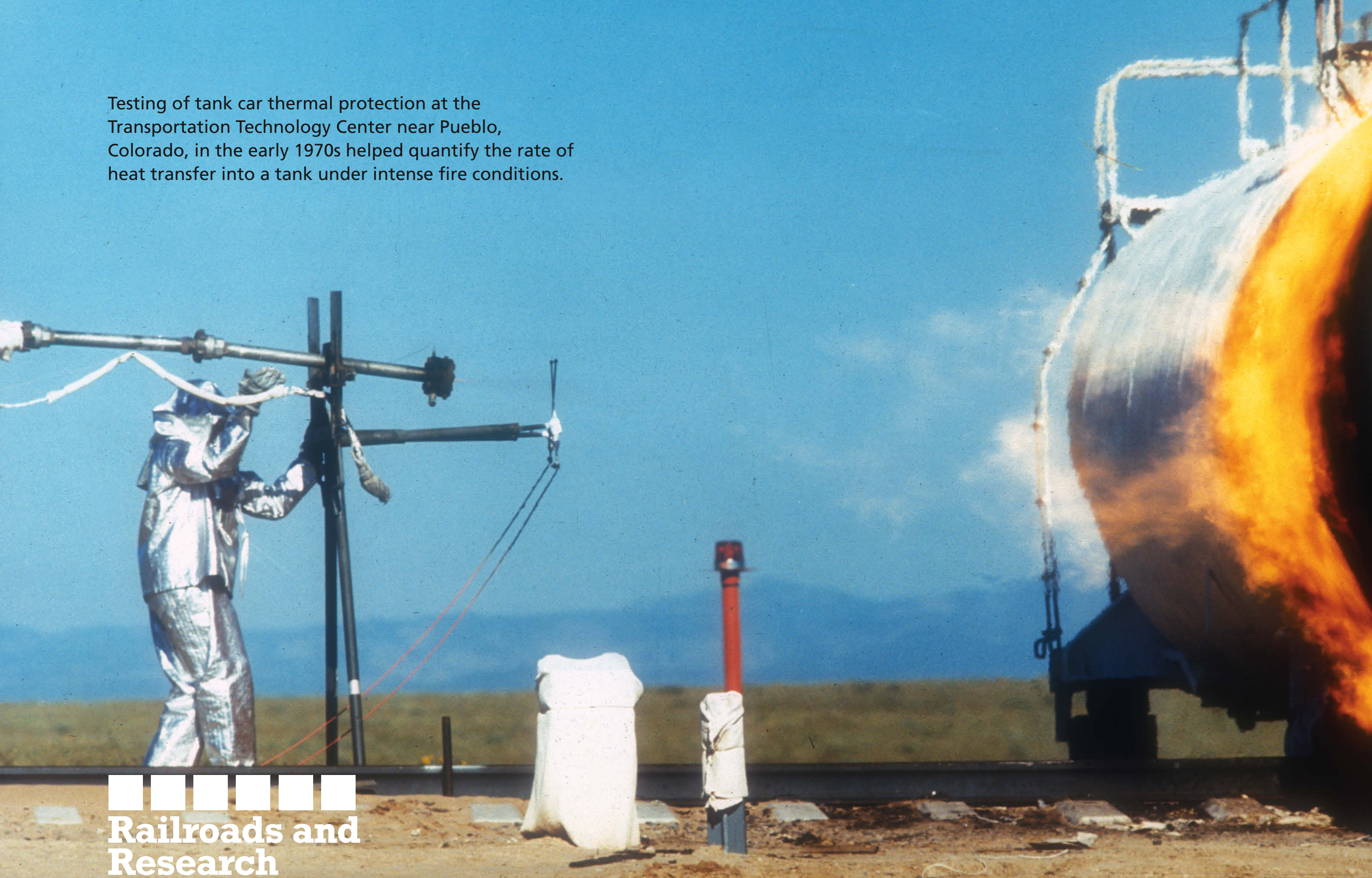

Testing of tank car thermal protection at the Transportation Technology Center near Pueblo, Colorado, in the early 1970s helped quantify the rate of heat transfer into a tank under intense fire conditions.

**Railroads and Research**
Sharing Track

# Cooperative Research in Tank Car Safety Design

## How Science and Engineering Are Reducing the Risk of Rail Transport of Hazardous Materials


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Railroad tank car safety in North America has improved continuously through cooperative testing, research, and standards development by industry and government. Although much of this progress has been evolutionary, in recent decades more revolutionary approaches have taken hold.

The railroad, tank car, and petrochemical industries have worked together with the government to develop and improve safety design standards for tank cars since the early 20th century (*1*). In 1903, the Master Car Builders' Association formed the Committee on Tank Cars, composed of the mechanical officers from several railroads and a representative from Union Tank Line, then the major tank car owner. The committee recommended practices that were soon established as industry standards for the construction and repair of tank cars.

The American Railway Association and its successor, the Association of American Railroads (AAR), later adopted the standards. The AAR Tank Car Committee is charged with reviewing and revising standards to advance tank car safety.

The public's interest was represented early on—in 1912, the Interstate Commerce Commission referenced the tank car standards as the basis for federal regulations. The public sector's oversight role—now under the auspices of the U.S. Department of Transportation (DOT)—has expanded (2), as private- and public-sector stakeholders work toward the common goal of ever-safer transportation of hazardous materials.


Photo: American Car & Foundry Company, Edward S. Kaminski collection

Tank car built in 1924 by American Car & Foundry was state of the art for rail transport of chlorine.

## Improving Tank Car Safety

The substantial economies offered by the safe, reliable bulk transport of petroleum and chemical products led to a proliferation of increasingly specialized tank car designs to accommodate an extraordinary variety of hazardous and nonhazardous liquid products. As the tank car has evolved, new materials, designs, and manufacturing technologies have contributed to technical solutions for a variety of challenges.

Tank cars today are the second most common type of railroad freight car in North America, accounting for approximately 20 percent of the rail car fleet. Each year, tank cars transport more than 1.6 million shipments of hazardous materials for a range of products and processes essential to the nation's economy, public health, and quality of life.

Nearly all of these shipments arrive safely at their destinations. Nevertheless, a train accident involving tank cars may release a hazardous material with a potential to harm humans, property, and the environment.

Building on a century of cooperative efforts, government and industry continue working together to improve tank car safety; recent design advances have followed three parallel and complementary approaches:

- Statistical analysis and optimization of safety design,
- Structural modeling, and
- Physical testing.

## Quantitative Analysis

A series of catastrophic tank car accidents in the late 1960s and early 1970s released flammable gases and toxic materials. Industry and government did not sufficiently understand the factors affecting these accidents and the principal failure modes that caused the releases. Two new cooperative research programs were initiated; one focused on train accident prevention and the other on tank car safety improvement.

The Railroad Tank Car Safety Research and Test Project started in 1970 under the auspices of the Railway Progress Institute—now the Railway Supply Institute—and AAR. The project conducted research and testing with U.S. DOT to identify and evaluate design concepts for improving the damage resistance of tank cars in accidents. This research led to such now-common safety features as head shields, shelf couplers, and thermal protection on tank cars carrying materials that pose the highest hazard; these features protect against the most likely failure modes.

U.S. DOT regulations and AAR standards incorporating these safety features have reduced tank car releases in accidents substantially. As the first major design elements with the sole purpose of protecting tank cars from damage in accidents, these features were revolutionary in their time.

Although effective in tests, the new design elements required proof on cars in service. The RSI-AAR Safety Project therefore launched a parallel effort to record extensive information about tank car performance in accidents. In 43 years, the effort has collected data on more than 40,000 damaged tank cars and 26,000 accidents (3).

Complementing this database is the Railroad Accident–Incident Reporting System, which the Federal Railroad Administration (FRA) revamped and expanded in 1975 to improve analyses of accident causes and trends.

Together, these two databases—one on accident causes and characteristics, the other on damage to

An accident at Crescent City, Illinois, in 1970, released and ignited liquefied petroleum gas; industry and government soon launched new, cooperative research programs to improve railroad and hazardous materials transportation safety.

Physical tests of tank cars with head shields (*left*) and without head shields (*right*) were conducted in the 1970s. The head shield is designed to protect the end—or head—of the tank car from impacts in accidents.

the vehicles involved—provide an inferential capacity that is unparalleled in the safety databases for any other U.S. transportation mode or in any comparable rail safety database in the world. The databases enable detailed quantitative understanding of the frequency and severity of tank car accident failure modes and of the effects of different design features.

## Optimizing Safety Design

The expansion and refinement of the RSI-AAR database has allowed increasingly robust statistical analyses of the performance of tank car designs and variations. For the first time, the relative benefits of alternative tank car designs could be evaluated with "what if" analyses. The combinations of changes most likely to maximize safety benefits could be quantitatively assessed, leading to a new approach to improving tank car safety.

The traditional approach was to overpackage hazardous products—that is, to transport them in tanks with higher pressure specifications than necessary. Now that the performance of each part of the tank car affecting safety could be quantified, an optimization model could be developed, combining the statistical estimates with data on tank car engineering design and economics, to assess the costs and potential benefits of candidate designs (*4*). The combinations offering the greatest benefit for the least cost—primarily represented as additional weight—could be identified (Figure 1, page 15).

Most tank car safety design enhancements involve thicker steel, which increases weight. Increasing a car's weight, however, reduces its carrying capacity because of the maximum allowable gross rail load or total weight. This in turn may require more shipments and more railcars to move the same quantity of goods.

### *Informing Standards*

The optimization model revealed which combination of design features offered the greatest safety benefit for the least amount of incremental weight, helping

Photo: TrinityRail


(*Left:*) Modern, nonjacketed tank car equipped with a half-height head shield. Many cars are built with a full-height head shield that is integral with a steel jacket enveloping the tank, to provide insulation or thermal protection.

(*Right:*) Double-shelf couplers are designed to prevent disengagement during derailments, so that adjacent cars cannot batter and puncture the tank car.

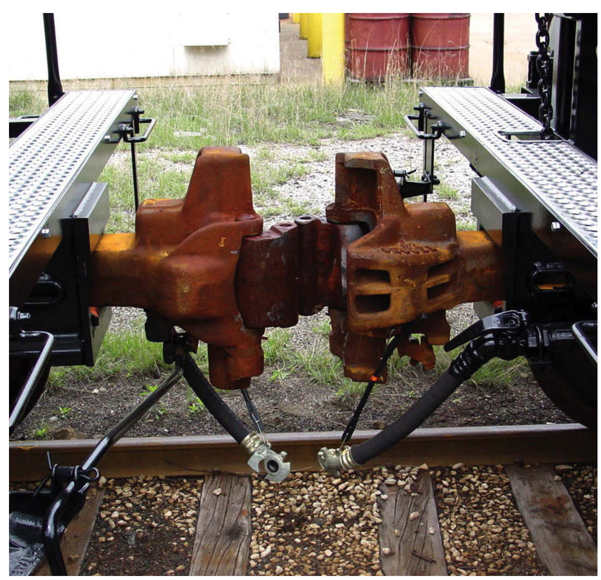


Photo: Union Tank Car

to identify the most efficient approaches to enhancing safety. The AAR Tank Car Committee used the tank car safety design optimization model results to develop several new standards, including design requirements for tank cars with higher carrying capacity (*5*).

One petition for U.S. DOT rulemaking led to new standards for toxic-inhalation hazard (TIH) tank cars (Figure 2, below). More than 1,600 new cars have been built since, and the risk of transporting TIH products in these cars has dropped by an estimated 60 to 65 percent. The AAR Tank Car Committee has used the results from the model to develop another petition for rulemaking for new, improved standards for flammable materials.

The optimization technique helps determine which combination of features will most efficiently achieve a given level of safety performance but does not answer the question, "how safe is safe enough?" Performance requirements of tank car designs vary widely, depending on the hazards associated with the material being transported. Industry and government have grappled with this question for decades, as understanding of different hazards has become more sophisticated, shipping patterns have changed, and societal expectations of tolerable risk have evolved.

### *Clarifying Trade-Offs*

Assigning relative value to harmful impacts can be technically challenging and sometimes controversial. Nevertheless, with improved quantitative rigor, decision making becomes more objective, traceable, and accountable, so that all parties are informed about the necessary trade-offs.

Analysis of the FRA and RSI-AAR databases yields information about risk and helps determine an appropriate level of safety to incorporate into tank car design. Safety design should be commensurate with the hazard posed by the materials, with more hazardous materials warranting greater protection.

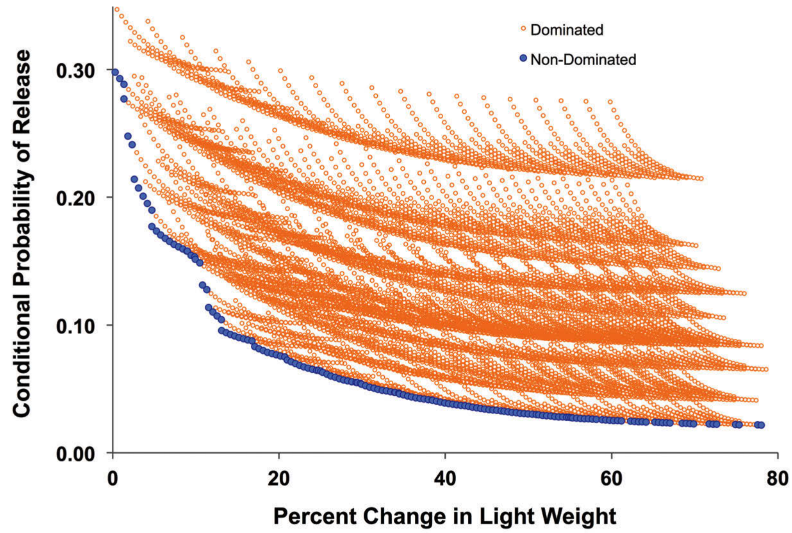


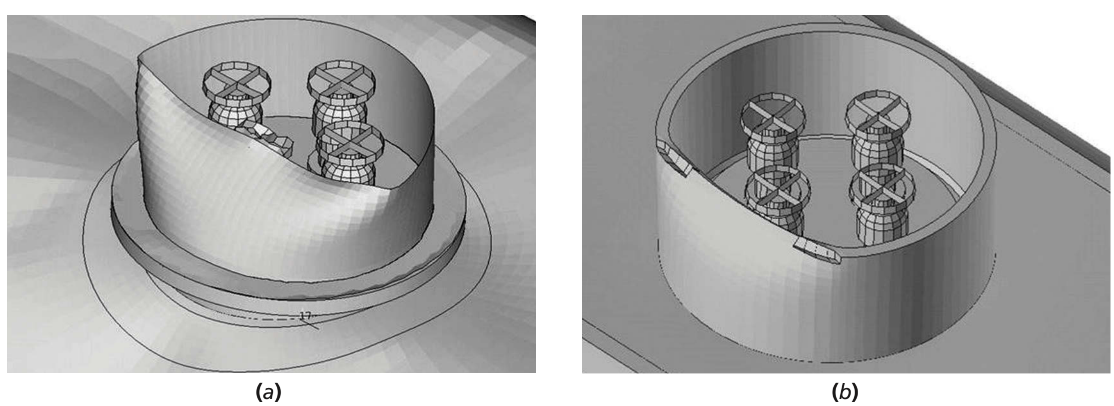

**FIGURE 1 Pareto optimal analysis of various combinations of tank car safety enhancements. The blue "nondominated" points represent the most efficient family of options to improve safety, minimizing the increase in tank car weight and consequent loss in capacity (*4*).**

As noted, tank cars can be made safer by increasing the damage resistance of various components; however, this generally can have the effect of making the tank cars less efficient for transportation and more costly to purchase. University of Illinois researchers developed a quantitative framework to assess the cost of losses of different hazardous materials—the incremental benefit of avoided costs was compared with the cost of more robust tank cars. Higher-hazard materials offered larger benefits for an equivalent level of tank car safety improvement.

## New Safety Design Concepts

From 1980 to 2012, the rate of hazardous materials releases caused by train accidents declined by more than 90 percent as a result of tank car safety enhancements and of a dramatic reduction in accidents, as shown in Figure 3 (page 16). Several accidents in the mid-2000s, however, caused fatal releases of

**FIGURE 2 Results of simulated rollover analyses of (*a*) conventional top-fittings protection compared with (*b*) a new design for pressure tank cars.**



(*a*) (*b*)

IMAGE: TRINITYRAIL

TIH tank car that conforms to new, more robust standards required by AAR and FRA. These cars are approximately 60 to 65 percent less likely to release their contents in an accident than cars conforming to the previous standard.


Photo: TrinityRail

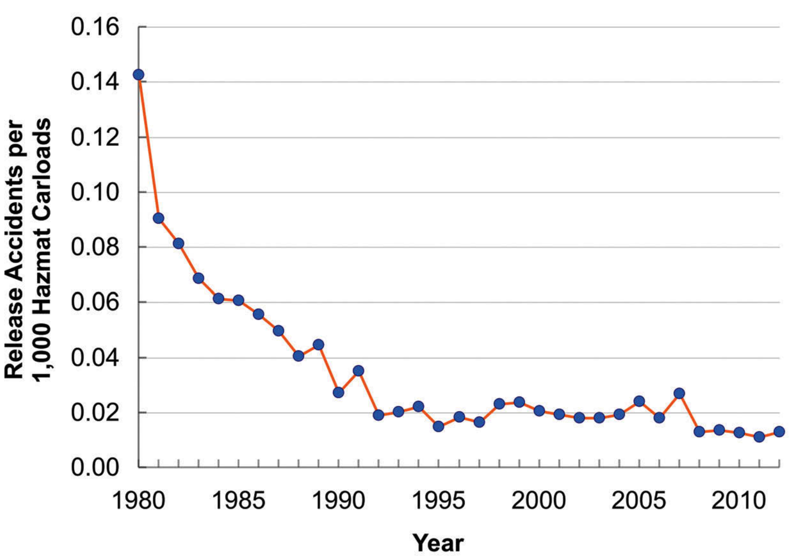
(*Below, left:*) Thermal protection can shield a tank and its contents from a buildup of heat-induced pressure in an accident that triggers an engulfing fire.

(*Below, right:*) Lower-profile protection for top fittings of TIH tank cars.

Photo: TrinityRail

Photo: TrinityRail

**FIGURE 3 The occurrence of hazardous materials releases caused by railroad accidents has declined more than 90 percent since 1980, with improvements in tank car safety design and substantial reductions in accidents** (Source: FRA)**.**




hazardous materials and stimulated renewed interest in tank car safety design.

Although further improvements were possible by making tank cars thicker and heavier, statistical analysis indicated diminishing returns to this approach. A consensus emerged that a more effective approach might be to consider new materials, structural designs, and components that would yield substantial safety benefits without as much additional weight.

In 2006 Dow Chemical, Union Pacific Railroad, and Union Tank Car Company formed a partnership to develop the next-generation rail tank car (NGRTC). The coalition soon expanded to include several other industry and academic partners, as well as U.S. DOT and Transport Canada, with the goal of improving tank car safety more effectively and efficiently. Extensive research explored innovative concepts in tank car crashworthiness, including computer modeling of the dynamics of train derailment and tank car response (as shown in Figure 4, at right), materials testing, full-scale crash testing, and tank car design optimization modeling (*4, 6, 7*).

***Impact Tests***

This work included a series of full-scale impact tests that examined the puncture resistance of the tank car head and shell and evaluated the performance of several designs hit by impactors with different sizes, shapes, and speeds. Accelerometer measurements were converted into force and displacement histories to characterize the force-crush response of the tank. The data were compared with results from finite element analysis models developed to simulate the tests and were found to be in reasonable agreement.

FRA also conducted impact tests on high-strength, low-alloy steels in welded sandwich panels as a possible means of protecting tanks during impacts (*8*). In addition, FRA is studying the vulnerability of tank car fittings—such as valves and other appurtenances—in accidents. Full-scale rollover tests have quantified the nature and magnitude of the forces on the cars and appurtenances (*9*). The test data can be used to refine and validate models now in development to predict tank car behavior and performance in accidents (Figure 5, page 18).

Union Tank Car Company or UTLX has constructed several "Tank Cars of Tomorrow," incorporating a tank-within-a-tank or sandwich design, along with other new safety features derived from the

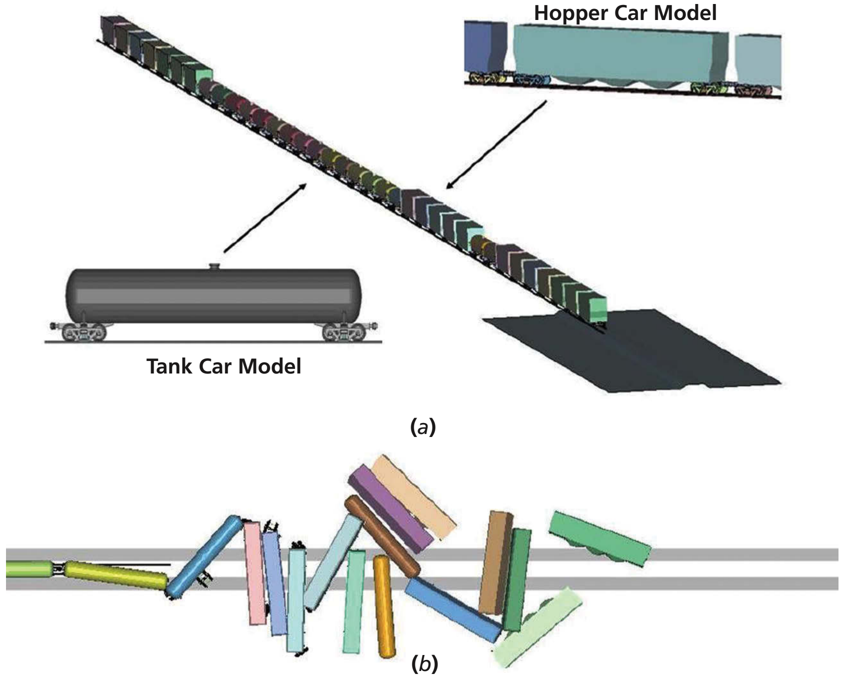



**FIGURE 4 Computer simulation models of the dynamics of train derailment were developed to understand the force of impacts on different parts of tank cars in accidents: (*a*) 36-car train model and (*b*) calculated response of train 25 seconds after derailment (*7*).**

Full-scale impact test setup at the Transportation Technology Center for evaluating various safety improvement concepts in the Next-Generation Rail Tank Car project (*7*).

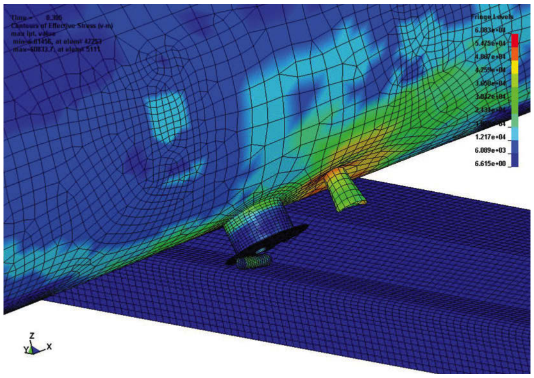


**FIGURE 5 A finite element analysis model simulating the response of the top fittings and the tank structure during a tank car rollover after derailment (*9*).**

research and development under the Next-Generation Rail Tank Car Project.

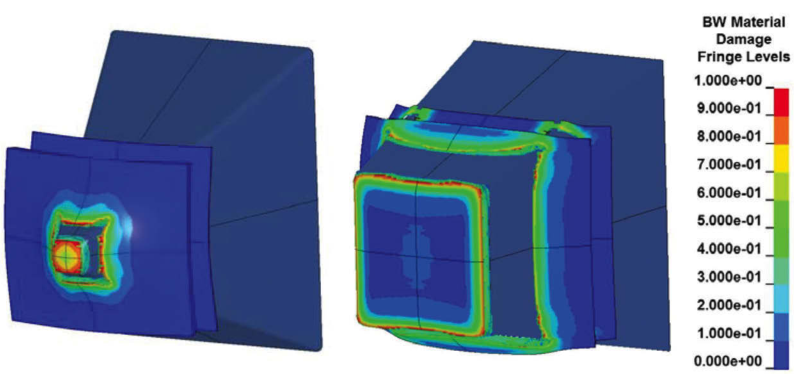
### *Simulation Tests*

In 2009 a larger coalition was formed to continue the work on the NGRTC. The Advanced Tank Car Collaborative Research Program (ATCCRP) includes AAR, RSI, the American Chemistry Council, the Fertilizer Institute, and the Chlorine Institute—representing private-sector stakeholders—and U.S. DOT, the U.S. Transportation Security Administration, and Transport Canada.

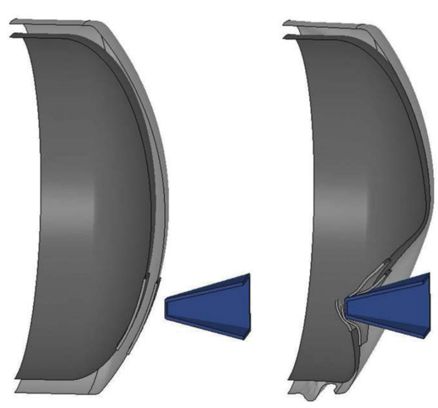
Informed by the extensive safety data and by the results of the physical testing and modeling research, the ATCCRP partners developed an extensive list of potential projects. The first two were (*a*) to identify the most appropriate failure criteria in modeling the performance of tank steels, as well as the material properties to support accurate use of those criteria, and (*b*) to simulate a variety of scenarios for tank head and shell impacts, to estimate how much energy each tank design could absorb.

Both projects aimed to improve assessments of the relative performance of tank car designs by improving the accuracy of the models in the finite element software, providing greater fidelity in predicting the failure process. For each type of tank steel, the most appropriate failure criteria—that is, the set of assumptions about how that material's failure will unfold at the microstructural level—were identified for use in larger impact scenarios.

The tank impact simulation project sought to refine the design of physical tests for developing a performance standard and to understand the forces acting on a tank in an accident. Many interesting findings emerged. For example, the size and shape of the impacting object in the tests started out as a major topic of debate, but the simulations made clear that larger impactors—including those with irregular shapes and angles—were essentially equivalent to smaller, sharper impactors in this context (Figure 6, at left). The element of a large impactor that makes initial contact with the tank acts like a small, sharp impactor, doing much of its damage quickly.




**(*a*)**



**(*b*)**

**FIGURE 6 The effect of different sizes and shapes of impactors was modeled to understand the relationship between failure mode and the geometry of objects that might strike a tank car in an accident: (*a*) calculated puncture behaviors with a 3-by-3-inch and a 12-by-12-inch impactor; and (*b*) initial impact conditions (*left*) and puncture response of the head (*7*).**

## Follow-Up Projects

Several follow-up projects are now under way to

- ◆ Derive up-to-date, empirical estimates from the RSI-AAR Safety Project and FRA databases for the probability that a derailed car will lose some or all of its contents or lading and through which components;
- ◆ Simulate the performance of tank protection systems fabricated from composite materials and compare the results with those for different types of steel;
- ◆ Develop mathematical relationships between the empirical lading-loss probabilities and the estimated energy absorption results from tests and simulations;
- ◆ Develop testing protocols to determine whether a new design meets specified performance criteria; and
- ◆ Evaluate new protective design systems, including additional layers of protective material surrounding the tank.

Photo: Union Tank Car


Several "Tank Cars of Tomorrow" were constructed in 2012 applying findings from the Next-Generation Rail Tank Car project; the tank cars are undergoing field tests.

The findings from these research projects may be used to design and build a prototype for a new generation of tank cars for TIH materials, with a much-improved accident performance. The lessons learned also can be applied to tank cars transporting other hazardous materials. As these new design concepts are developed, tested, and perfected for implementation, the optimization techniques can help decide which combinations will offer the most effective design for tank car safety.

## Impressive Advances

In 2012 the accident rate for mainline freight trains reached an all-time low. Although technical challenges remain, the vision is that when the new tank car design concepts now under development are implemented, further significant improvements will be possible.

Working together for more than a century, industry and government have conducted research and development that has generated impressive advances in tank car safety. These advances have served the public interest by making the transportation of hazardous materials safer.

### Dedication

The authors dedicate this article to the memory of the late William J. Harris, Jr., who played a critical role in establishing the modern era of cooperative tank car safety research. Harris was a leader in the formation of the Railroad Tank Car Safety Research and Test Project of the Railway Progress Institute and the Association of American Railroads. Much of the progress in tank car safety improvements in the past four decades can be attributed to his visionary leadership.

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