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13. ABSTRACT

The Transportation Technology Center, Inc. (TTCI), under the Federal Railroad Administration's Hazmat Transportation Safety Research and Development Strategic Plan, conducted a study of vent and burn as a method of hazardous materials incident mitigation. The purpose of the study was to develop guidelines and tools to aid emergency response personnel in making decisions about when to use the vent and burn procedure and to help guide them through the process. This report covers Phase II of the project, which carries through with the recommendations arrived at by the work accomplished in Tank Car Vent and Burn Process Study: Phase I, February 2003. A checklist and flow chart to be followed during a vent and burn procedure were further developed with review and input from experienced incident commanders. A portable electronic database containing the itemized checklist, tank car material specifications, Universal Machine Language Equipment Register information, and commodity characteristics was developed in a format compatible with personal digital assistants and laptop computers. TTCI developed a standardized comprehensive incident report form and reporting procedure. The computer models of explosive charge parameters were further developed and verified using full-scale tests on coupons and a complete tank car.

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METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.50	centimeters	cm
ft	feet	30.00	centimeters	cm
yd	yards	0.90	meters	m
mi	miles	1.60	kilometers	km
		AREA		
in^2	square inches	6.50	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.80	square meters	m^2
mi^2	square miles	2.60	square kilometers	km^2
	acres	0.40	hectares	ha
		MASS (weight)		
oz	ounces	28.00	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.90	tonnes	t
		VOLUME		
tsp	teaspoons	5.00	milliliters	ml
Tbsp	tablespoons	15.00	milliliters	ml
fl oz	fluid ounces	30.00	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.80	liters	l
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yd^3	cubic yards	0.76	cubic meters	m^3
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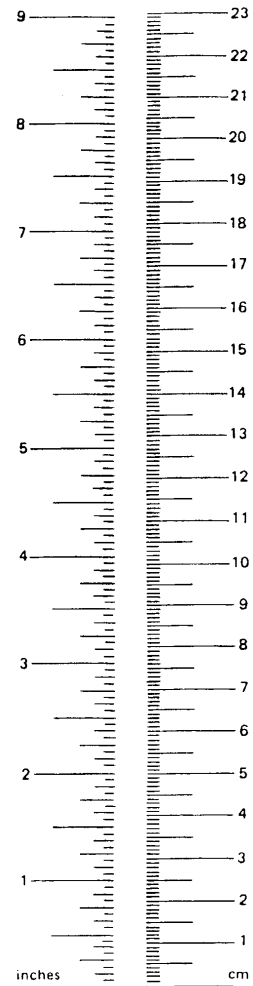
* 1 in. = 2.54 cm (exactly)



Approximate Conversions from Metric Measures

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m	meters	1.10	yards	yd
km	kilometers	0.60	miles	mi
		AREA		
cm^2	square centim.	0.16	square inches	in^2
m^2	square meters	1.20	square yards	yd^2
km^2	square kilom.	0.40	square miles	mi^2
ha	hectares (10,000 m^2)	2.50	acres	
		MASS (weight)		
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kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
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l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
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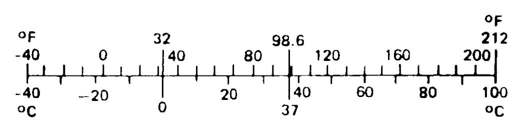


Table of Contents

List of Figures

List of Tables

Executive Summary

Vent and burn is an effective process used by emergency response personnel when dealing with serious railroad emergencies involving bulk hazardous material shipments transported in tank cars.

Emergency response personnel use this process primarily when uncontrolled release of large amounts of hazardous material because of tank failure is imminent. The vent and burn procedure uses two separate explosive charges to cut holes in the tank car in an attempt to avoid an uncontrolled release of product. One charge is placed at the highest point on the tank, over the product vapor space. This charge is designed to safely relieve internal vapor pressure. A second charge is placed at or near the lowest point of the tank to allow product to drain into a prepared containment pit where it can be disposed of through controlled burning.

In an effort to update the vent and burn process, the Transportation Technology Center, Inc. (TTCI) conducted a two-phase project. During Phase I, TTCI conducted a comprehensive study of past and current practices under direction of the Federal Railroad Administration's (FRA) Hazmat Transportation Safety Research and Development (R&D) Strategic Plan. The objective of the study was to develop a checklist of items to be considered and a process map to be used as tools to aid emergency response personnel in the decisionmaking process and help guide them through the procedure. The research undertaken in Phase I concluded that the vent and burn procedure is most effective when two-point penetration is used (one charge to vent internal pressure and the second to drain the tank), and each shape charge is designed to penetrate the jacket, thermal protection, and tank shell. Phase II of this project acted on the recommendations of Phase I, resulting in completion of the following tasks:

- Develop updated operational and reporting processes for emergency responders and railroads to use when considering and implementing vent and burn procedures. Items included to aid in the process include the following. (The appendices of this report include a hard copy of each form listed below and instructions for using the database; a CD of all the forms listed and the Vent and Burn database is included for Microsoft Word and Microsoft Access users.)

    1. A checklist of steps to consider as the decision to conduct a vent and burn procedure is evaluated.
    2. A flow chart or process map to follow as preparations are made for the vent and burn procedure.
    3. A formal reporting procedure that includes a post-event vent and burn report form to be completed after each incident. These forms will be submitted to the Accident Investigation (AX) Subcommittee of the Association of American Railroads (AAR) Tank Car Committee and to AAR/Railroad Supply Institute (RSI) Tank Car Safety and Research Project to be included in their databases. This will provide an increasing body of information to be

used when considering future changes and improvements to the recommended vent and burn procedures.

4. A database containing relevant information such as tank car specifications, commodity characteristics, and the Vent and Burn Checklist.

- The next generation of computer simulations modeling shape charge performance was completed. The results of these simulations were validated by actual explosives testing using an actual U.S. Department of Transportation 105J tank car, as well as 3-foot square test coupons. During the full-scale test, TTCI performed two separate vent and burn sequences using two different shape charge designs.

1.0 Introduction

FRA, through Contract Number DTFR53-93-C-00001, Task Order No. 135, Tank Car Vent and Burn Process Study Phase I, tasked AAR TTCI to develop a process that safely determines when and how to employ the vent and burn emergency product removal technique in railroad tank car accidents.

Vent and burn is a method of last resort used in certain circumstances when an uncontrolled release of large amounts of hazardous materials because of tank failure is imminent. This process uses two separate controlled explosive charges to cut holes in a damaged tank car in order to relieve internal vapor pressure and evacuate product for destruction through controlled burning. The study was conducted as part of FRA's Hazmat Transportation Safety R&D Strategic Plan. The work performed in Phase I resulted in the following recommendations designed to continue to improve the vent and burn process:

- Refine an itemized checklist to a final form to be used by incident commanders while considering and performing a vent and burn procedure.
- Compile information important to the vent and burn process, such as the itemized Vent and Burn Checklist, tank car material specifications, and commodity characteristics, into an electronic database that can be installed on portable tools, such as laptop computers.
- Finalize a standardized reporting procedure and related report form that can be used to build a nationwide database of vent and burn incidents. Data uniformly recorded for each incident would include shape charge design, charge location, vent times, atmospheric conditions, and details of the car condition.
- Perform computer simulations and actual validation tests to determine the shape charge designs that can successfully be used to penetrate tank jacket, insulation, and shell in one shot and to gather more information about the duel charge, time delay method that is commonly used. The duel charge method uses a vent charge on the highest parts of the tank, followed by a second charge at or near the lowest part of the tank after the internal pressure has been relieved.

Phase II addresses all of the recommendations listed above. In addition, TTCI developed a detailed flow chart and a process map to aid incident commanders through the steps of the vent and burn process.

1.1 Background

Derailments or similar accidents involving railroad tank cars containing hazardous materials often present unique challenges to emergency response personnel. Because normal recovery options are sometimes limited due to fire, severity of tank damage, or possible hidden damage, more extreme measures must sometimes be considered. One such option is the technique of vent and burn. This method should safely reduce the internal vapor pressure in the tank to decrease the potential for sudden and catastrophic failure of the tank and to empty the contents of the tank to facilitate disposal by burning. The vent and burn method is generally used only when a high probability of tank shell failure exists, which would result in an uncontrolled release of hazardous material.

The vent and burn procedure involves the use of two separate explosive charges to cut holes in the tank car. One charge is placed at the highest point on the tank over the product vapor space. This charge is designed to safely relieve internal vapor pressure. A second charge is placed at or near the lowest point of the tank to allow product to drain into a prepared containment pit where it can be disposed of through controlled burning. Due to the inherent hazards associated with high-pressure vessels, hazardous commodities, and the use of explosive devices, many factors must be carefully considered before selecting vent and burn as a method of mitigation. Figures 1 and 2 illustrate a tank car payload configuration and the vent and burn process.

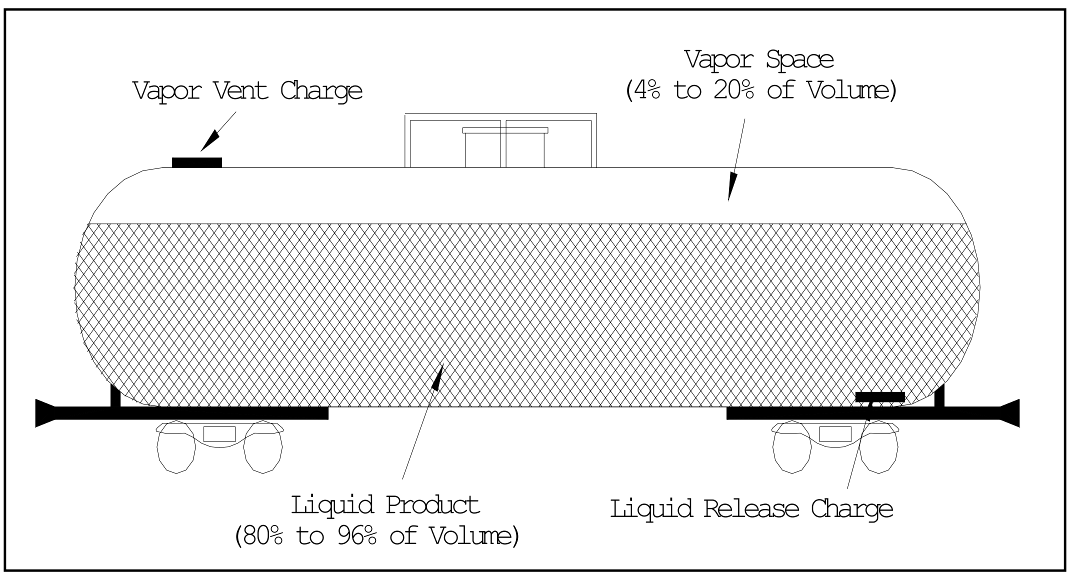


Figure 1. Schematic of Tank Car Displaying Vapor and Liquid Spaces

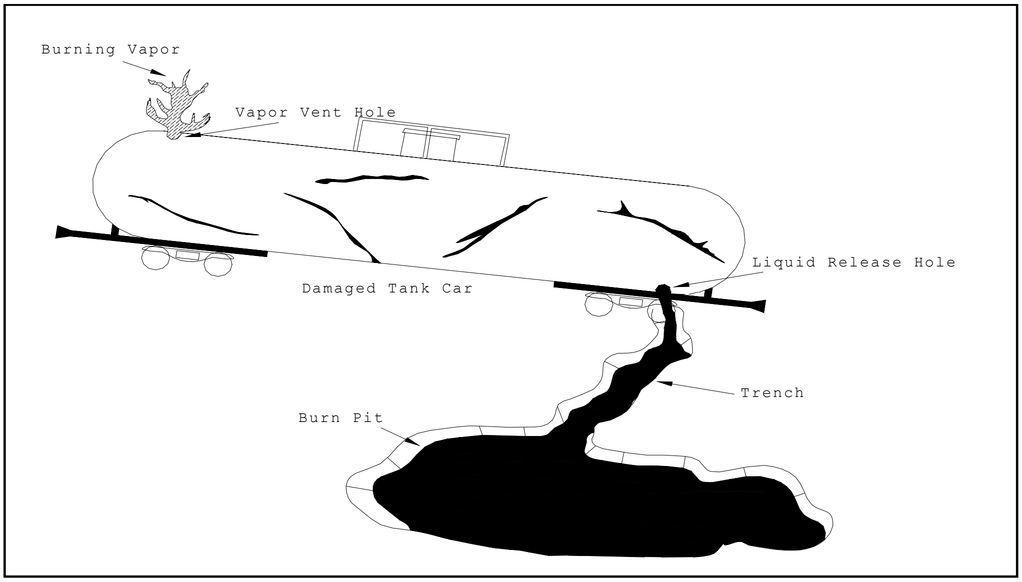


Figure 2. Application of Vent and Burn Process

2.0 Objective

The objective of both phases of this project is to develop a checklist of items to be considered when considering the vent and burn option, as well as a process map or flow chart to help obtain a predictable outcome and minimize the chances of any unexpected and/or undesirable consequences occurring when employing the vent and burn method. These tools are intended for use by emergency response personnel to determine if and when the vent and burn option should be used and to guide them through the procedure. The project objectives also call for recommendations on validating charge parameters and methodologies, as well as identifying product disposition concerns.

3.0 Scope

This project looks at past and current North American railway industry standards and practices as they apply to the vent and burn process and produced tools relevant to that specific market. This project does not consider or evaluate international practices. In addition, this study considers only the vent and burn option and does not address or discuss other emergency mitigation options (i.e., vent and drain for noncombustible and/or cryogenic materials).

4.0 Approach

4.1 Project Advisory Committee

The Project Advisory Committee, comprised of industry experts formed in Phase I of this project, continued to oversee and guide the work to finalize the checklist, database, flow chart, and reporting procedure as TTCI completed them. The appendices of this report include a hard copy of each form defined below and instructions for using the database; a CD of all the forms developed and the Vent and Burn database is included for Microsoft Word and Microsoft Access users.

4.2 Vent and Burn Checklist

Input from experienced incident commanders was used to refine an itemized checklist into final form, to be used by commanders while considering and performing a vent and burn procedure.

4.3 Vent and Burn Flow Chart

Input from experienced incident commanders was also used to refine a process map or flow chart to be used by commanders while considering and performing a vent and burn procedure.

4.4 Vent and Burn Database

A database containing relevant information for use during a vent and burn event was completed after considering input from the Project Advisory Committee and experienced incident commanders. Information includes tank car structural specifications and commodity characteristics, as well as the Vent and Burn Checklist.

4.5 Vent and Burn Report Form

With help from the Project Advisory Committee to determine what information should be included and the preferred reporting format, TTCI finalized a standardized procedure for collecting and reporting pertinent vent and burn information after an actual incident.

4.6 Finite Element Simulation of Shape Charges

In Phase I of this project, Lawrence Livermore National Laboratories conducted a computational study analyzing the performance of various shape charge designs on a standardized target. The following parameters were varied to maximize the hole size in the tank shell, including shape charge diameter, high explosive (HE) type, shape charge cone angle, and tank insulation thickness. Laboratory testing found that the hole size was sensitive to shape charge diameter and cone angle. As a followup to Phase I, Lawrence Livermore National Laboratories conducted subscale or coupon validation tests and full-scale experiments using the associated computational simulations in Phase II. Lawrence Livermore National Laboratories used a 2D hydrodynamics computer code called "CALE" (arbitrary Lagrangian Eulerian code; Tipton, 1997) to perform simulations to evaluate the performance of various shape charge- and explosive-formed projectile designs. Harry Keo Springer conducted a study to determine the effects of shape charge diameter, shape charge cone angle, HE type and tank shell thickness on resulting hole sizes. Springer considered the following three types of explosives:

1. C-4 (a mixture of 91 percent cyclonite (RDX), 2.1 percent polyisobutylene, 5.3 percent diethylhexyl sebacate, and 1.6 percent motor oil)
2. Composition B3 (a mixture of 64 percent RDX and 36 percent trinitrotoluene)
3. Helix (a proprietary formula)

The boat-tail, shape charge design was ultimately selected for the finite element parametric study and the validation testing using coupons. The variables of this design used were:

- 6-inch diameter utilizing both 90-and 120-degree cone angles
- 10-inch diameter utilizing both 90-and 120-degree cone angles
- C-4 and Helix explosives using each variable combination

Each shape charge utilized a 0.108-inch thick mild steel casing, a 0.093-inch copper liner, and a 2-inch standoff distance. Figure 3 shows the shape charges.

Figure 3. 6-Inch x 120-Degree, 10-Inch x 90-Degree, and 10-Inch x 120-Degree Shape Charges

Lawrence Livermore personnel used the Jones-Wilkins-Lee equation-of-state (EOS) for all three explosives in the CALE simulations. Lawrence Livermore personnel used a programmed burn feature for HE initiation (single-point) and detonation wave propagation. Data was readily available on high strain-rate material (including constitutive EOS) for copper and mild steel because the materials are commonly used in shape charges. Lawrence Livermore personnel used the Steinberg-Guinan model for the constitutive response of each copper and mild steel, whereas the Gruneisen EOS model was used for shock response.

Lawrence Livermore personnel used the Steinberg-Guinan model for the constitutive response of the TC128B normalized steel. No strain rate effects were considered in the formulation of this model due to lack of experimental strength data in these intense loading regimes. In addition, it was necessary to draw comparisons to the shock response of other steels to construct an EOS model. This was a reasonable assumption since most steels are primarily composed of iron and carbon. The failure model utilized was a simple effective plastic strain (EPS) limit. When an element in the simulation reaches this EPS limit, the deviatoric stress is set to zero (loses strength), and only the EOS model is active. The EPS limit was initially based on the reduction-in-area data for TC128B normalized steel but was iteratively modified to bring hole-size predictions (simulations) in agreement with subscale experimental results as part of the computational method validation process.

4.7 Validation Testing with Explosives

An explosive expert performed the testing using variations of HE type, shape charge diameter, and shape charge standoff distance on 3-foot square coupons cut from actual tank cars. Two combinations of tank shell thickness and jacket thickness were used, including 5/8-inch shell plus 11-gage jacket and 1-inch shell plus 11-gage jacket. As a result of the coupon testing, Lawrence Livermore selected two shape charge designs for use in a full-scale test of a complete tank car. TTCI and Lawrence Livermore personnel completed two separate vent and burn tests using a DOT 105J car with the following specifications:

- Union Tank No. UTLX 28298, DOT 105J500W, manufactured August 1973
- Outer Jacket–11-gage mild steel
- Inner Shell–0.779-inch AAR TC-128 Grade B as rolled steel
- Insulation–4 inches of urethane foam–2.65-pound per cubic foot density
- Shell Capacity–17,300 gallons
- Empty Weight–81,500 pounds

TTCI and Lawrence Livermore chose this car because it offered the thickest shell material in relatively common use. It was also thought that the 2.65-pound per cubic foot foam would offer more resistance to penetration than a matte material of fiberglass or similar material. The car was loaded with approximately 15,600 gallons of water to bring the level to within about 18 inches below the manway. The resulting gross car weight was 209,000 to 210,000 pounds. Compressed air was applied to the space above the water level to bring the internal pressure to 105-100 psi before each test. The test was designed to collect the following data for each vent and burn sequence:

- Internal tank pressure at four locations: (1) center of each tank head, (2) manway, (3) bottom of the tank on the lateral, and (4) longitudinal center lines. See Figures 4, 5, and 6.

- The bottom of tank at lateral and longitudinal center line and near the base of the manway. See Figures 6, 7, and 8.

Data from each channel was collected at a rate of 40,000 samples per second (Hz) and filtered at 15,000 Hz.

Figure 4. Pressure Transducer in A-End Tank Head

Figure 5. Pressure Transducer at Manway Longitudinal Tank Shell Strain on the Top of the Tank

Figure 6. Pressure Transducer and Strain Gage on Bottom Surface of Tank

Figure 7. Strain Gage Near Shell to Head Weld, A-End

Figure 8. Strain Gage at Base of Manway

5.0 Results

5.1 Project Advisory Committee

Recognized subject matter experts from North American railroads, response contractors, academia, and Federal agencies were chosen to form the Project Advisory Committee. The committee was comprised of the following:

- Danny Simpson–Manager, Emergency Response Training Center, TTCI
- Al Maty–Chief Inspector, Bureau of Explosives, TTCI
- Patrick Brady–Assistant Director, Environmental and HAZMAT, Burlington Northern Santa Fe Corporation
- Jose Pena–Mechanical Engineer, FRA
- Chet Cully–General Director, Environmental and Hazmat Department, Kansas City Southern Railway Company
- Hank Cox–Manager, Field Services, Hazardous Materials Systems, CSX Transportation
- Billy Poe–President, Explosive Services International, LTD

5.2 Vent and Burn Checklist

With the help of the Project Advisory Committee and experienced vent and burn incident commanders, a vent and burn checklist was finalized. Appendix A shows the list, containing 24 items to consider before initiating a vent and burn procedure. The Vent and Burn Database contains the list, which can be stored and accessed on a laptop computer in Microsoft Word format.

5.3 Vent and Burn Flow Chart

With the help of the Project Advisory Committee and experienced vent and burn incident commanders, a vent and burn flow chart or process map was finalized. The database contains this flow chart (Appendix B) in Microsoft Word format detailing 19 steps that should be followed while completing a vent and burn process.

5.4 Vent and Burn Database

With the help of the Project Advisory Committee and experienced vent and burn incident commanders, a vent and burn database was finalized. This database contains the following:

- A comprehensive list of hazardous commodities, their HAZMAT codes, the suitability of each for the vent and burn procedure, and additional HAZMAT commodity information that may aid in a decision as to whether a vent and burn procedure should be attempted.

- Construction information, such as minimum shell thickness for each class of tank car.

- The Vent and Burn Checklist described in Section 5.2.

The database is in Microsoft Access format to be used with any laptop computer with the Access software installed. Appendix C contains the instructions to use the database.

5.5 Vent and Burn Report Form

With the help of the Project Advisory Committee and experienced vent and burn incident commanders, a vent and burn report form was finalized (Appendix D). The report form contains approximately 20 categories for which information can be provided that will describe a vent and burn event. Submission of these reports to the AX Subcommittee of the Tank Car Committee and to the AAR/RSI Tank Car Safety Research Project will allow the building of a comprehensive database of vent and burn events.

5.6 Finite Element Simulation of Shape Charges

TTCI previously completed a set of simulations during Phase I of this project. The following briefly summarizes the parameters evaluated and results:

- Parametric analysis was performed to evaluate the effects of shape charge diameter and cone angle, HE type, and standoff distance of the diameter of the resulting hole.
- The nonvariable shape charge specifications used included the following: 0.25 centimeter Cu liner, 2 inches from cone vertex to aft end, and 0.25 centimeter SS304 casing (plastic casing suggested to minimize collateral damage because steel casing not needed for confinement).
- Tank shell and jacket specifications used included the following: material–American Society for Testing and Standards (ASTM) A516 Grade70, Shell–1-inch thickness; Jacket–11-gauge (0.1196-inch) thickness.
- The primary conclusion from this study was that the size of the hole was most sensitive to shape charge diameter and cone angle and less sensitive to HE type. The conclusion also included the idea that increasing standoff reduced exposure to high pressure gases.

During Phase II, Lawrence Livermore National Laboratories updated material properties to model TC128B normalized steel instead of ASTM A516 Grade 70. The following lists additional modifications or additions to the model parameters used during Phase II:

- Elastic-plastic response was included according to the Steinberg-Guinan model.
- Material yield strength was modeled to be independent of pressure and rate of strain.
- The equation of state is generic for steel material.
- Cumulative damage can be triggered by a number of metrics, including pressure, EPS, and setting the deviatoric strength to zero once the material is fully damaged.

EPS was varied as a function of tank shell thickness to calibrate the CALE model. The EPS value was based on reduction in area measurements made after coupon testing. Table 1 shows the results of the finite element simulations of the coupon tests.

TTCI performed finite element simulations of the full-scale vent and burn test. This was not a parametric study so the range of variables investigated was limited. For these simulations, the operator set the tank shell at 0.779 inch and the jacket thickness at 11 gage (0.1196 inch). Table 2 shows the results of the simulations for the full-scale test. The data in Tables 1 and 2 show that simulation results generally predicted sizes of the holes within 10 percent of those produced during the coupon and full-scale tests. Sources of differences between predicted and actual results could include lack of accurate high strain rate or true stress versus strain data for TC128B, a difference in effectiveness between hand-packed and precision-machined shape charges, or lack of uniformity in the liners. The simulation results also indicate that the shape charge with the 90-degree cone angle results in a slightly larger size hole than that with the 120-degree cone angle. Reasons for this difference could be connected with liner fragmentation. The simulations also predicted that the Helix would produce a larger size hole than the C-4, with all other variables being equal.

Table 1. Simulation and Coupon Test Results—TC128B Normalized

Shape Charge Diameter (in)	Explosives Type	Cone Angle Degrees	Shell Thickness (in)	Standoff Distance (in)	Hole Diameter Simulation (in)	Test Hole Diameter (in)
10	C-4	120	5/8	2	6.5	6
6	C-4	120	5/8	2	2.3	2
6	C-4	90	5/8	2	2.7	2.5
10	C-4	90	5/8	2	6.4	6.5
10	C-4	90	1	2	3.9	4
10	Helix	120	1	2	5.8	6

Table 2. Simulation and Full-Scale Test Results

Charge Location	Shape Charge Diameter (in)	Explosives Type	Cone Angle Degrees	Standoff Distance (in)	Hole Diameter Simulation (in)	Test Hole Diameter (in)
Top	6	Helix	161	4	5.5	6.0
Bottom	6	Helix	161	4	7.1	9.0 x 5.5
Top	6	Comp-B	90	4	5.2	19.0 x 7.0
Bottom	6	Comp-B	90	4	6.4	10.0 x 4.0

5.7 Validation Testing with Explosives

Validation was first completed using tank shell and jacket sections cut from existing cars. Shell thicknesses of 1 inch and 5/8 inch were used. Records were not complete on the type of steel used in the test coupons. It was confirmed that the 5/8-inch material was AAR TC128 Grade B steel, but the material type for the 1-inch shells could not be determined with certainty. The explosive expert mated all tank shell samples with 11-gage jackets using spacers to form a stand off for 4 inches. No insulation was used for the coupon tests. Figure 9 shows the typical test sample configuration. Figures 10 and 11 show the placement of the shape charge on the sample and the resulting hole.

Figure 9. Typical Test Sample for Coupon Test

Figure 10. 10-Inch x 120-Degree Shape Charge on Test Sample

Figure 11. Hole from 10-Inch x 120-Degree Shape Charge on 5/8-Inch Shell and 11-Gage Jacket

Table 1 shows the results of the coupon test. Observations resulting from the coupon or subscale tests include the following:

- The C-4 charge with the 90-degree cone angle produced a slightly larger hole than the 120-degree cone angle.
- Helix outperformed C-4 despite lower energy and slower detonation wave speed.
- Ten-inch charge diameters outperformed 6-inch charge diameters, possibly because of scaling effects where the jet diameter scales with the charge diameter.
- Ninety-degree cone angles outperformed 120-degree cone angles, possibly because of liner breakup. This is evidenced by a mottled appearance of the plate surface around the holes created in some of the test coupons. This is predicted in simulations by breakup of the exterior of the liner during jet formation.

The full-scale vent and burn testing at TTC was completed in October 2004. Test operators used Helix shape charges for the first test with the vent or top charge placed near the A-end of the car and the drain or bottom charge placed toward the B-end (see Figures 12 and 13).

Figure 12. Preparation of Vent Charge for Test 1, A-End of Car

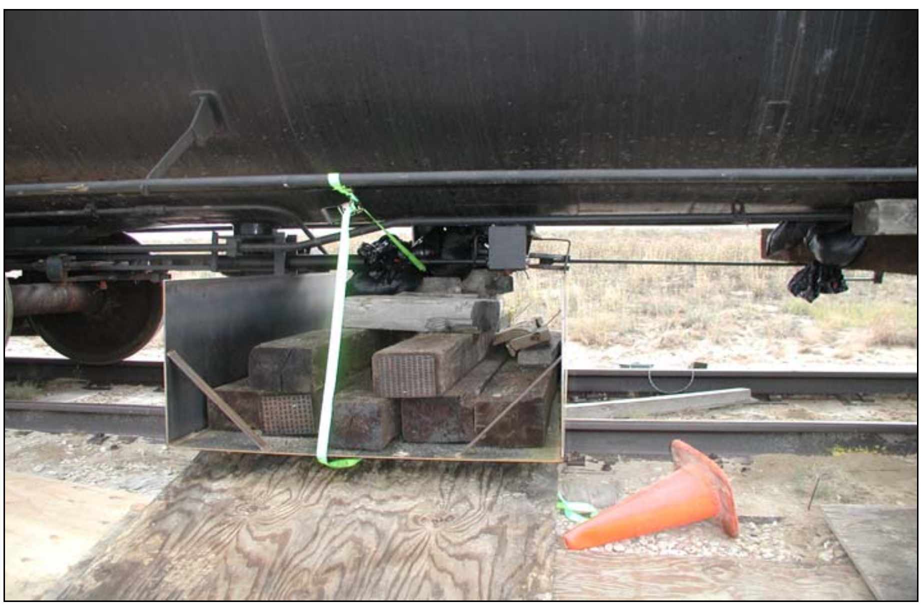


Figure 13. Drain Hole Charge for Test 1, Near the A-End of Car

The shape charges used by the explosive expert for both the vent and drain portions of the first test were of experimental design employing a modified explosively formed projectile (EFP) (see Table 2). This package is designed to form a projectile when the explosive charge detonates. The projectile penetrates the target in a manner similar to a cookie cutter. The HE used in this charge design is a relatively new formula known as Helix. This Binary explosive is similar to another two-part system known as Picatinny Liquid Explosive. Helix has a detonating velocity of approximately 22,000 feet/second, and the stable ingredients of fuel and oxidizer can be easily transported. Once the ingredients are at the location where the explosives are needed, they can be mixed to form a HE charge. The EFP for this shape charge design was a 6-inch diameter copper plate with a 4-inch standoff. The charge for the top vent hole contained a net explosive weight of 3 pounds of Helix HE; the charge for the bottom drain hole contained a net weight of 4 pounds of Helix. (See Table 2 for a summary of the hole sizes created.) The car was completely drained of water within 20 minutes of the drain charge detonation (Figure 14). Pressure and strain gage data was not recorded for the first test because of a sudden failure of a data acquisition system connection at the time of detonation of the vent charge.

Before the second test, TTCI personnel patched the holes in the tank shell created by the first test by welding 3/8-inch thick plate over the holes (Figure 15). The car was filled again with water to the level obtained before the first vent and drain sequence. For the second test, the explosive expert placed the vent charge near the B-end of the car and the drain charge towards the A-end. The shape charges used for the vent and drain portions of the second test were constructed from 4 pounds of Composition B explosives using 6-inch diameter conical charges, 90-degree cone angles, and a 4-inch standoff distance. (See Table 2 for a summary of the hole sizes created.)

Figure 14. Water Draining After Full-Scale Vent and Drain Test 1

Figure 15. Patch Welded Over Drain Hole from Test 1

Figures 16 and 17 show the vent and drain holes from Test 1 using the Helix-shape charge. Figures 18 and 19 show the holes created using the Composition B-shape charge in Test 2. After the vent charge was detonated, the internal air and liquid shock waves lasted 0.078 seconds, and approximately 2.5 seconds were required for the internal tank pressure to decrease from 105 psi to atmospheric. In the second test, the car was completely drained of water within 17 minutes of the drain charge detonation. Tables 3, 4, 5, and Figure 20 summarize pressure and strain/stress data recorded from the second test.

Figure 16. Vent Hole from Test 1 Using Helix-Shape Charge

Figure 17. Drain Hole from Test 1 Using Helix-Shape Charge

Figure 18. Vent Hole from Test 2 Using Composition B-Shape Charge

Figure 19. Drain Hole from Test 2 Using Composition B-Shape Charge

Table 3. Internal Pressure Response for Vent Detonation–Test 2

Location	Peak Pressure (psi)	Time After Detonation (s)
A-End Tank Head	1,285*	0.031
B-End Tank Head	656	0.023
Bottom of Tank	1,172*	0.016
Base of Manway	Transducer Failure	

Note: All pressure transducer circuits failed at the time of the second detonation.
*Data collection system was scaled for a maximum pressure of 1200-1300 psi. These values are within approximately 80 percent of the true peak. Transducers were capable of a maximum pressure of 2000 psi.

Table 4. Stress on Outer Tank Surface for Vent Detonation–Test 2

Location	Before Detonation (psi)	Peak Stress (psi)	Time After Detonation of Peak (s)
A-End Top Near Head	4,230	11,100	0.016
B-End Top Near Head	3,780	24,570	0.001
Bottom of Tank	6,180	15,600	0.057
Base of Manway	4,365	49,620	0.029

Table 5. Stress on Outer Tank Surface for Drain Detonation–Test 2

Location	Before Detonation (psi)	Peak Stress (psi)	Time After Detonation of Peak (s)
A-End Top Near Head	0.0	3,375	0.006
B-End Top Near Head	3,765	7,140	0.008
Bottom of Tank	0.0	24,879	0.004
Base of Manway	0.0	3,012	0.028

As the data shows, the maximum stress on the outer shell surface was almost 50,000 psi in the circumferential axis recorded at the base of the manway during the initial vent blast. This stress level is about 71 percent of the yield for TC128 steel. Lower stress levels of about 24,000-25,000 psi were recorded near the B-end head weld joint during the vent blast and at the bottom center of the car during the drain blast. The stress recorded on the top B-end of the car was oriented in the longitudinal axis, and the stress on the bottom center of the tank was oriented in the circumferential axis. The strain/stress at the base of the manway reached a peak at the same instant that the pressure reached a peak at the A-end of the car. The peak stress at the top B-end of the car does not coincide with the peak values of any of the pressure transducers. The peak stress recorded by this gage occurred before any of the pressure peaks, indicating that this stress was induced by the force or shock of the vent blast transmitted through the steel plate. In addition, the peak stress recorded at the bottom center gage did not coincide with any of the pressure peaks actually occurring immediately after the drain blast. This is an indication that this stress peak was induced by the shock and not by pressure waves or surges.

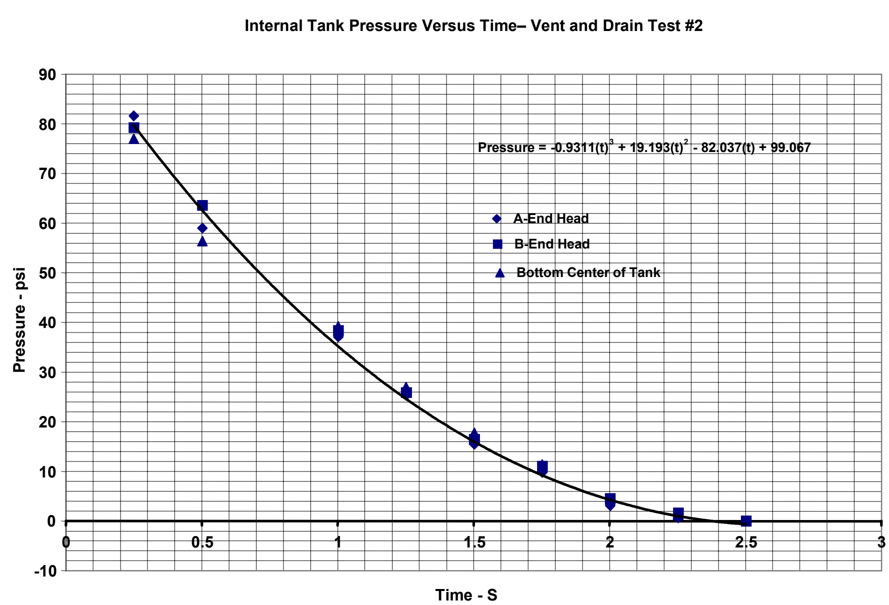


Figure 20. Tank Pressure versus Time, All Three Operational Pressure Transducers

6.0 Conclusions

- The finite element simulation software developed at Lawrence Livermoore National Laboratories is capable of predicting the size of holes created in test coupons by HE shape charges to within 10 percent. The simulation prediction of hole size diameter was less successful for the holes created during the full-scale tests. The disparities between simulations and full-scale test results could be due to several factors:
  - Lack of accurate high strain rate data for TC128 Grade B steel
  - Different characteristics between precision-machined explosives (simulation) and hand-packed plastic explosives (full-scale test)
  - Lack of uniformity in the copper liners
  - The simulation of metal tearing and petaling is not currently well formulated and validated
- A single 10-inch diameter, 90-degree cone angle shape charge using either Composition B or experimental Helix HE is capable of producing holes of sufficient size in both tank car jackets and shells to satisfy the requirements of a successful vent and burn procedure. Since this capability was demonstrated on a car with 0.779-inch shell, 11-gage jacket, and 4-inch thick layer of urethane foam, it should hold true for almost all HAZMAT tank cars.
- The full-scale test results indicate that the Helix explosives are a better choice than Composition B for the vent and burn procedure. Observations showed that the Helix HE left a cleaner, more symmetrical hole in the shell with less of a tendency for tears in the steel to travel away from the holes. With the use of the Helix, less of a tendency may exist for more brittle shell steels to fail catastrophically due to the fast and extensive growth of tears or cracks immediately after a vent and burn event.

7.0 Recommendations

- Incident commanders should use the Vent and Burn Checklist, as shown in Appendix A.
- Incident commanders should use the Vent and Burn Flow Chart or process map, as shown in Appendix B.
- Incident commanders should use the Vent and Burn Database as a valuable resource as they prepare for a vent and burn event.
- Incident commanders should use the Vent and Burn Report Form, as shown in Appendix D, to document the important variables and events surrounding a vent and burn incident. This form should then be filed with the AX Subcommittee of the Tank Car Committee and to the AAR/RSI Tank Car Safety Research Project in order to build a comprehensive database of vent and burn events.
- A single 6-inch diameter, 90-degree cone angle Helix-shaped charge is recommended to be placed on the jacket to create the required holes in both the jacket and tank shell during a vent and burn procedure.
- Further simulation and testing should be conducted to determine the minimum Helix- or similar EFP-shaped charge size that can be used to produce hole sizes large enough to complete a successful vent and burn sequence.

  It is possible that a hole size of 3- to 3.5-inch diameter is sufficient to produce acceptable results. Previous testing measuring flow through tank car safety vent nozzles indicated only a 0.9 percent reduction in flow rate when nozzle size was reduced from 6.5-inch diameter to 3 inches (internal pressure 181.5 psi).[1]
- The stress data recorded during the full-scale vent and burn test should be used along with fracture mechanics analysis tools to determine if the peak stresses on the shell surface during a vent and burn sequence are high enough to result in rapid brittle fracture under certain combinations of steel properties and environmental conditions.
- Perform additional computational simulations of the vent and burn process on the most common tank car designs to create a database of preferred shape charge designs that can be used in a decision matrix for accident response.

Reference

1. Treichel, T.T.; Widell, G.W.; and Barkan, C.P.L. (January 1998). "The Effectiveness of Tank Car Safety Vent Surge Pressure Reduction Devices." *Technology Digest* TD-98-001, Association of American Railroads, Risk Management Division.

Appendix A.
Vent and Burn Checklist

(Place a check mark in the box next to the response that best describes the situation.)

Damage Assessment

Is tank car being impinged upon by fire?	Yes		Close to Fire		No	
Are contents of tank car burning?	Yes				No	
Is tank car venting continuously?	Yes				No	
Is shell rupture imminent?	Yes		Possible		No	
Is tank damaged?	Yes		Somewhat		No	
Has tank specification and construction material been determined?	Yes				No	
Is ambient temperature cold enough to cause brittle fracture?	Yes		Possible		No	

Location/Environment/Site Assessment

Is the tank close to other tank cars?	Yes		Somewhat		No	
Is the tank near buildings or structures?	Yes		Somewhat		No	
Is tank near habitation?	No		Within .025 mile		Within 0.5 mile	
Have inhabitants been evacuated?	Yes		In process		No	
Is excavation of burn pit possible?	No		Within .025 mile		Within 0.5 mile	
Is accident scene close to water sources?	No		Within .025 mile		Within 0.5 mile	
Will windspeed and direction produce dangerous product fallout?	Yes		Somewhat		No	

Product Considerations

Is product combustible?	Yes				No	
Is product polymerization a possibility?	Yes				No	
Will controlled release exceed toxicity levels?	Yes				No	
Will products of combustion exceed toxicity levels?	Yes				No	
What is the permeability of the soil?	High		Medium		Low	
What is the viscosity of the product?	High		Medium		Low	

Resources/Product Containment

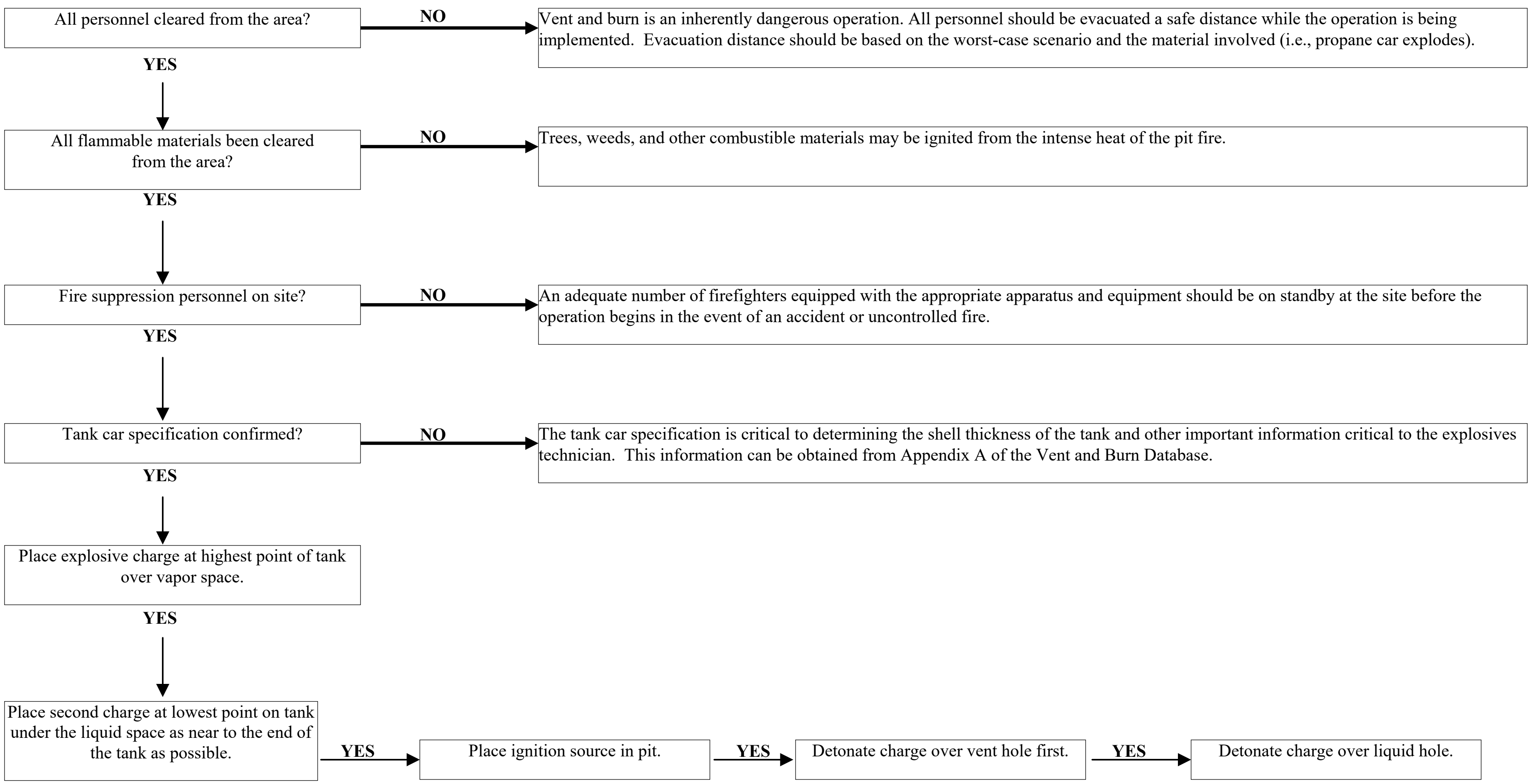
Are local fire suppression personnel present?	Yes		On Call		No	
Is equipment available to dig pit and trench?	Yes		En route		No	
Is an explosives expert available?	Yes		En route		No	
Are proper explosives available?	Yes		En route		No	

Appendix B.
Vent and Burn Flow Chart

YES ↓	NO →
Have all other options been considered?	Vent and burn is generally used only when a total, uncontrolled release of hazardous materials due to tank failure is imminent.
Is product suitable for vent and burn?	Ensure that the material is flammable or combustible. The products of combustion may be toxic, corrosive, or pose other hazards. What are the consequences of an uncontrolled release of product in the event of catastrophic tank shell failure if vent and burn is not employed? See Vent and Burn Database for product suitability.
Experienced explosives expert available?	Vent and burn should not be attempted by inexperienced people. If private contractors are not available, military or police may be a resource.
Necessary explosives available?	If explosives technicians do not have their own explosives, local military bases or police may be a source of explosives.
Required environmental permits in hand?	Virtually any jurisdiction will require burn permits or other such permits for an operation such as vent and burn.
Pit of sufficient size available?	Failure to contain all the material may result in spreading of the fire to undesired areas. The pit should be far enough from the other cars in the derailment that the fire will not adversely affect other cars or equipment. See the Vent and Burn Database for the formula to calculate pit dimensions.
Channel excavated from liquid hole to pit?	The channel should be wide enough and deep enough to contain the forceful flow of product from the drain hole.
Wind direction and speed?	Given the large volume of material to be burned, consideration must be given to where the smoke and other products of combustion will be carried by the wind.
Monitors installed downwind?	Monitoring of the products of combustion will help ensure that emergency personnel, as well as the general public, will not be exposed to any hazards. It will also serve to document, for liability purposes, that no hazardous products of combustion were spread as a result of the operation.
Site safety plan been developed?	Carefully thinking through all steps in the operation and all eventualities will ensure that resources are on hand to deal with them.

YES

Vent and Burn Flow Chart—continued

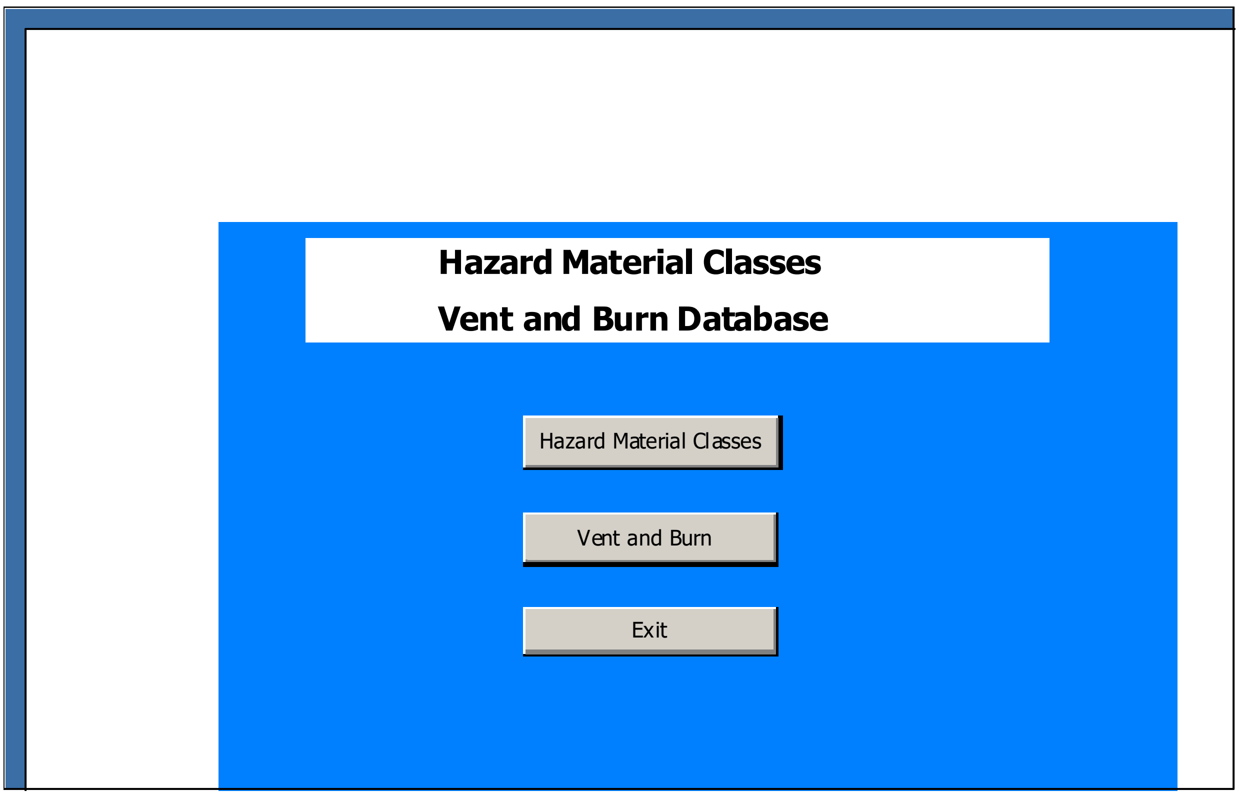


Appendix C.
Instructions for Vent and Burn Database

The following are snapshots of screens that will display on your computer when running the database.

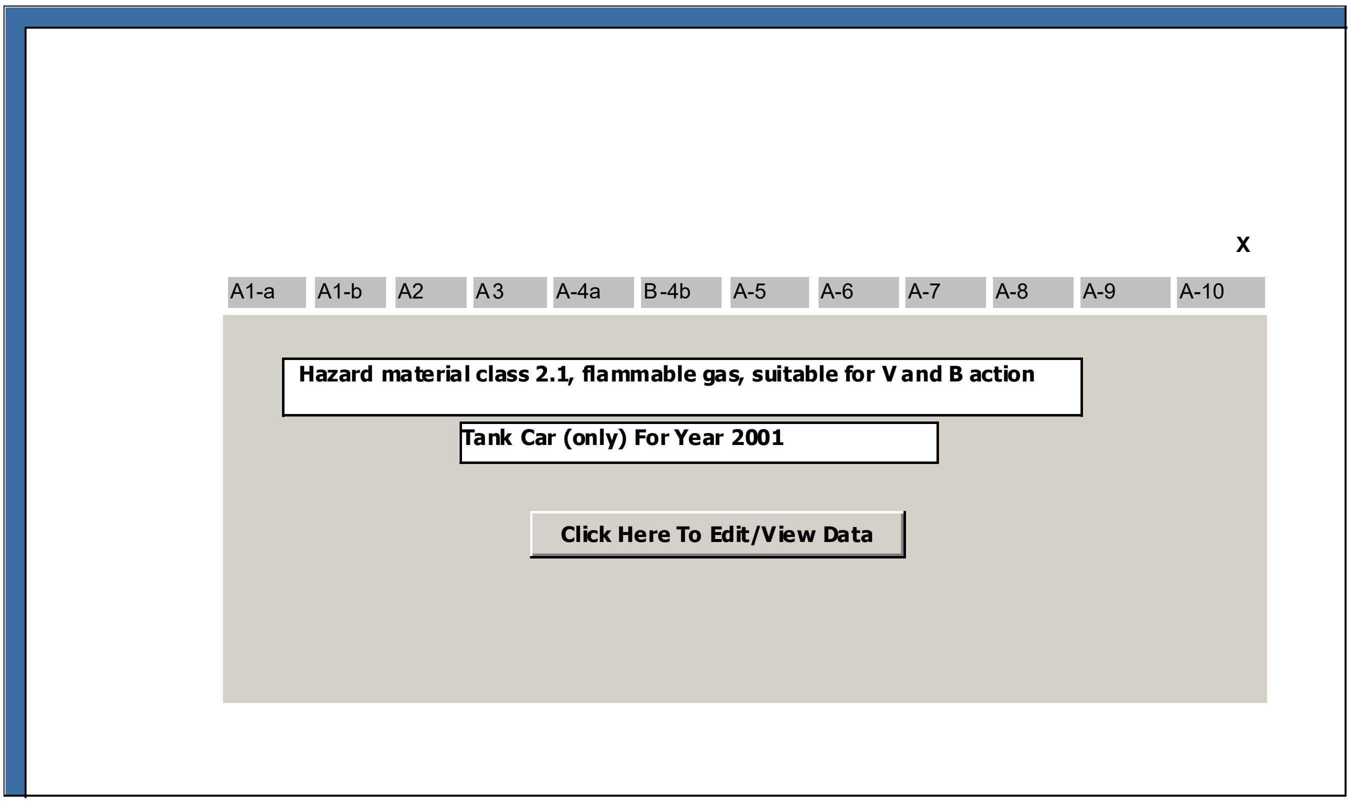
- Click on the database icon on your desktop to launch the program. The following menu will appear. Click on the appropriate button.

Note: Exit will take you completely out of the program



- Click on “Hazard Material Classes” to open a screen like the one shown.
- Click on the appropriate tab, and click on “Click Here” to Edit/View Data.
- Table A1-a is used as an example. All of the other tables will use the same instructions as outlined in this document.
- When a Microsoft Excel message box appears, click on “ENABLE MACROS” to properly activate macros.

Note: To close the screen, click on “x” in upper right hand corner.



When a table is chosen, a spreadsheet will appear:

Filter Find Delete

Table A-1a Hazard material class 2.1, flammable gas, suitable for V&B action.

Haz Mat Code	Tank Car (only) For Year 2001 Hazard Class 2.1 Flammable Gas Description	VB Code
4905423	BUTANE	ok
4905788	BUTANE	ok
4905789	BUTANE	ok
4905706	BUTANE	ok
4905702	BUTANE	ok
4905715	BUTYLENE	ok
4905428	BUTYLENE	ok
4905742	DIMETHYL ETHER	ok
4905725	DIMETHYL ETHER	ok
4905749	HYDROCARBON GAS MIXTURE, LIQUEFIED, N.O.S.	ok
4905430	ISOBUTANE	ok
4905759	ISOBUTANE	ok
4905753	ISOBUTANE	ok
4905747	ISOBUTANE	ok
4905748	ISOBUTYLENE	ok
4905757	ISOBUTYLENE	ok
4905763	LIQUEFIED GAS, FLAMMABLE, N.O.S.	ok
4905457	PETROLEUM GASES, LIQUEFIED	ok
4905711	PETROLEUM GASES, LIQUEFIED	ok
4905417	PETROLEUM GASES, LIQUEFIED	ok
4905780	PETROLEUM GASES, LIQUEFIED	ok
4905752	PETROLEUM GASES, LIQUEFIED	ok
4905707	PETROLEUM GASES, LIQUEFIED	ok
4905762	PETROLEUM GASES, LIQUEFIED	ok
4905421	PROPANE	ok
4905791	PROPANE	ok
4905781	PROPANE	ok

Notes: (ok) No intrinsic chemical property reason for not employing V&B action.

Code	Description
(ok)	**No intrinsic chemical property reason for not employing V & B action. Operational risk is viewed comparable to propane.**
(sr)	**Potentially self-reactive if exposed to fire of long duration.**
(phf)	**Potentially shock sensitive because of positive heat of formation.**
(env)	**Potential elevated environmental risk on burning due to presence of amine or halogen groups or other toxic elements or reaction products.**

Explanation of buttons:

Filter Button: For the filter to work, make sure all of the down arrows are visible for Hazmat Code and the Description. If they are not visible, click on the Filter button until they appear. Click on the down arrow over one of the columns. The search can be reduced in scope as desired. To reset the filter, click on the Filter button twice until the down arrows reappear. The filter must be reset when changing from one column to another.

Find Button: Click on this button to Find/Replace a record. When a column is highlighted, enter the value of interest in "Find What." To remove the highlight, click anywhere in Column H.

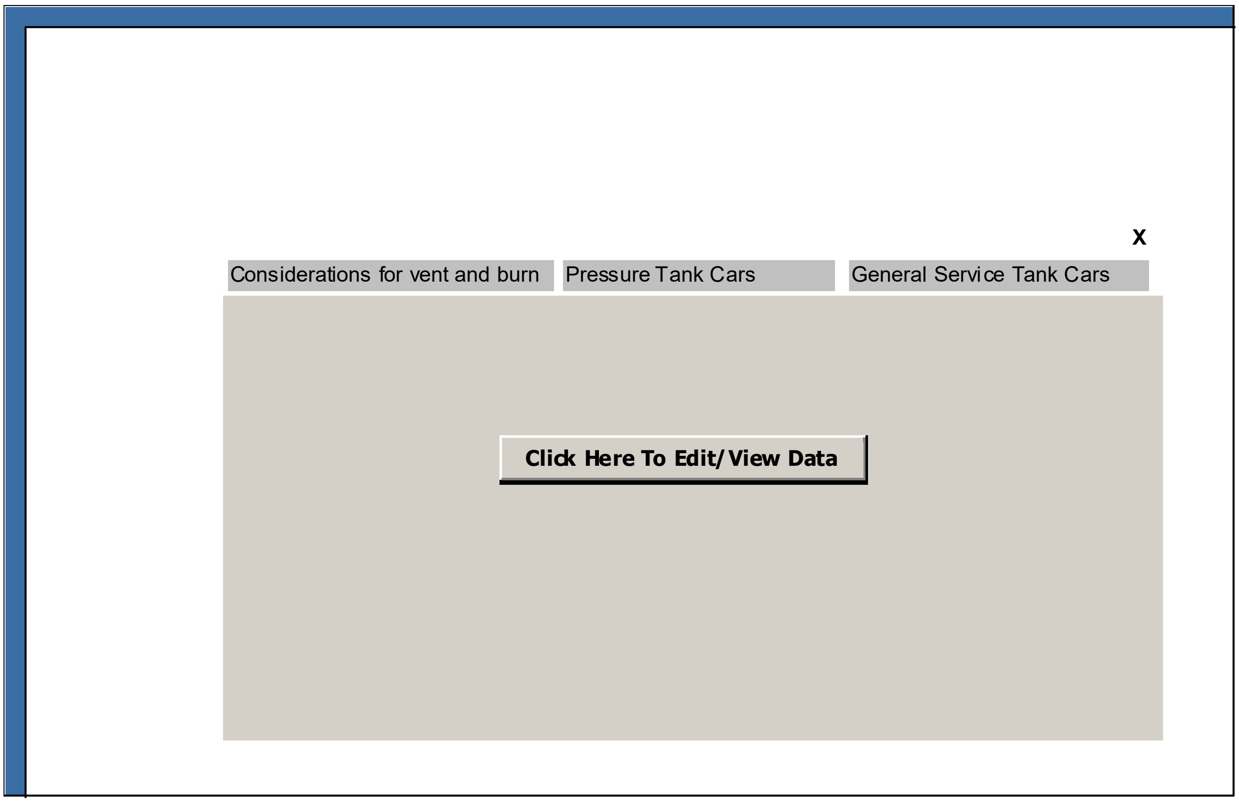
Delete Button: To delete a record, place the mouse cursor on the row number to be deleted, click and highlight the row. Click on the Delete button. The program will ask for confirmation if the record is really to be deleted. If the record is to be deleted, click on OK, otherwise, click on NO or on the "x" in upper right hand corner. To remove the highlight, click anywhere in column H.

There are 10 extra blank lines with boxes for each table. To create additional lines move to the last blank line, put the mouse arrow on the row number, click and highlight the row. Next click on "Insert Rows" from the toolbar for adding additional lines. Repeat these steps for each new row created. Next highlight the last line with the box around it, right click and select "Copy." Highlight the blank rows just created and right click and select "Paste." This will place the boxes in the new rows.

If “Vent and Burn” is selected on the main menu, this screen will appear.

- Click on the appropriate tab to reveal the same buttons as explained in “Hazard Material Classes.” Select “ENABLE MACROS” when the Microsoft Excel message box appears.
- The instructions for using the buttons and inserting additional lines are the same.

Note: To close the above, click on “x” in upper right hand corner.



Below are sample screens for each type of table.

Filter   Find   Delete

Group

Vent and Burn Checklist

1 **Damage Assessment**

1	Is tank car being impinged upon by fire?	Yes		Close to Fire	No	
1	Are contents of tank car burning?	No			Yes	
1	Is tank car venting continuously?	No			Yes	
1	Is shell rupture imminent?	Yes		Possible	No	
1	Is tank damaged?	Yes		Somewhat	No	
1	Has tank specification & construction material been determined?	Yes			No	
1	Is ambient temp. cold enough to cause brittle fracture?	Yes		Possible	No	

2 **Location/Environment/Site Assessment**

2	Is the tank close to other tank cars?	No		Somewhat	Yes	
2	Is the tank near buildings or structures?	No		Somewhat	Yes	
2	Is tank near habitation?	No		~0.5 mile	~0.25 mile	
2	Have inhabitants been evacuated?	Yes		In process	No	
2	Is excavation of burn pit possible?	No		~0.5 mile	~0.25 mile	
2	Is accident scene close to water sources?	No		~0.5 mile	~0.25 mile	
2	Will wind speed and direction produce dangerous product fallout?	No		Somewhat	Yes	

3 **Product Considerations**

3	Is product combustible?	Yes			No	
3	Is product polymerization a possibility?	No			Yes	
3	Will controlled release exceed toxicity levels?	No			Yes	
3	Will products of combustion exceed toxicity levels?	No			Yes	
3	What is the permeability of the soil?	High		Medium	Low	
3	What is the viscosity of the product?	High		Medium	Low	

Filter Find Delete

Tank Car Materials of Construction By Specification

Pressure Tank Cars

Specification	Tank Material	Tank Thickness (minimum)	Jacket	Insulation	Head shield
105A100ALW	Aluminum	5/8”	Yes	Yes	No
105A200ALW	Aluminum	5/8”	Yes	Yes	No
105A300ALW	Aluminum	5/8”	Yes	Yes	No
105A100W	Steel	9/16”	Yes	Yes	No
105A200W	Steel	9/16”	Yes	Yes	No
105A300W	Steel	11/16”	Yes	Yes	No
105A400W	Steel	11/16”	Yes	Yes	No
105A500W	Steel	11/16”	Yes	Yes*	No
105A600W	Steel	11/16”	Yes	Yes	No
105J300W	Steel	11/16”	Yes	Yes	Yes
105J400W	Steel	11/16”	Yes	Yes	Yes
105J500W	Steel	11/16”	Yes	Yes	Yes
105J600W	Steel	11/16”	Yes	Yes	Yes
109A100ALW	Aluminum	5/8”	Optional	Optional	No
109A200ALW	Aluminum	5/8”	Optional	Optional	No
109A300ALW	Aluminum	5/8”	Optional	Optional	No
109A300W	Steel	11/16”	Optional	Optional	No
112A200W	Steel	9/16”	Optional	Optional	No
112A340W	Steel	11/16”	Optional	Optional	No
112A400W	Steel	11/16”	Optional	Optional	No
112A500W	Steel	11/16”	Optional	Optional	No
112J340W	Steel	11/16”	Yes	Yes	Yes
112J400W	Steel	11/16”	Yes	Yes	Yes
112J500W	Steel	11/16”	Yes	Yes	Yes
112S340W	Steel	11/16”	No	No	Yes
112S400W	Steel	11/16”	No	No	Yes
112S500W	Steel	11/16”	No	No	Yes
112T340W	Steel	11/16”	No	No	Yes
112T400W	Steel	11/16”	No	No	Yes
112T500W	Steel	11/16”	No	No	Yes
114A340W	Steel	11/16”	Optional	Optional	No
114A400W	Steel	11/16”	Optional	Optional	No
114J340W	Steel	11/16”	Yes	Yes	Yes
114J400W	Steel	11/16”	Yes	Yes	Yes
114S340W	Steel	11/16”	No	No	Yes
114S400W	Steel	11/16”	No	No	Yes
114T340W	Steel	11/16”	No	No	Yes
114T400W	Steel	11/16”	No	No	Yes
120A200ALW	Aluminum	5/8”	Yes	Yes	No
120A100W	Steel	9/16”	Yes	Yes	No
120A200W	Steel	9/16”	Yes	Yes	No
120A300W	Steel	11/16”	Yes	Yes	No

Filter Find Delete

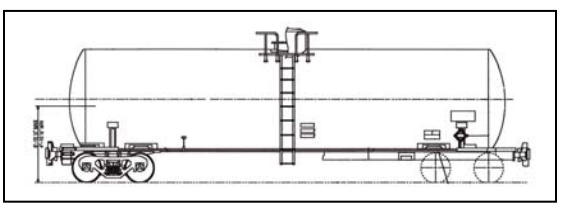
Tank Car Materials of Construction By Specification

General Service Tank Cars

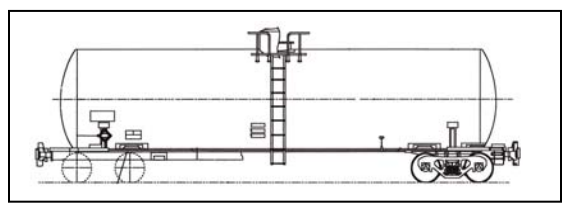
Specification	Tank Material	Minimum Tank Thickness	Jacket (1/8")	Insulation	Head shield
103-ALW	Aluminum	½”	Optional	Optional	No
103AW	Steel	7/16” – ½”	Optional	Optional	No
103ALW	Aluminum	½”	Optional	Optional	No
103ANW	Nickel	7/16” – ½”	Optional	Optional	No
103BW	Steel	7/16” – ½”	Optional	Optional	No
103CW	Alloy Steel	7/16” – ½”	Optional	Optional	No
103DW	Alloy Steel	7/16” – ½”	Optional	Optional	No
103EW	Alloy Steel	7/16” – ½”	Optional	Optional	No
103W	Steel	7/16” – ½”	Optional	Optional	No
104W	Steel	7/16” – ½”	Yes	Yes	No
111A60ALW1	Aluminum	½”	Optional	Optional	No
111A60ALW2	Aluminum	½”	Optional	Optional	No
111A60W1	Steel	7/16”	Optional	Optional	No
111A60W2	Steel	7/16”	Optional	Optional	No
111A60W5	Steel	7/16”	Optional	Optional	No
111A60W6	Steel	7/16”	Optional	Optional	No
111A60W7	Alloy Steel	7/16”	Optional	Optional	No
111A100ALW1	Aluminum	5/8”	Optional	Optional	No
111A100ALW2	Aluminum	5/8”	Optional	Optional	No
111A100W1	Steel	7/16”	Optional	Optional	No
111A100W2	Steel	7/16”	Optional	Optional	No
111A100W3	Steel	7/16”	Yes	Yes	No
111A100W4	Steel	7/16”	Yes	Yes	No
111A100W5	Steel	7/16”	Optional	Optional	No
111A100W6	Alloy Steel	7/16”	Optional	Optional	No
111A100W7	Alloy Steel	7/16”	Optional	Optional	No
111J100W	Steel	7/16”	Yes	Yes	Yes
115A60ALW*	Aluminum	7/16” Outer tank 3/16” Inner tank	Optional*	Optional*	No
115A60W1*	Steel	7/16” Outer tank 1/8” Inner tank	Optional*	Optional*	No
115A60W6*	Alloy Steel	7/16” Outer tank 1/8” Inner tank	Optional*	Optional*	No

Appendix D.
Post-Incident Vent and Burn Report Form

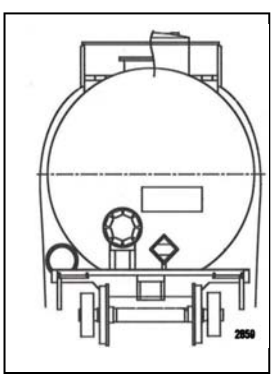
Tank Car Number	
Carrier	
Specification	
Product	
Location (town or station)	
Date & Time	
Ambient Temperature	
Tank Shell Condition	
Tank Car Orientation	
Was car involved in fire or impinged on by fire?	
Description of Charges & Explosive Compound	
Location of Charges (indicate w/ “x” below)	



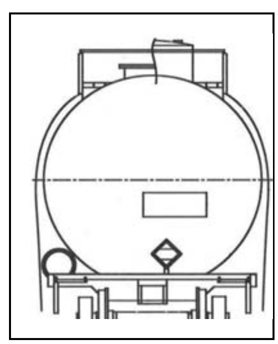
R-Side



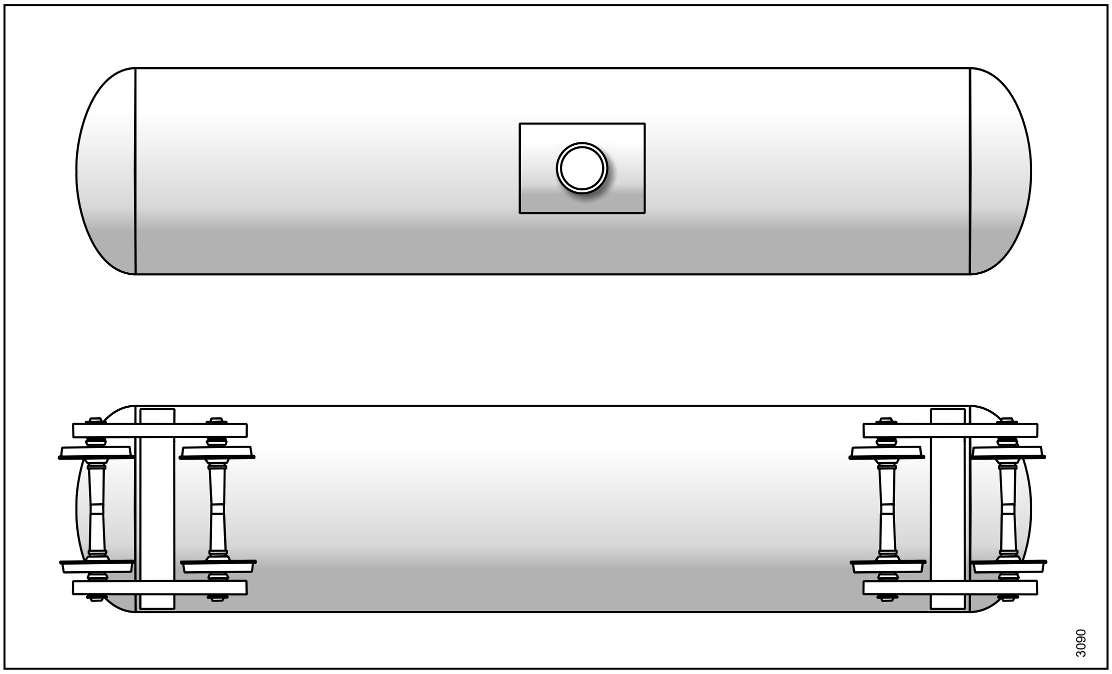
L-Side



B-End



A-End



Top and Bottom of Car

Time elapsed between vent charge detonation and drain hole charge detonation	
Condition of Tank Shell After Charge Detonations (any cracks?)	
Vent Hole Shape and Size	
Drain Hole Shape and Size	
Technician Comments (What was done & why?)	

Acronyms

AAR	Association of American Railroads
ASTM	American Society for Testing and Materials
AX	Accident Investigation
EFP	explosively formed projectile
EOS	equation-of-state
EPS	effective plastic strain
FRA	Federal Railroad Administration
HE	high explosive
Hz	hertz
R&D	Research and Development
RSI	Railroad Supply Institute
TTC	Transportation Technology Center (the Site)
TTCI	Transportation Technology Center, Inc. (the Company)