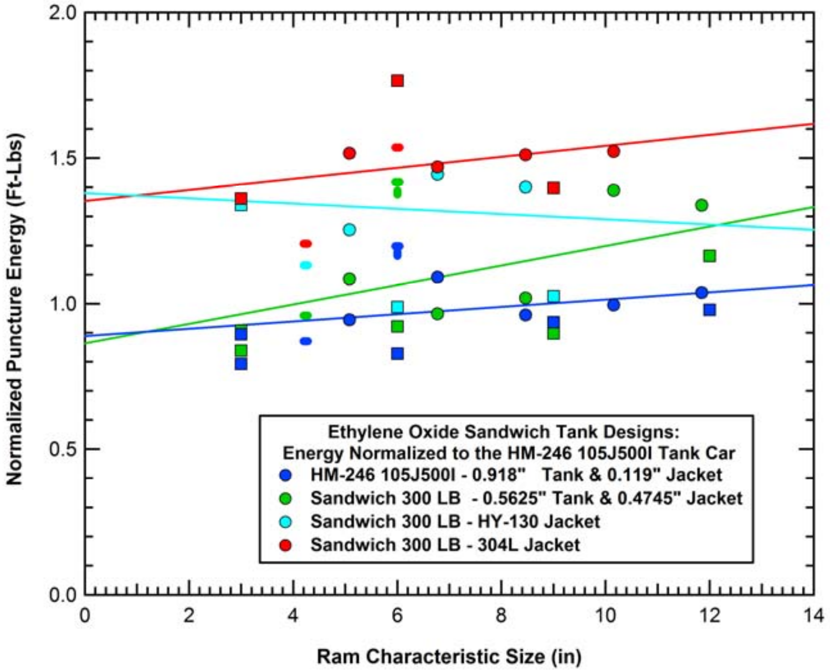


Figure 10. Relative side-impact puncture energies for EO jacket materials

Comparisons of sandwich Cl tank side impacts with different jacket materials are shown in Figure 11. In this case we are comparing double tank sandwich designs based on a 300 psi commodity tank (resulting in a thicker jacket) and the results are normalized to the 105J600I tank design (HM-246 interim specification car). The TC128B sandwich design provides on average approximately a 10% benefit with the largest benefit for small impactors. The HY-130 and 304L stainless steel sandwich tank designs provide on average 40% and 80% improvements, respectively. (Note that these levels of improvement depend on idealized sandwich designs and puncture behavior that has not been validated against a full-scale impact test on these designs yet, and on failure models for these materials that were not characterized to the detailed level of other tank car materials, and therefore may not be reachable under real conditions.) The Cl tank results show similar performance trends to EO, where HY-130 strength improvement is greatest for small impactors and reduced for large impactors.

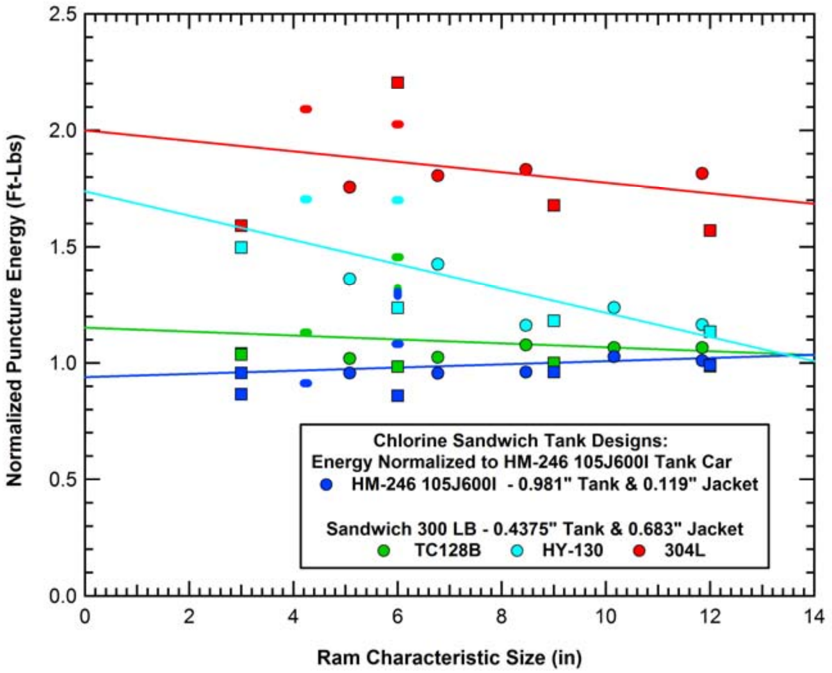


Figure 11. Relative side-impact puncture energies for CI jacket materials

TWP-22 - Development of Advanced Head Protection Concepts

The TWP-22 project (Development of Advanced Head Protection Concepts) was initiated with a phase I effort to evaluate four double head protection concepts, as shown in Figure 13. The first two are for a double head system, with a large and small standoff distance between the heads. The third concept is a double thickness head. The fourth concept included an inverted internal head allowing a large standoff between the inner and outer heads.

Puncture analyses were performed for these concepts with the baseline 6x6-inch square impactor in the baseline offset impact configuration. In all four cases the inner head was pressurized to 100 psi. For comparison to a known baseline, it was assumed that each concept design is for a 100-inch inside diameter tank intended for chlorine service. Each concept design was modeled to determine its ability to withstand puncture.

The calculated force-deflection behaviors and calculated puncture energies for the offset impact with the 6-inch square impactor for the four systems are shown in Figure 12. The designs have significant variations in the peak puncture forces but all of the puncture energies were within approximately a 20 percent variation. For comparison, a pressurized 500 psi chlorine tank head with a flanged and dished ½-inch head shield was calculated in the NGRTC program to have a puncture force of 952,000 lbs and puncture energy of 1.1 million ft-lbs [1]. The concepts were not found to provide significant benefits compared to more traditional head and head shield designs.

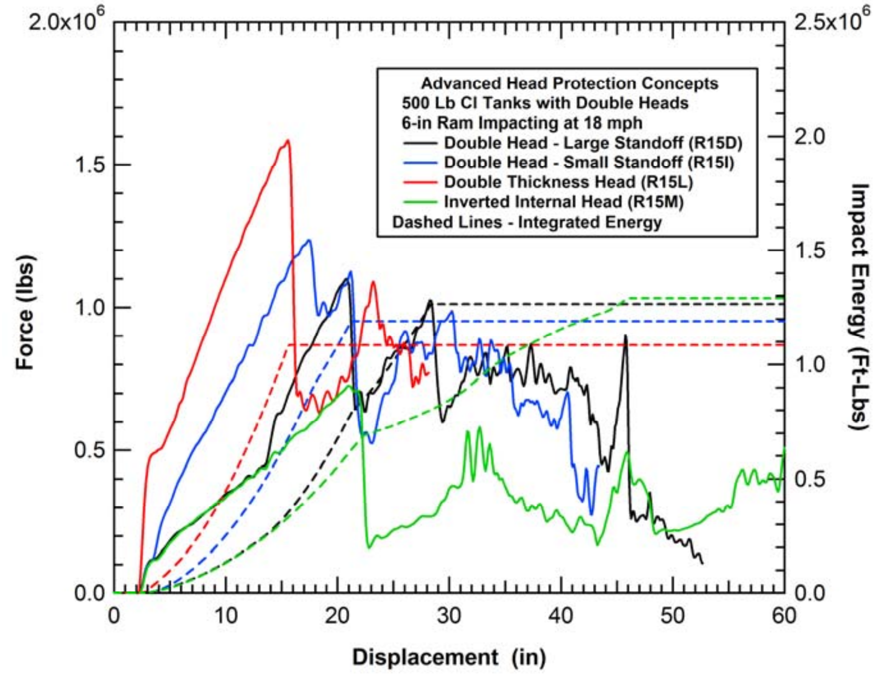
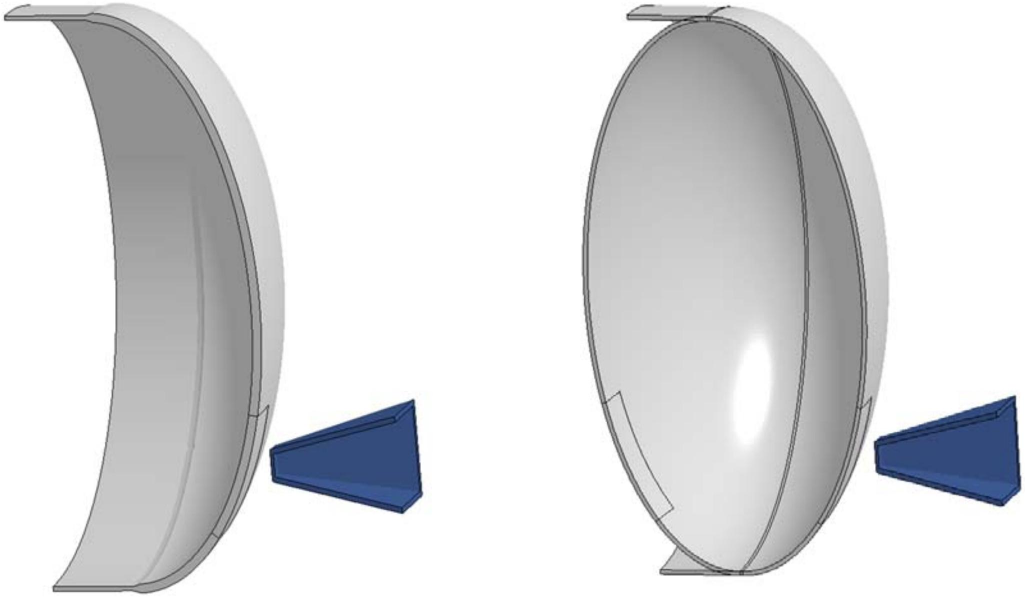


Figure 12. Calculated force-deflection histories for the baseline head protection concepts.

A secondary effort of the TWP-22 project was performed to investigate the effects of the tank constraint boundary conditions on the impact and puncture behavior. All of the head impact testing and the majority of the analyses in the NGRTC and ATCCRP efforts used a fully constrained tank head for the impact scenarios. The concern is that by not allowing the tank to move freely away from the impact, we may introduce a bias that benefits a particular type of design over another (e.g. a stiff design with a high puncture force vs. a compliant design with a lower puncture force.

A secondary series of analyses were performed with the designs to evaluate the head impact performance on an unconstrained tank. The relaxed constraint had a large effect on the puncture energy as the impactor has to travel a larger distance to account for the motion of the tank. This impact energy is primarily converted to kinetic energy of the impacted tank. All of the head systems evaluated experienced between 92 and 100% increase in the puncture energy with the unconstrained impact scenario. However, the increases were approximately proportional and the relative ranking of the performance for the various systems was unchanged. As a result, the highly constrained impact scenario remains a valid approach for evaluating the performance of head protection designs. Note that a unconstrained side impact test configuration would also result in higher puncture energies. However, the relative increases in the side impact puncture energies would be smaller since some movement of the tank center of gravity occurs as the tank is pushed against the wall (e.g. a partially constrained side impact configuration).

(a) Double Head – Large Standoff **(b) Double Head – Small Standoff**



(c) Double Thickness Head **(d) Inverted Internal Head**

Figure 13. Models of the four baseline head protection concepts.

TWP-17 - Revising and Updating Conditional Probability of Release Estimates

The TWP-17 project generated updated formulas for estimating FRA-reportable conditional probability of release (CPR) and quantity lost for each of the four car components (head, shell, top and bottom fittings), and for the whole car, for all "conventional" designs [14]. These formulas indicate which variables have a significant effect on each component CPR.

The most recent previous report that provided CPR estimates had been RSI-AAR Safety Project report RA-05-02 [15]. The TWP-17 analyses updated that previous work, including all accident data from 1980-2011, and employed more robust approaches to the statistical analysis of the data. They also added several new variables not addressed in the previous RA-05-02 report including car features, train speed, derailment severity, etc. The ATCCRP-related objective of this effort was to support TWP-11 with the most powerful and up-to-date data available.

"CPR" as defined in TWP-17 is the fraction of tank cars of a given description (i.e., the probability that one such tank car of that description) that will lose some quantity of lading from impact damage, given that they are derailed in an accident that requires a report from the railroad to the FRA. Damage and losses caused by exposure to heat are not part of the CPR calculation.

TWP-17 produced CPR estimates for TIH cars as shown in Table 1. The table also compares the accident performance of interim specification cars to legacy cars that are used for the same commodity.

Table 1

CPRs for Selected TIH Tank Cars
Under Average Mainline Derailment Conditions*

Chlorine

Car Spec.	Head Thickness (in.)	Shell Thickness (in.)	Jacket	Head Shield	Shell Inside Diameter (in.)	CPR	Percent Improvement Over Pre-HM-246 Baseline
105A500W	0.812	0.775	Yes	No	100.45	0.042	n/a
105J600I	0.954	0.954	Yes	Full	100.45	0.019	54.8 %

Anhydrous Ammonia

Car Spec.	Head Thickness (in.)	Shell Thickness (in.)	Jacket	Head Shield	Shell Inside Diameter (in.)	CPR	Percent Improvement Over Pre-HM-246 Baseline
112J340W	0.625	0.625	Yes	Full	119	0.033	n/a
112J500I	0.900	0.900	Yes	Full	116.75	0.016	51.5 %

Ethylene Oxide

Car Spec.	Head Thickness (in.)	Shell Thickness (in.)	Jacket	Head Shield	Shell Inside Diameter (in.)	CPR	Percent Improvement Over Pre-HM-246 Baseline
105J300W	0.603	0.562	Yes	Full	117.87	0.041	n/a

105J500I	0.900	0.900	Yes	Full	116.75	0.016	61.0%

* Train speed at time of derailment = 26 mph, 11 cars derailed, tank car is the 6th car derailed

The car dimensions shown in Table 1 are meant to be illustrative. They are based on the most commonly built designs as of the publication of this report.

TWP-11 - Relating Conditional Probability of Release to Modeling and Tests

The TWP-11 project was needed to develop an analytical method to estimate CPR for tank cars or tank car design elements for which satisfactory empirical data on accident performance do not exist. It is necessary to bridge the gap between the statistical and the analytical/testing approaches in the NGTRC efforts and other ATCCRP projects in order to understand how new designs will perform in response to the distribution of forces tank cars experience in accidents and thus quantitatively estimate the effect on safety and risk. Quantitative improvements in tank puncture force/energy do not readily translate into estimates of improvements in risk via CPR estimates. Without this relationship, it is difficult to quantify the benefits of new designs.

The TWP-11 project to date has been performed as a proof-of-concept Phase I effort. The approach was to perform a set of detailed derailment simulations for a range of derailment conditions and scenarios determined using a design of experiments approach. For the Phase I effort the scenarios were limited to a more specific set of derailments rather than trying to capture the entire range of possible events. These included derailments of trains within a defined range of speeds and train lengths on tangent track. The simulations determined the number and severity of impacts experienced by each tank car in all of the simulations. For any given distribution of impactor sizes, a corresponding number of tank punctures could also be obtained from the simulations.

The calculated tank puncture probabilities in the derailment simulations were then compared to the expected probability each of the tanks would be punctured using the TWP-17 CPRs. Impactor size distributions were generated that minimize the differences between the simulated CPRs and TWP-17 CPRs. The results of the TWP-11 Phase I simulations resulted in a family of impactor size distributions that each provide equivalent correlations of the CPR. There is still significant work needed in an expanded Phase II effort to ensure that the simulations consider all the necessary parameters to be representative of the real world derailment environment.

1.3 Conclusions

1.3.1 We have vastly improved our understanding of tank impact and puncture behaviors and developed a wealth of new experimental data and analytical results to support ongoing and future tank car safety efforts.

The above summary provides a series of key findings and results from the ATCCRP and associated tank car safety research. The projects have created a large resource of new information that can be used to inform decision-making or rulemaking efforts. These include the relative performance of different tank designs for various commodities (Cl, AA, and EO).

1.3.2 No new high technology design or material that produced significant new protection levels (e.g. composites, crushable foams, advanced engineered energy absorbing sandwich panels) has been identified. Traditional tank car designs with monolithic layers of good quality steel are relatively efficient structures for resisting the impact threats in the railroad safety environment.

All of the work to date suggests that the standard tank and jacket construction (or double tank sandwich cars) is relatively efficient at resisting impacts and punctures and that advanced protection concepts (e.g. composites, crushable foams, and engineered metal sandwich panels) have not been found to produce increased protection levels.

In an effort to improve on the interim specification car protection levels, various sandwich design concepts were also analyzed. Some improvements were possible with on average between 10%-20% increase in puncture energy in the double tank designs over the HM-246 interim specification tank designs. To achieve significant improvements over the interim specification cars required both the double tank sandwich car design and the use of exotic materials in the outer jacket such as 304L stainless steel or a 130 ksi high strength steel (HY130). For these designs, as much as an additional 50% improvement over the HM-246 interim specification design was observed. However, it should be noted that these results were based on material models that were not characterized to the detailed level of other tank car materials and have not yet been proven in any full-scale impact testing. An improved characterization of 304L stainless steel is ongoing in the ATCCRP to partially address this shortcoming.

1.3.3 The HM-246 interim specification cars provide a significant level of improvement over the legacy designs. The HM-246 interim specification car puncture energy improvements were on average 90%, 100%, and 45% for the anhydrous ammonia (AA), ethylene oxide (EO),

and chlorine (Cl) cars respectively. Empirically-derived probabilities of lading release for interim specification cars were 51% to 61% lower than those of legacy cars.

Another finding is that the HM-246 interim specification cars provide a significant advancement in puncture protection over the legacy designs. The HM-246 interim specification car puncture energy improvements were on average 90%, 100%, and 45% for the AA, EO, and Cl respectively. Empirically-derived CPR estimates support this finding: CPRs for interim specification cars were 51% to 61% lower than those of legacy cars. In addition, retrofit designs where the legacy design tank was retrofit with a correspondingly thicker jacket to achieve an equivalent combined thickness of tank and jacket as the HM-246 interim specification car achieved comparable puncture protection levels.

1.3.4 The only option identified for possible improvements in puncture protection over the HM-246 interim specification car designs are potential optimized sandwich designs, requiring alternative steels in the jacket (outer tank) for enhanced puncture protection. This conclusion is based on puncture analyses performed for various tank design configurations. Functional tank car designs for these sandwich cars were not developed in the research and the protection levels have not been proven by testing.

References

1. Kirkpatrick, S.W., “Detailed Puncture Analyses of Various Tank Car Designs,” ARA Final Technical Report, Prepared for the Next Generation Railroad Tank Car (NGRTC) Project, January, 2009.
2. T.L. Anderson, Rose, B., McKeighan, P.C., and S.W. Kirkpatrick, “Quantifying and Enhancing Puncture Resistance in Railroad Tank Cars Carrying Hazardous Materials: Phase II – Development and Validation of a Puncture Resistance Evaluation Methodology” Technical Report, Prepared for The Chlorine Institute, December 20, 2007. (LinkedIn)
3. T.L. Anderson and S.W. Kirkpatrick, “Quantifying and Enhancing Puncture Resistance in Railroad Tank Cars Carrying Hazardous Materials: Phase I – Preliminary Study” Technical Report, Prepared for The Chlorine Institute, September 1, 2006.
4. Anderson, T.L., Rose, B., McKeighan, P.C. and Kirkpatrick, S.W., “Quantifying and Enhancing Puncture Resistance in Railroad Tank Cars Carrying Hazardous Materials: Phase II – Development and Validation of a Puncture Resistance Evaluation Methodology” Technical Report, Prepared for The Chlorine Institute, December 20, 2007.
5. RSI-AAR Railroad Tank Car Safety Research and Test Project, “Railroad Tank Cars – Safely Transporting Hazardous Materials,” 2009.
6. http://www.dow.com/commitments/debates/chemsec/railtankcar.htm, accessed 4/5/10.

7. "User's Manual for LS-DYNA MAT162 Unidirectional and Plain Weave Composite Progressive Failure Models," Univ. of Delaware Center for Composite Materials, Materials Sciences Corporation, November, 2005.
8. Yen, C.F., "Ballistic impact Modeling of Composite Materials," Proceedings of the 7th International LS-DYNA Users Conference, Dearborn Michigan, May 19-21, 2002.
9. Matzenmiller, A., Lubliner, J., and Taylor, R.L. (1995). "A Constitutive Model for Anisotropic Damage in Fiber-Composites," Mechanics of Materials, 20, pp. 125-152.
10. Xiao, J.R., Gama, B.A., and Gillespie, J.W. Jr., "Progressive Damage and Delamination in Plain Weave S-2 Glass/SC-15 Composites Under Quasi-Static Punch-Shear Loading," Composite Structures Vol. 78, pp. 182–196, 2007.
11. Waliul Islam, S.M., "A Quasi-Static Penetration Model for Ballistic Energy Absorption of Thick Section Composite," Univ. of Delaware Center for Composite Materials, presented at the UD-CCM 2005 research Reviews, March 2, 2005.
12. Deka, L.J., S.D. Bartus, U.K. Vaidya, "Numerical Modeling of Simultaneous and Sequential Multi-Site Impact Response of S-2 Glass/Epoxy Composite Laminates", Composites and Polycon 2007, Oct. 17-19, 2007.
13. Gama, B.A., Xiao, J.R., and Haque, Md. J., "Experimental and Numerical Investigations on Damage and Delamination in Thick Plain Weave S-2 Glass Composites Under Quasi-Static Punch Shear Loading," Army Research Laboratory Report No. ARL-CR-534, Prepared by the Univ. of Delaware Center for Composite Materials, February 2004.

14. Treichel, T.T., et al. "Conditional Probability of Release (CPR) Estimates for Railroad Tank Cars in Accidents". RSI-AAR Railroad Tank Car Safety Research and Test Project Report RA-16-xx (still in draft as of this writing).

15. Treichel, T.T., et al. "Safety Performance of Tank Cars in Accidents: Probabilities of Lading Loss". RSI-AAR Railroad Tank Car Safety Research and Test Project Report RA-05-02. January 2006.