U.S. Department
of Transportation
Federal Railroad
Administration

VENT AND BURN METHOD OF FIELD PRODUCT REMOVAL

Office of Research and
Development
Washington D.C. 20590

DOT/FRA/ORD-94/17

May 1994
Final Report

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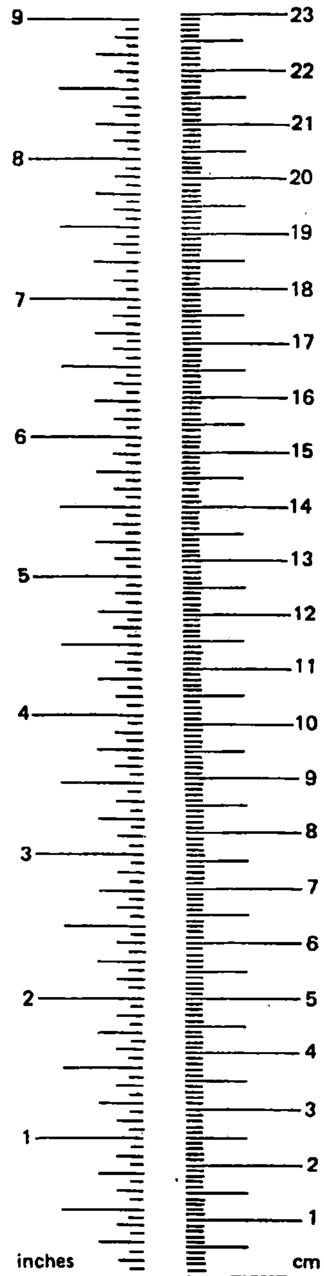
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

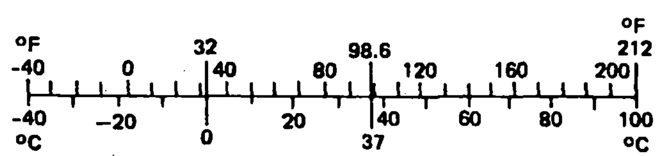
Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
in	inches	*2.50	centimeters	cm
ft	feet	30.00	centimeters	cm
yd	yards	0.90	meters	m
mi	miles	1.60	kilometers	km
	AREA			
in^2	square inches	6.50	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.80	square meters	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
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
	TEMPERATURE (exact)			
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

* 1 in. = 2.54 cm (exactly)



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
mm	millimeters	0.04	inches	in
cm	centimeters	0.40	inches	in
m	meters	3.30	feet	ft
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)			
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
	VOLUME			
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.10	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	36.00	cubic feet	ft^3
m^3	cubic meters	1.30	cubic yards	yd^3
	TEMPERATURE (exact)			
°C	Celsius temperature	9/5 (then add 32	Fahrenheit temperature	°F



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November 12, 1993
CON/ERW/93-213

Mr. Robert McCown
Contracting Officer's Technical Representative

Federal Railroad Administration
Office of Research & Development, RDV-31
400 Seventh Street, S.W., Room 5106
Washington, DC 20590

Subject: Draft Final Report

Reference: Contract DTFR53-82-C-00282
Task Order No. 31

Dear Mr. McCown:

Forwarded are two copies of the draft final report titled "Vent and Burn Method of Field Product Removal" covering AAR's activities relative to testing conducted under the auspices of the referenced task order.

After receipt of FRA's comments the final version will be prepared and forwarded to you.

Sincerely,

ASSOCIATION OF AMERICAN RAILROADS

Edward R Walsh

Edward R. Walsh
Manager, Contracts & Materiel

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May 24, 1994
CON/ERW/94-131

Mr. Robert S. Spratling
Contracting Officer

Federal Railroad Administration
Office of Procurement, RAD-30
400 Seventh Street, S.W., Room 8222
Washington, DC 20590

Subject: Final "Reports"

Reference: Contract DTFR53-82-C-0-00282
Task Order No. 31

Dear Mr. Spratling:

Forwarded are the "camera-ready" originals of the subject reports entitled "Vent and Burn Method of Field Product Removal" and "Handbook for Vent and Burn Method of Field Product Removal."

For all practical purposes AAR now considers its work efforts as having been satisfactorily completed.

Sincerely,

ASSOCIATION OF AMERICAN RAILROADS

Edward R. Walsh/jp

Edward R. Walsh
Manager, Contracts & Materiel

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16. Abstract

The Federal Railroad Administration tasked the Association of American Railroads, Transportation Test Center Hazardous Materials Training Center, to research and develop safe, reliable operating procedures for of the Vent and Burn method of field product removal, and to define when or if this procedure should be used in the event of tank car derailments involving hazardous materials. The Vent and Burn procedure uses explosive charges to cut holes in the damaged tank car to relieve internal vapor pressure and subsequently drain the liquid product from the car for destruction.

Vent and Burn is inherently dangerous and other methods of field product removal or car rerailment must be considered first. This procedure is applicable to some compressed gases and some flammable or combustible liquids shipped in pressure or general service tank cars.

Testing was performed both on a sample tank car head and on four full scale DOT 112T340W tank cars. Combinations of jacketing, insulation, and thermal protection materials were explosively cut on the sample tank head to determine procedures to gain access to the tank shell of a jacketed car. Tests on full scale, unjacketed tank cars varied internal tank pressure and liquid fill levels to represent expected lading conditions. The full scale tank cars were explosively cut both on bare steel and through spray-on thermal protection. The scope of this program included the following:

- Definition of the field application of the Vent and Burn procedure through quantified testing of sample materials and full scale tank cars.
- Selection of shaped explosive charges that successfully and repeatably cut target tank car and jacketing materials.
- Specification of explosive charge sizing and application locations.
- Determination of explosive charge orientation, charge mounting, and charge continuity for cutting success.
- Modeling tank car internal pressure release and liquid drainage to determine expected discharge times.

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LIST OF ABBREVIATIONS

AAR - Association of American Railroads

ASTM - American Society for Tests and Measures

DOT - Department of Transportation

DRI - Denver Research Institute

fps - Frames per second

FRA - Federal Railroad Administration

gr/ft - Grains per foot

LSC - Linear Shaped Charge

NAX - North American Explosives

psi - Pounds per square inch

psia - Pounds per square inch, absolute

psig - Pounds per square inch, gage

RDX - An explosive composed of Cyclonite (cyclo-1,3,5-trimethylene-2,4,6-trinitramine), Trimethylentrinitramin, and Hexagene

TC - Transport Canada

TIP - Test Implementation Plan

TTC - Transportation Test Center

EXECUTIVE SUMMARY

The Federal Railroad Administration tasked the Association of American Railroads, Transportation Test Center Hazardous Materials Training Center, Pueblo, Colorado, to research and develop safe, reliable operating procedures for the Vent and Burn method of field product removal, and to define when or if this procedure should be used in the event of tank car derailments involving hazardous materials. This project resulted in the selection of explosive charges to cut both tank car jacketing material and the tank car shell. This document is accompanied by a procedural handbook, "Handbook for Vent and Burn Method of Field Product Removal," report number DOT/FRA/ORD-94/18.

Vent and Burn involves the use of explosive charges to cut holes in the damaged tank car to relieve internal vapor pressure and subsequently drain the liquid product from the car for destruction. It is an inherently dangerous and uncontrolled process. Vent and Burn should be considered only as a final option of field product removal and then only under the strict adherence to product applicability and procedural guidelines. This procedure may be used with some compressed gases and some flammable or combustible liquids shipped in pressure or general service tank cars.

It was decided to place the charges at the highest and lowest points on the barrel portion of the tank car shell, avoiding both head shields and tank valving equipment. Target hole sizes were determined from theoretical modeling of product flow rates and a review of past Vent and Burn applications. Discharge holes should be 7 inches in diameter; tank jacket material should be removed in an 18-inch diameter to allow sufficient tank shell access.

An explosive compound of Cyclonite (cyclo-1,3,5-trimethylene-2,4,6-trinitramine), Trimethylentrinitramine, and Hexagene (known as RDX) was selected. The strength of the explosive charge is rated by a measure of explosive material weight per unit length of charge, typically given in the units of grains of explosive material per linear foot (gr/ft). A flexible form of this explosive is manufactured with a closed-cell polystyrene foam backing. Field tests showed the tank jacket should be cut with a charge strength of 300 gr/ft. The tank shell should be cut with a charge strength of 5,400 gr/ft. The explosive charge should be formed into a closed ring and secured directly to the tank surface.

Field tests were conducted on an actual tank car head equivalent to the minimum thickness required on a typical liquefied petroleum gas pressure tank car, or the maximum thickness found on a typical general service tank car. It was divided into regions to simulate combinations of insulation and/or thermal protection covered by typical jacket material such as 1/8-inch steel plate. Full scale testing was performed on four undamaged, full scale DOT 112T340W tank cars previously used in liquefied petroleum gas service. These tanks were filled with water up to 12 percent outage and pressurized with air up to 250 psi to simulate a range of lading conditions found in cars carrying various hazardous materials.

Other types of explosive charges were also tested. Positive preliminary results were seen with an RDX charge encased in copper. This charge could not reliably cut the tank car shell material during full scale testing.

Shaped explosive charges were used in this test program to cut both tank car shell and tank car jacket material. A shaped charge orients its explosive material in a specific geometry to focus the explosive force in a powerful and predictable manner. Less explosive material is required while the repeatability of the explosive cut is increased. Upon detonation, two explosive wave fronts are formed and added to create a focused gas jet to cut through the target material, much as an oxy-acetylene torch.

Protecting response personnel was first priority during the development of Vent and Burn procedures. The explosive material was chosen to reduce the associated handling risk while assuring tank car cutting. Several past field applications of this procedure have failed to cut the desired holes and even resulted in tank failure.

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1.0 INTRODUCTION

The Federal Railroad Administration (FRA), through Contract Number DTFR53-82-C-00282, Task Order 31, Task E, Modification 4 -- Vent and Burn Method of Field Product Removal -- tasked the Association of American Railroads (AAR), Transportation Test Center (TTC) Hazardous Materials Training Center, Pueblo, Colorado, to research and develop safe, reliable operating procedures for the Vent and Burn method of field product removal, and to define when or if this procedure should be use in the event of tank car derailments involving hazardous materials. The Vent and Burn procedure uses explosive charges to cut holes in the damaged tank car to relieve internal vapor pressure and subsequently drain the liquid product from the car for destruction.

1.1 DEFINITION OF VENT AND BURN

Vent and Burn is an emergency response procedure designed to quickly and effectively release railroad tank car internal vapor pressure and liquid products to avoid disastrous, uncontrolled tank rupture and environmental contamination. During derailment accidents, tank cars may become structurally compromised and/or subject to external heating and associated increase in internal pressure. The Vent and Burn procedure is applied to damaged tank cars only when all other emergency product removal methods have been considered and rejected, and the consequences of not relieving the internal tank car pressure are determined to be greater than the consequences of not using this procedure.

The Vent and Burn procedure involves the use of two explosive charges to cut holes in the tank car. The first charge is placed at the highest point of the tank car, over the product vapor space. Its detonation relieves the tank's internal vapor pressure. A second charge is placed at the lowest point of the liquid space to allow drainage of the product into a safe containment pit, where it is expected to be burned in a controlled setting, both neutralizing its environmental hazard and removing the potential for uncontrolled explosion. Figure 1 depicts the application of two explosive charges on a tank car. Figure 2 portrays Vent and Burn in progress.

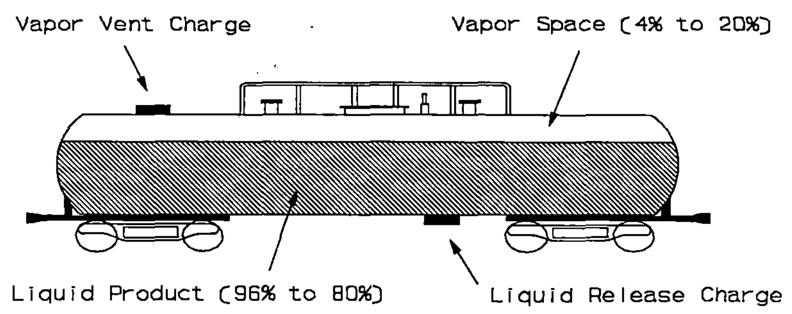

Figure 1. Schematic of Tank Car Displaying Vapor and Liquid Spaces; Application Points of Explosives Indicated

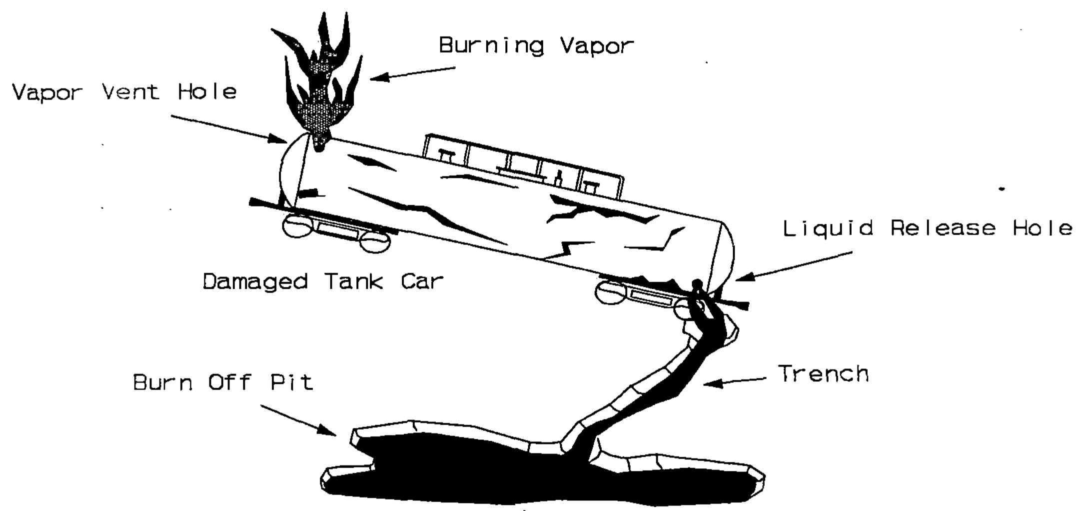

Figure 2. **Application of Vent and Burn Procedure on Flammable or Combustible Liquid**

1.2 BACKGROUND

Vent and Burn is an emergency response procedure used when tank cars carrying products such as flammable compressed gases and flammable or combustible liquids are involved in a derailment and cannot be safely handled by other, more conventional means.

Candidate cars for this procedure may be subject to severe structural damage or have their unloading valves inoperable, inaccessible, or sheared off. The product in the tank may have lost its inhibitor, making polymerization a possibility and rapid unloading a necessity.

Several factors must be taken into consideration before selecting this procedure. A partial list is provided below.

- The product(s) involved
- The container type(s)
- The proximity of the subject tank to other tanks, buildings, and habitation
- The topography of the accident scene and surrounding area, such as hills, swales, and waterways
- The weather conditions, including wind speed, direction, and air temperature
- The availability of fire and vapor suppression personnel
- The availability of excavating equipment
- The type and permeability of soil (clay will not absorb material as rapidly as sand)
- The availability of the explosives expert
- The availability of the proper explosives

It is necessary that the response agencies understand why this drastic action must take place so that they can prepare for potential problems and can inform the public of the impending action.

Vent and Burn has been performed during past derailments. The lack of a standardized procedure has made each application unique and dangerous. Several past field applications have failed to cut the desired hole and even resulted in tank failure. The following is a brief list of example historical Vent and Burn operations.

- Several tank cars containing Vinyl Chloride monomer, Muldraugh, Kentucky, mid-1970's
- Several tank cars containing Liquid Propane Gas, Molino, Florida, 1978
- One tank car containing Methanol, Covington, Tennessee, May, 1990
- One tank car containing 2,4-Butadiene, White, Ontario, Canada, July, 1990

2.0 OBJECTIVE

The primary objective of this project was to determine the type, amount, and configuration of explosive charges required to accurately and consistently cut holes in tank cars to:

- permit a rapid release of internal vapor pressure, and
- allow the liquid product to flow from the tank car into a pit for controlled burning.

3.0 APPLICATIONS FOR VENT AND BURN

3.1 PRODUCT TYPES

Vent and Burn is intended for use with some compressed gases and some flammable or combustible liquids. This procedure should be discussed with the product manufacturer for further determination of this procedure's applicability.

3.1.1 Flammable Compressed Gases

Flammable compressed gases such as propane, butane, or butadiene are candidate products for the application of Vent and Burn. *Only Products with no secondary hazard of "Poison - Inhalation Hazard" should be considered for this procedure.*

3.1.2 Flammable or Combustible Liquids

Flammable or combustible liquids such as alcohols, petroleum products, esters, and ketones are candidates for Vent and Burn. Corrosives, oxidizers, or poisonous liquids would require evaluation on an individual basis. Factors to consider include (1) the presence of sufficient flammability characteristics to allow the product to burn, (2) the release of potentially harmful by-product of thermal oxidation, and (3) the dangers of secondary explosions and other uncontrolled releases.

Tank cars also carry certain materials which may be subject to polymerization; violent tank car rupture is possible if such products are exposed to fire. For example, materials such as acrylates are shipped with inhibitors which can be lost in a fire situation. In such cases, Vent and Burn may be the best alternative to prevent uncontrolled polymerization and tank rupture.

3.2 TANK CARS TYPES

3.2.1 Pressure Tank Cars

The types of tank cars most likely to become candidates for the Vent and Burn procedure are pressure cars, classes 105, 112 or 114, carrying flammable compressed gases. These tank cars are manufactured to specifications of the United States Department of Transportation (US DOT), or, in Canada, Transport Canada (TC).

The tank cars are manufactured of ASTM A-516, Grade 70, or AAR TC-128, Grade B, steels. The steel used in pressure car tanks is normalized, with thicknesses ranging from 9/16 inch to 1 1/4 inch -- car owners will occasionally specify a tank thickness greater than the minimum required.

Tank cars used for the transportation of flammable compressed gases are required to be equipped with thermal protection. This may consist of a coating applied directly to the tank, either brushed, sprayed, or troweled on -- Figure 3 displays a sample of spray-on thermal protection. Alternatively, a blanket type insulation or thermal protection material may be used, held in place by an outer steel jacket, nominally 1/8 inch thick. Figure 4 shows a blanket thermal protection under steel jacketing. This protective material must be removed during the Vent and Burn procedure to allow access to the tank shell. Methods of explosively cutting through the jacketing, insulation, and thermal protection were explored.

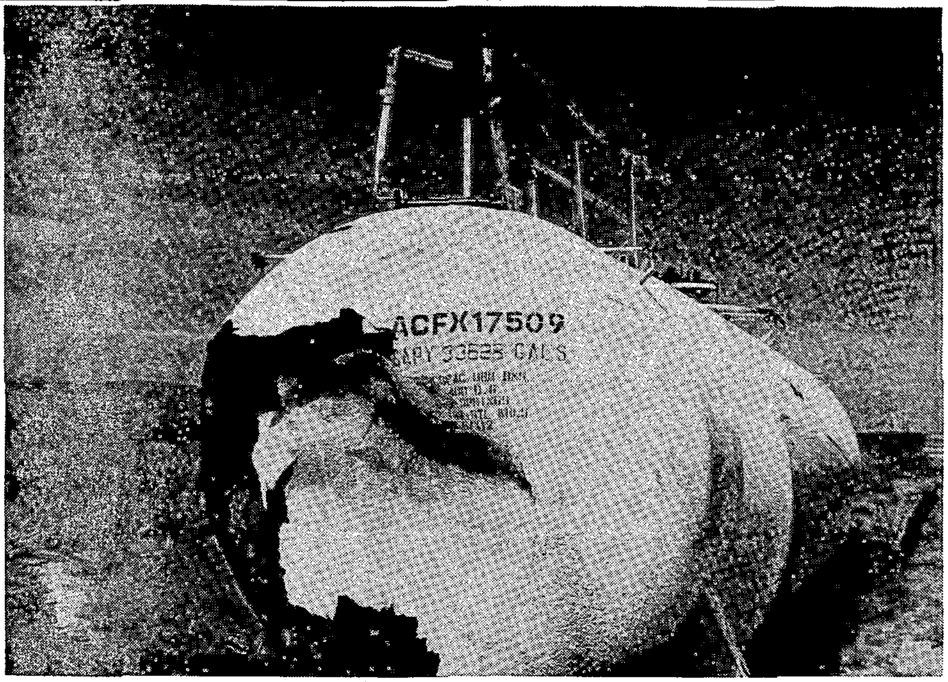

Figure 3. Spray-on Thermal Protection Applied to Tank Car

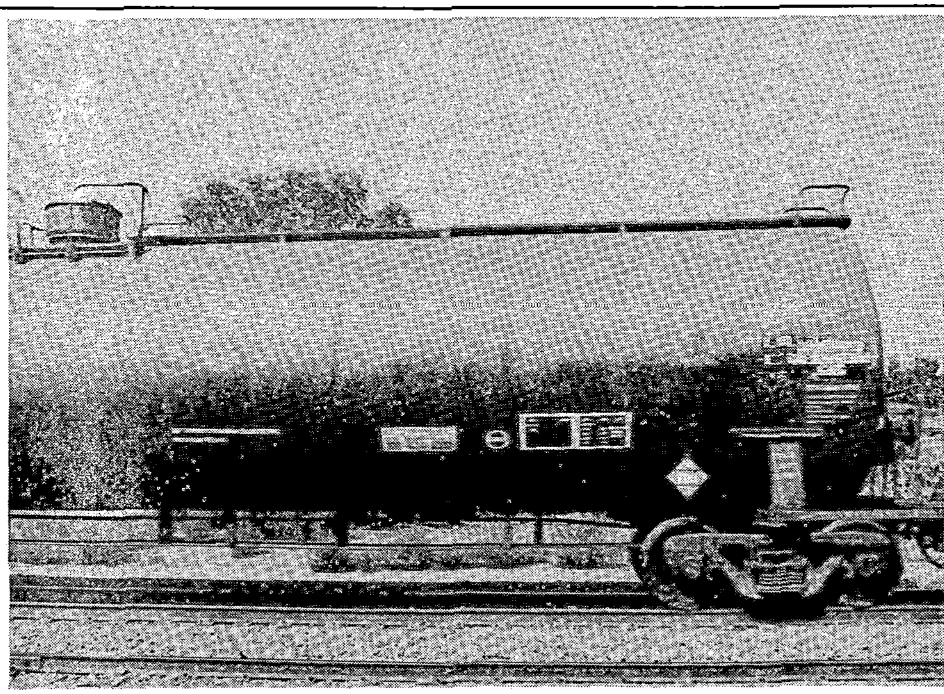

Figure 4. Blanket Thermal Protection Under Jacket, Applied to Tank Car

Tank cars used for flammable compressed gases are also required to have head shields. These are constructed of 1/2-inch-thick steel, and may either be a trapezoidal shape protecting the lower half of the tank head, a domed shield welded to the lower half of the head, or the full-head design which appears to be part of the jacket. Figures 5, 6, and 7 show the trapezoidal shield, half shield, and full shield, respectively. Head shields are designed to protect tank cars during impact and derailment accidents. However, they may interfere with placement of explosive charges during preparation for the Vent and Burn procedure. The presence of head shields must be noted by response personnel; this project explored procedures to cut head shields prior to final tank cutting.

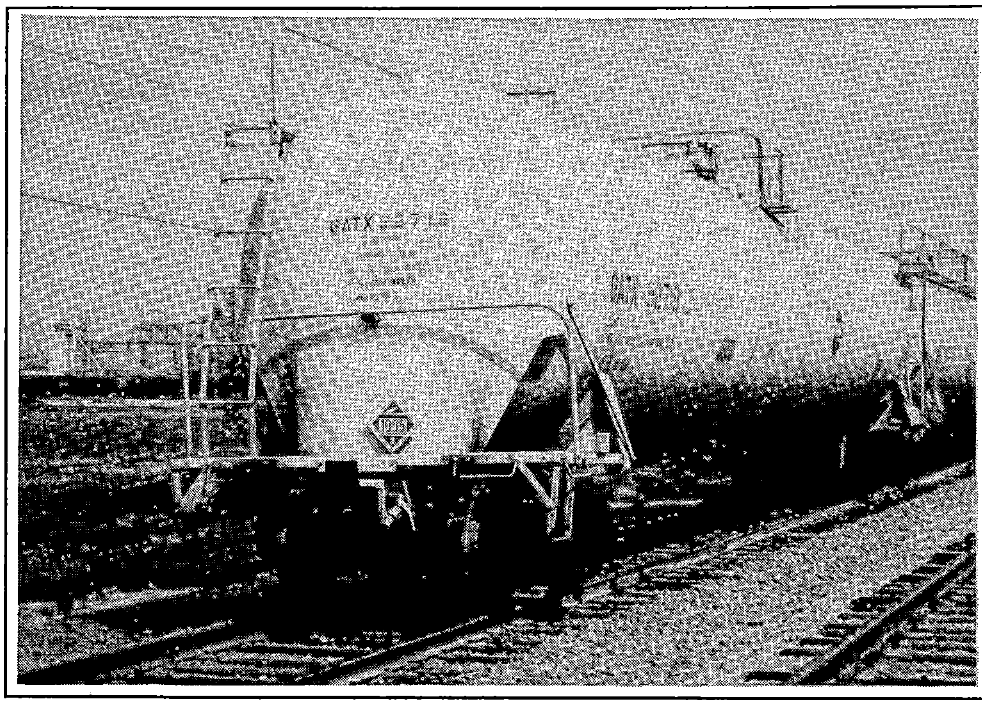

Figure 5. Trapezoidal Head Shield Installed on Tank Car

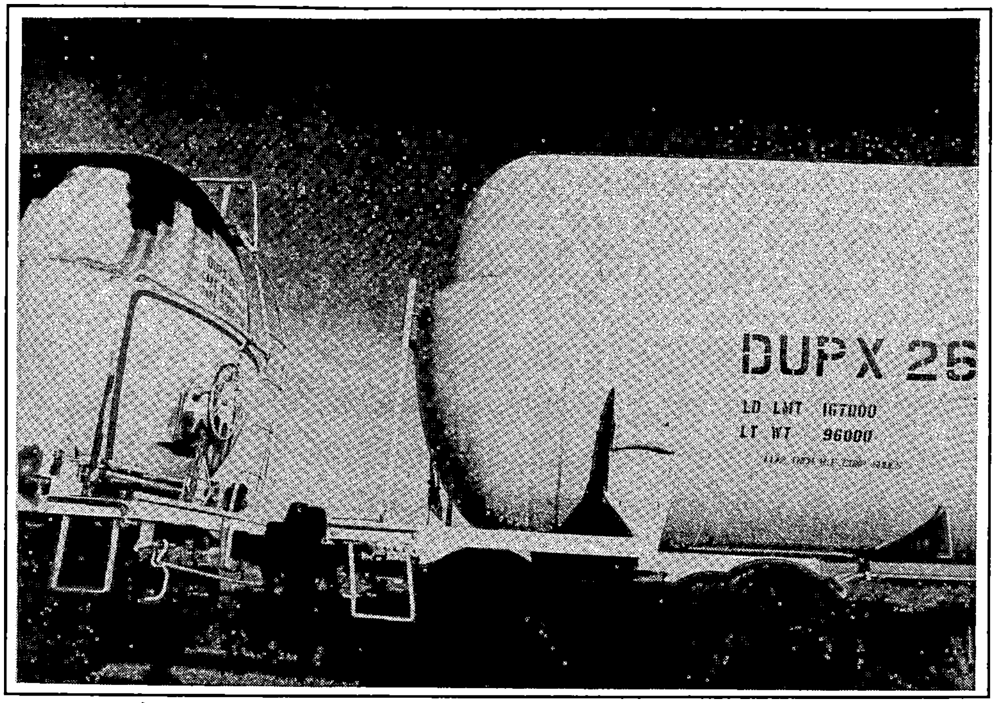

Figure 6. Half Head Shield Installed on Tank Car

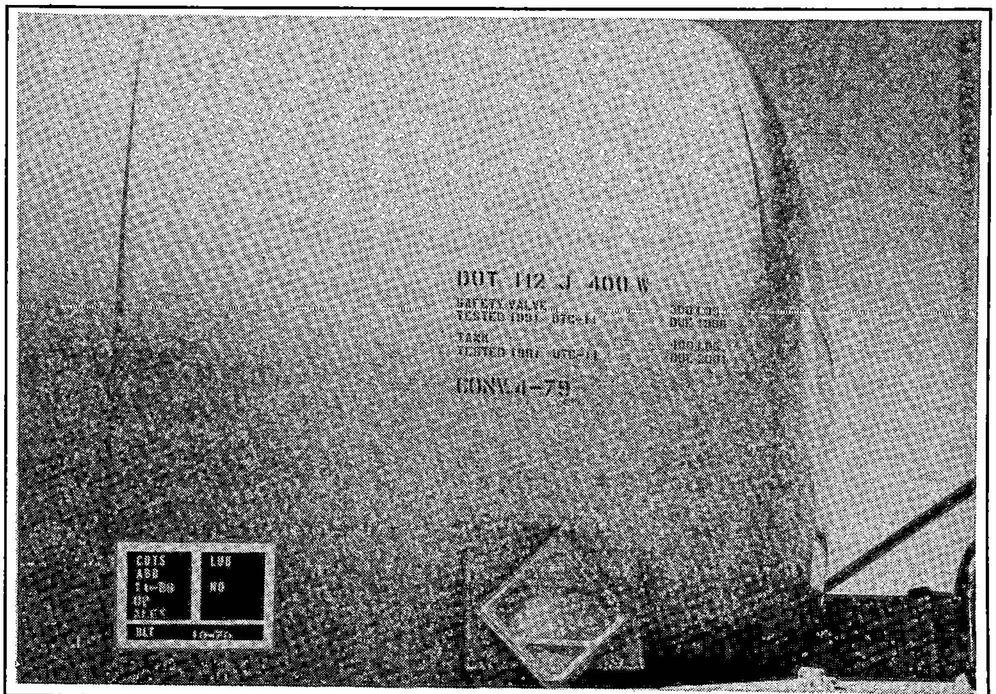

Figure 7. Full Head Shield Installed on Tank Car -- Shield Looks Like Tank Jacket

Test pressures on tank car classes 105, 112, and 114 range from 100 psi to 600 psi. Typically, the products transported in these cars are shipped at pressures ranging from 60 psi to 250 psi.

3.2.2 General Service Cars

General service (also referred to as general purpose, low pressure, or non-pressure) tank cars may also be candidates for the Vent and Burn procedure. These cars are typically classed as DOT or TC 111; AAR 211 cars are constructed essentially the same as DOT 111 cars.

Tank test pressures of general service cars are 60 psi and 100 psi, with the majority being 100 psi. Products carried in these cars usually have vapor pressures ranging from 5 psi to 25 psi.

General service cars are constructed of the same materials as high pressure cars, but the tanks are required only to be 7/16 inches to 9/16 inches thick. Many general service cars also have blanket insulation under a 1/8-inch-thick steel jacket, depending upon the particular specification. A new DOT/TC 111 J general service car is now being produced, which will have head shields and jacketed thermal protection much the same as the DOT/TC 112 J pressure car.

4.0 LITERATURE SEARCH

As a first step in the exploration of Vent and Burn methods, a literature search was conducted from June, 1992, until October, 1992. Sources of information were found through the AAR Washington Library as well as discussions with a veteran hazardous materials responder who has performed this procedure in the past. Unfortunately, no literature was found that specifically pertained to Vent and Burn. A list of references consulted during the literature search is included in this document.

5.0 TEST IMPLEMENTATION PLAN

The Test Implementation Plan (TIP), outlining test methods, procedures, and scheduling, was completed August 5, 1992, and submitted to the FRA August 11, 1992.

6.0 IDENTIFICATION OF EXPERTS FOR CONSULTATION

Information about potential consultants was obtained by discussions with AAR personnel and knowledgeable hazardous materials responders. A review was performed of related hazardous materials response documents. Additional information was obtained from The Institute of Makers of Explosives in Washington, DC.

After an extensive review of companies with experience in the field, Denver Research Institute (DRI), of the University of Denver, Denver, Colorado, was selected as a consultant on the application of explosives. This decision was based on site visits, technical discussions, and logistical considerations. DRI offered field expertise within 100 miles of TTC. DRI had extensive previous experience with projects involving controlled explosions, including pressure-relief-hole cutting on pressure vessels. Their representative, Mr. William Snyer, was very knowledgeable in technologies involving the application of explosives.

7.0 CANDIDATE TANK CARS AND MATERIAL SAMPLES FOR TESTING

The TIP outlined the evaluation explosive charge cutting abilities through testing on flat steel samples, 4 foot by 4 foot in size, of the same stock used for the manufacture of candidate tank cars. Upon further discussions, AAR/TTC personnel felt that sample testing would be more realistic if actual tank car heads, with in-service curvature and specifications, could be used instead of 4-foot-square specimens. Final testing was to be performed on full scale pressure tank cars.

7.1 PROCUREMENT OF TANK CAR HEADS

Tank car manufacturers were approached in an attempt to procure tank car heads to test cutting of holes with explosive charges. Six tank heads were procured from Union Tank Car Company, constructed of TC-128, Grade B normalized steel with a diameter of 119 inches.

These heads were to be used on the AAR/TTC Anvil Car, a specially designed test car previously developed for tank head impact tests; the car contains a vessel that could be filled and pressurized to simulate expected lading conditions. After receiving the heads, it was determined that the Anvil Car could not be pressurized to the level required for full scale testing.

A sample tank head was mounted instead on a support frame to conduct various preliminary tests. Four areas of the tank head were used to simulate bare tank head material and combinations of blanket insulation, thermal protection, and jacketing for testing of various types of explosive charges. The sample head was 0.609 inches thick.

7.2 PROCUREMENT OF FULL SCALE TANK CARS

Final Vent and Burn testing was to be performed on full scale tank cars filled with water to best simulate field conditions. One high pressure car and one general service car were sought to test the two candidate tank car material thicknesses. Cars with a less ductile steel, as used in tank cars built prior to 1967, were also considered. Candidate tank cars were identified from the available stock owned by AAR/TTC. However, in light of limited project resources, it was decided that post-1967 high pressure tank cars would best represent the thickest and most ductile steel -- the most difficult to cut.

E. I. du Pont de Nemours and Company donated four pressure tank cars classified as DOT112T340W. The four tank cars were built to the specifications provided in Table 1.

Table 1. Test Sample Full Scale Tank Car Characteristics

Car Numbers	DUPX 20462, DUPX 26740 DUPX 26761, DUPX 26770
Tank Material	AAR TC-128B, Grade B Normalized
Material Thickness	0.669 inches, Head and Shell
Total Capacity	33,500 gallons
Inside Diameter	114.662 inches
Test Pressure	340 psi
Estimated Light Weight	93,000 pounds
On-rail Load Limit	263,000 pounds
Built Date	1971
Tank Covering	1/8-inch Spray-on Thermal Protection

7.3 IDENTIFICATION AND PROCUREMENT OF CANDIDATE EXPLOSIVES

The literature search showed that shaped explosive charges offered the ability to accurately and consistently cut plate steel material as compared to other bulk explosive charges. A shaped charge orients its explosive material in a specific geometry; detonation creates explosive forces that add to form a gas jet able to cut accurately through the target material. Figure 8 depicts how the explosive energy is focused. A shaped charge promised the repeatable cutting of tank car material required to define Vent and Burn procedures.

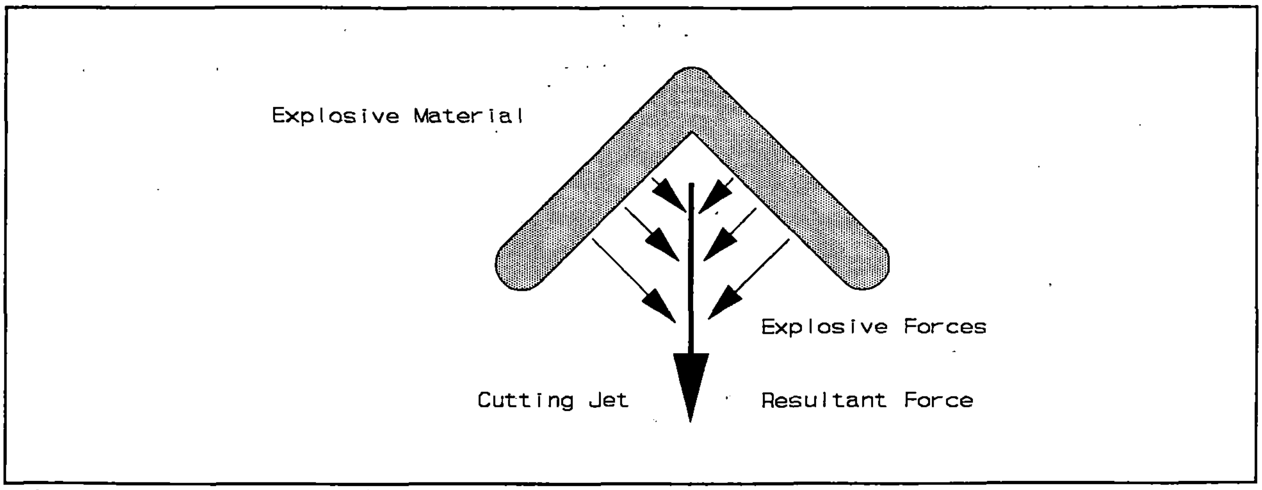

Figure 8. Focusing of Explosive Forces during the Detonation of a Shaped Charge

As Figure 8 indicates, the explosive forces do not focus immediately, but only at certain distance away from the explosive material. The shaped charge cannot be placed directly on the target material, but must be held off the surface a certain distance; this distance is known as the "stand-off."

The "jet-forming angle" is a measure of charge geometry -- the angle of separation of the two legs of explosive material. Angles of 90 degrees and 72 degrees were used within this program.

An explosive composed of Cyclonite (cyclo-1,3,5-trimethylene-2,4,6-trinitramine), Trimethylentrinitramine, and Hexagene (known as RDX) was used during testing. The strength of the explosive charge was rated by a measure of explosive material weight per unit length of charge, typically given in the units of grains of material per linear foot (gr/ft).

The charges used in this program utilized a sheathing material to hold the explosive at a specific angle; copper, lead, and closed-cell polystyrene foam sheathed explosives were recommended by DRI for testing. Copper offers excellent focusing and allows relatively low amounts of RDX to be used. The charge is stiff and straight, thus referred to as a linear shaped charge (LSC). The copper sheathing does fragment upon charge detonation, spraying shrapnel within the firing range. Lead has good focusing and is flexible. Little fragmentation occurs as the lead vaporizes upon charge detonation; ... is a health hazard to vapor inhalation. Foam does not focus the explosive f... ...ll and the strength of RDX therefore must be increased to approximat... ...ble that of a metal-sheathed charge to retain equal cutting ability. The foam charg... ...ble and presents no fragmentation risk.

Deto... ... the explosive material must be initiated with a blasting cap. The cap is a smal... ...ive charge that can be set off by electrical current or physical fuse. DRI recom... ...he use of Number 6 Engineering Special caps (or better).

A bo... ...arge of detonation ("det") sheet was recommended to assure good initiation o... ... by the blasting cap.

The ... ...heathed material used in this program was manufactured by Explosives ... ...gy of California and Jet Research of Texas. The lead-sheathed material wa... ...tured by Explosives Technology of California. The foam-sheathed explosives ... ...ufactured by North American Explosives (NAX) of Kentucky.

8.0 EVALU... ...F THEORETICAL FLOW RATES

Tank car p... ...harge was mathematically modeled at TTC to estimate flow rates to be expec... ...g the application of the Vent and Burn procedure. Such modeling aided in the... ...nation of acceptable hole sizes and geometries, anticipated vapor discharge ra... ...cipated liquid product discharge rates, and time required to empty a tank car.

8.1 DISCHA... ...IOLE SIZING

Vapor pressur... ...iquid product can be discharged from a candidate tank through any size exit ho... ... vapor or liquid discharge rate will be a maximum at initial hole cutting and ... ...e to zero as the product is removed from the tank; flow rates cannot be controlle... ...he tank has been cut. To avoid catastrophic tank failure during venting or ... ..., however, discharge hole sizing must be determined from the product type ... ...ysical characteristics.

Depen... ...n accident scene temperature and barometric pressure, most compressed ... ...d some candidate liquid products will have been held above their nominal boil... ...erature by tank internal pressure. With the loss of this pressure, the liquid product will boil. Boiling will both cool the liquid and add significantly to the vapor volume to be vented; boiling will continue until the remaining liquid product cools to its nominal boiling point or all product is vaporized.

The escaping vapor will most likely be ignited by the vent-cutting explosion and burn in a flare just above the tank surface. This vapor flare will warm the liquid product in the tank and cause more violent boiling. As a result, the internal pressure will increase and create the possibility of tank rupture.

The exiting liquid product also will likely be ignited by the drain-cutting charge or burn pit fusees, introducing burning product at the tank shell. This will further heat the remaining liquid product and create the potential for tank rupture.

Both vapor venting and liquid product drainage could add enough energy to the tank car to cause rupture, if a sufficient discharge rate is not maintained to quickly release the expanding product before dangerous heat build up can occur within the tank.

Historical records were consulted for estimates of safe tank vent and drain times. Two past FRA tests were conducted with a 33,000 gallon DOT112A340W tank car and a 33,000 gallon DOT112T340W tank car, both constructed of 0.625-inch-thick TC-128 steel. Separately, each car was fully engulfed in a pool fire and timed until tank rupture. The bare steel tank exploded at 24 minutes 30 seconds;[1] the thermally protected tank ruptured at 93 minutes 30 seconds.[2] A fully engulfing pool fire on a bare metal tank represents a much more severe environment than is expected for Vent and Burn procedure performed on a thermally protected tank with use of a burn pit or dirt embankment heat shields. Seven other documented fire-induced tank car ruptures occurred with bare metal tanks at times between 20 and 50 minutes after fire exposure.[2] By targeting a product discharge time of 25 to 30 minutes, it was felt that tank rupture could be sufficiently avoided.

The modeling effort showed a discharge area of 38.5 square inches, a 7-inch circular discharge hole, would vent a candidate tank in less than 30 minutes, depending on product species, and drain the tank car in less than 32 minutes. The vapor vent hole is recommended to be the same size as the liquid drain hole to reduce explosives inventory and to equalize pressure during liquid draining.

Hole shape does not affect discharge rates, though a round hole is recommended to avoid stress concentrations that may lead to tank material failures. Multiple holes, adding to the desired discharge area, are acceptable in cases where tank heating must be dispersed, or where physical obstructions do not allow a full sized hole to be cut.

8.2 VAPOR VENTING MODEL

The vapor vent model was derived from conservation of energy applied to a non-viscous, compressible, near-ideal gas undergoing adiabatic expansion. The pressure differential between the tank and atmosphere was related to exiting vapor flow rate. Tank internal pressure was decreased in incremental steps and the amount of gaseous mass that would have to exit the tank to result in this pressure decrease was found by the ideal gas law. A differential vent time was calculated assuming that the expelled gas exited the tank at constant velocity during each pressure step. Model inputs included ambient temperature, tank vapor volume, product molecular weights, and product specific heat values. Results are limited to single phase flow exiting a fixed volume of a specific product at specific atmospheric conditions.

Vent time corrections were found for boiling products by assuming a perfectly insulated tank car (no heat addition from a burning vapor flare). Saturated and superheated product conditions, based on tank internal temperature, were found in product-specific gas tables. The energy difference between product states was converted to a measure of additional gaseous mass loss from the tank; the additional mass was used to increase non-boiling vapor vent times. A boiling product may take more than 500 times longer to vent than would be expected by initial vapor volume; more than 40 percent of the liquid volume is expected to vaporize with a product such as propane. Results are limited to each specific product in a perfectly insulated tank car -- all field Vent and Burn procedures with vapor flaring will have significantly increased vent times.

Tables 2, 3, and 4 list expected vapor vent times for three classes of products through a 38.5-square-inch (7-inch diameter) discharge hole. Air is representative of a standing gas over a non-compressed product. Its vent times are relatively short, needing only to vent the initial vapor volume. Propane is an example of a low boiling point product -- its vent times are relatively consistent and long. n-Butane is an example of a high boiling point product; its vent times are relatively inconsistent. n-Butane will not boil or vent pressure at 30°F because its nominal boiling point is 31.1°F. However, a large volume of liquid product must boil and vent as gas to cool it from 100°F to 31.1°F.

Propane and n-Butane thermodynamic characteristics were found from Starling's equations of state as published by Sallet and Wu.[3]

Table 2. Expected Vapor Vent Times (Air)

		20,000 Gallon Tank	34,500 Gallon Tank
Tank Pressure (psig)	Tank Percent Outage	Vent Time (minutes:seconds)	
50	4	0:01	0:02
50	10	0:03	0:05
50	20	0:05	0:09
250	4	0:02	0:03
250	10	0:05	0:08
250	20	0:10	0:17

Exit area = 38.5 in^2, adiabatic expansion, standard atmospheric pressure (14.7 psia), 70°F ambient temperature.

Table 3. Expected Vapor Vent Times (Propane)

Tank Temperature and Pressure (°F) / (psia)	Tank Percent Outage	Vent Time (minutes:seconds) 20,000 Gallon Tank	Vent Time (minutes:seconds) 34,500 Gallon Tank
30 / 66.4	4	6:38	11:24
30 / 66.4	10	6:15	10:45
30 / 66.4	20	5:36	9:39
70 / 124.9	4	6:47	11:42
70 / 124.9	10	6:24	11:02
70 / 124.9	20	5:46	9:57
100 / 190.5	4	6:07	10:33
100 / 190.5	10	5:47	9:58
100 / 190.5	20	5:14	9:02

Exit area = 38.5 in^2, adiabatic expansion, insulated tank, Starling's equations of state, standard atmospheric pressure (14.7 psia), 70°F ambient temperature.

Table 4. Expected Vapor Vent Times (n-Butane)

Tank Temperature and Pressure (°F) / (psia)	Tank Percent Outage	Vent Time (minutes:seconds) 20,000 Gallon Tank	Vent Time (minutes:seconds) 34,500 Gallon Tank
30 / 14.4	4	0:00	0:00
30 / 14.4	10	0:00	0:00
30 / 14.4	20	0:00	0:00
70 / 31.2	4	5:12	8:54
70 / 31.2	10	4:52	8:22
70 / 31.2	20	4:21	7:29
100 / 51.3	4	7:52	13:32
100 / 51.3	10	7:24	12:45
100 / 51.3	20	6:37	11:24

Exit area = 38.5 in^2, adiabatic expansion, insulated tank, Starling's equations of state, standard atmospheric pressure (14.7 psia), 70°F ambient temperature.

Expected vent times will change with variations in the exit hole area. Tables 2, 3 and 4 were constructed for a 7-inch-diameter hole. However, a 6-inch-diameter hole would increase vent times to 136 percent of the times listed in the tables, while an 8-inch hole would reduce vent times to 77 percent of those listed.

8.3 LIQUID DRAINING MODEL

The liquid draining model was derived from conservation of energy applied to a non-viscous, non-compressible fluid under no external pressure (Bernoulli's equation). A differential equation was found that related the change in vertical fluid height to time. The tank cross sectional area was found as a function of fluid height for horizontal and angled right-cylindrical tanks. Numerical integration was used to find the drain time as the fluid level was decreased in incremental steps from the initial partial-outage fluid level to the top of the exit hole. Inputs included tank car diameter and length, angle of car orientation, percent outage, exit hole area, and a measure of exit hole roughness ("coefficient of discharge"). Results are valid only for the specific tank geometry, orientation, and filling. Ambient air pressure must be maintained over the liquid product.

The assumption of inviscid flow results in liquid drain times that are independent of product type for all but thick or sludgy materials. Table 5 presents expected liquid drain times for tank cars in a horizontal position. Tank cars were assumed to be right cylinders of the following dimensions: 20,000-gallon tank, 108 inch diameter by 42 foot length; 25,000-gallon tank, 108 inch diameter by 52.5 foot length; 30,000-gallon tank, 108 inch diameter by 63 foot length; 34,500-gallon tank, 114 inch diameter by 65 foot length.

Table 5. Expected Liquid Drain Times, All Liquid Products

	Tank Volume (gallons)			
	20,000	25,000	30,000	34,500
Tank Percent Outage	Drain Time (minutes:seconds)			
4	18:36	23:13	27:55	31:12
10	17:48	22:18	26:46	30:01
20	16:35	20:43	24:47	27:48

Coefficient of discharge = 0.62, exit area = 38.5 in^2, horizontal tank, 0 psig internal tank pressure.

Expected drain times will change with variations in the exit hole area or coefficient of discharge. Table 5 was constructed for a 7-inch-diameter hole of moderate roughness (coefficient of discharge = 0.62). However, a 6-inch-diameter hole would increase drain times to 136 percent of the times listed in Table 5, while an 8-inch hole would reduce drain times to 77 percent of those listed. Likewise a rougher hole (0.5) would increase drain times to 124 percent of time listed in Table 5, and a smoother hole (0.7) would reduce drain times to near 89 percent of Table 5 values.

Tank orientation has the greatest influence on liquid drain time. Drain times will decrease if the tank is slanted from its normal, horizontal position. Table 6 lists approximate drain time reduction factors based on tank angle.

Table 6. Effect of Tank Angle on Liquid Drain Time

Tank Angle (degrees)	Time Multiplier
5	0.73
10	0.63
15	0.55

As an example, the drain time for a 33,500-gallon tank filled to 20-percent outage, angled at a 10-degree incline, with a 8-inch exit hole will be calculated. Table 5 states the drain times for 30,000-gallon and 34,500-gallon tanks to be 24:47 and 27:48 minutes, respectively. Drain time for 33,500 gallons is found by linear interpolation to be 27:08 minutes for a 7-inch hole. This value must be multiplied by 0.77 to correct for the 8-inch hole size, resulting in a drain time of 20:54 minutes. Table 6 states that this value must be multiplied by 0.63 to correct for tank angle. Final drain time of the angled 33,500-gallon tank, 20-percent outage, through a 8-inch drain hole is 13:10 minutes.

Liquid drainage should be started after venting has stopped. Due to product boiling, this may not be practical; liquid drainage may be started after a significant drop in internal tank vapor pressure has occurred, marked by a lowering of vapor vent noise.

Theoretical discharge times are based on ideals and assumptions. Actual field tank conditions and explosive cutting effects will vary dramatically. The above information should be used only as a guideline. Variations of -25 percent to +50 percent are not unreasonable in real world applications.

9.0 TANK HEAD TESTS

All tank head tests were conducted at the TTC Burn Pit, an excavated area surrounded by dirt embankments. This site was chosen for its protection to both test personnel and the surrounding environment.

9.1 TEST PREPARATION

9.1.1 Sample Tank Head

The TTC Facilities machine shop constructed a frame to support a sample tank head. The frame held the tank head in a nearly vertical position to allow the force of the explosions to dissipate in an open area.

The sample tank head was constructed of 0.609-inch TC128B, Grade B normalized steel, with a diameter of 119 inches.

Mild steel jacket material was welded to three sections of the tank head in an effort to simulate the jacket material and insulation/thermal protection encountered on tank cars. Sections of jacket material were backed by 4-inch-thick fiberglass insulation, 1-inch-thick ceramic thermal protection, and both 4-inch fiberglass insulation and 1-inch ceramic thermal protection. Figure 9 displays the tank head and support fixture.

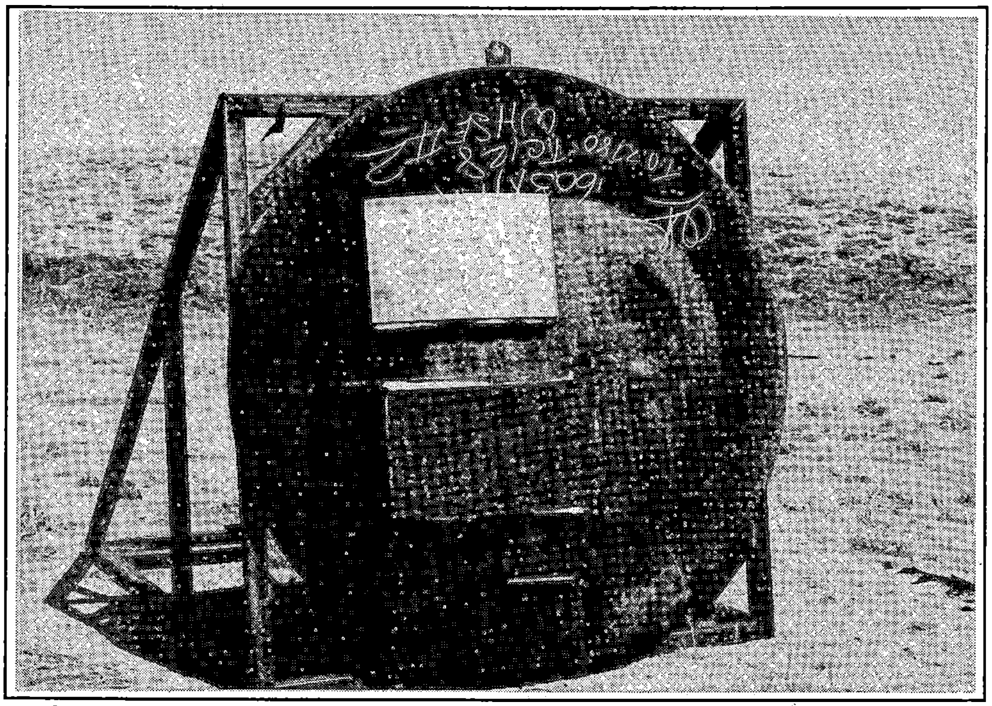

Figure 9. Full Scale Tank Head Used for Preliminary Testing, with Representative Insulation, Thermal Protection, and Jacketing

9.1.2 Explosive Charges -- Tank Head Testing

9.1.2.1 Copper-sheathed Charges

Copper-sheathed linear shaped charges of 1,000 gr/ft and 2,000 gr/ft were initially proposed to cut holes in the tank head. To allow a straight charge to open a "round" hole, the copper material was cut into segments and oriented in the shape of a hexagon. A hexagonal shape was chosen over a square shape in an attempt to have a short fabrication time while still minimizing stress concentrations in the tank material at the cut-form corners. Stress concentrations would increase the chances of tank material cracking under internal vapor pressure. Figure 10 depicts the hexagonal charges, showing both segment dimensions and cross sectional profiles. A 1,200 gr/ft charge was later used on full scale tank car tests.

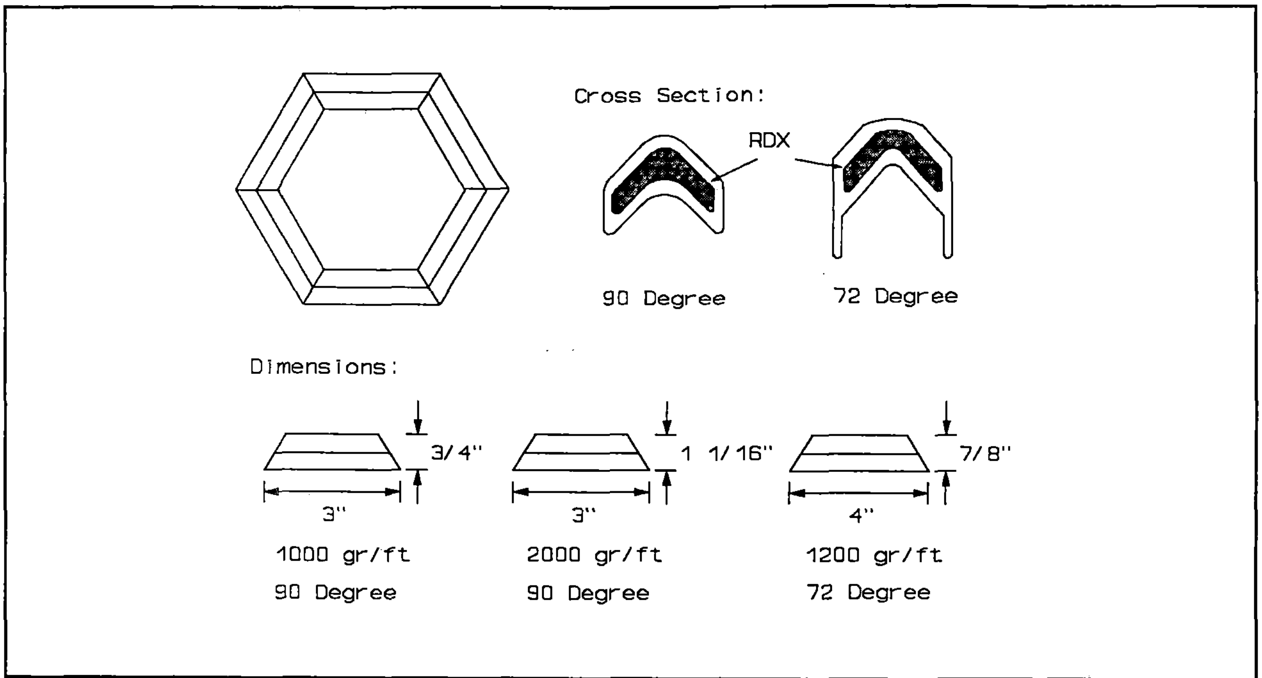

Figure 10. Construction of Hexagonal Copper-sheathed Charges

The hexagonal charges were fired by placing a non-electric detonator in the center of each leg of the copper charge. Six non-electric fuses ("primer-cord") were lead from the detonators to one central electric blasting cap (see Figure 11). This arrangement assured synchronous detonation of the copper charge without a complicated electrical detonation circuit.

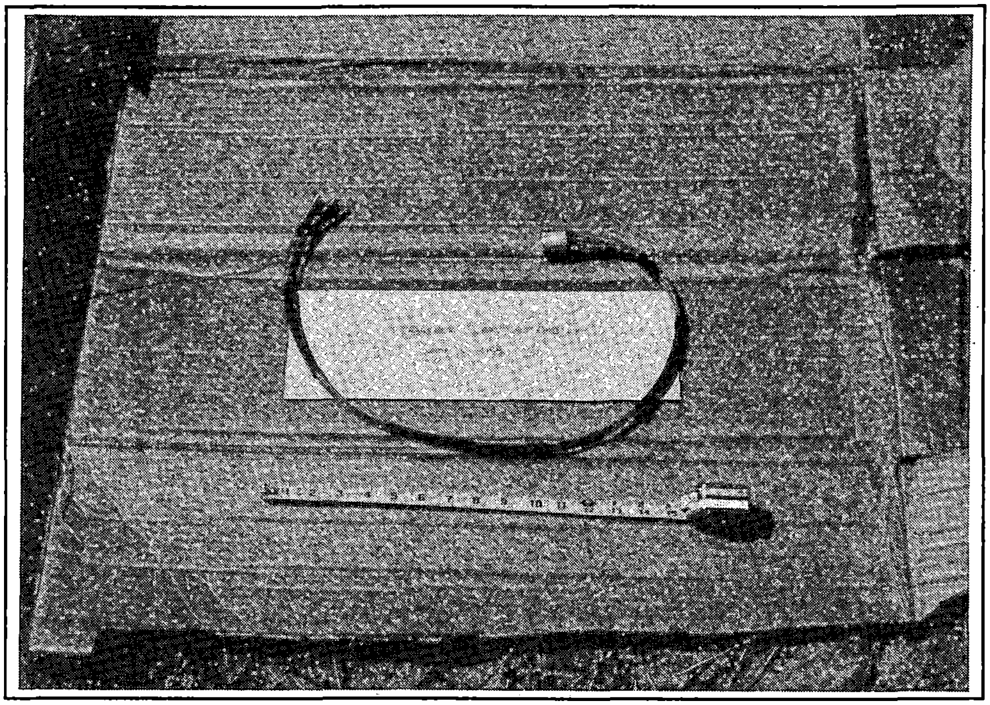

Figure 11. Electric Blasting Cap Linked to Six Detonators by Primer-cord

A notch was placed in the sheathing to allow the detonator to contact the RDX. Det sheet was placed between the detonator and the RDX to assure good initiation of the explosive. Figure 12 shows the use of detonators and det sheet with the hexagonal charges.

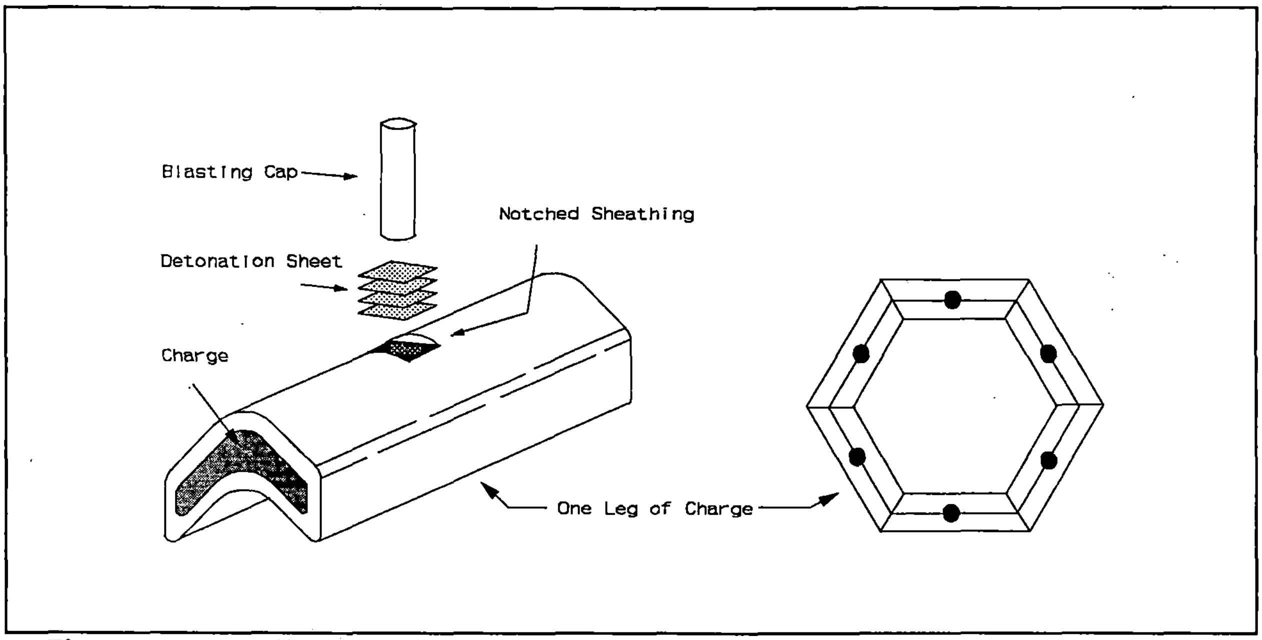

Figure 12. Application of Detonator/Blasting Cap and Det Sheet to Hexagonal Copper-sheathed Charges

To assure proper alignment of the charge components, a jig of 3/4-inch plywood was built for each charge. The jig held the segments of copper-sheathed charge in place by use of silicon based adhesive. Wooden tabs were drilled to support the detonators over the center of each segment. A second layer of 3/4-inch plywood allowed the desired stand-off distance to be achieved. Figure 13 depicts the jig for holding the segmented linear charge in place.

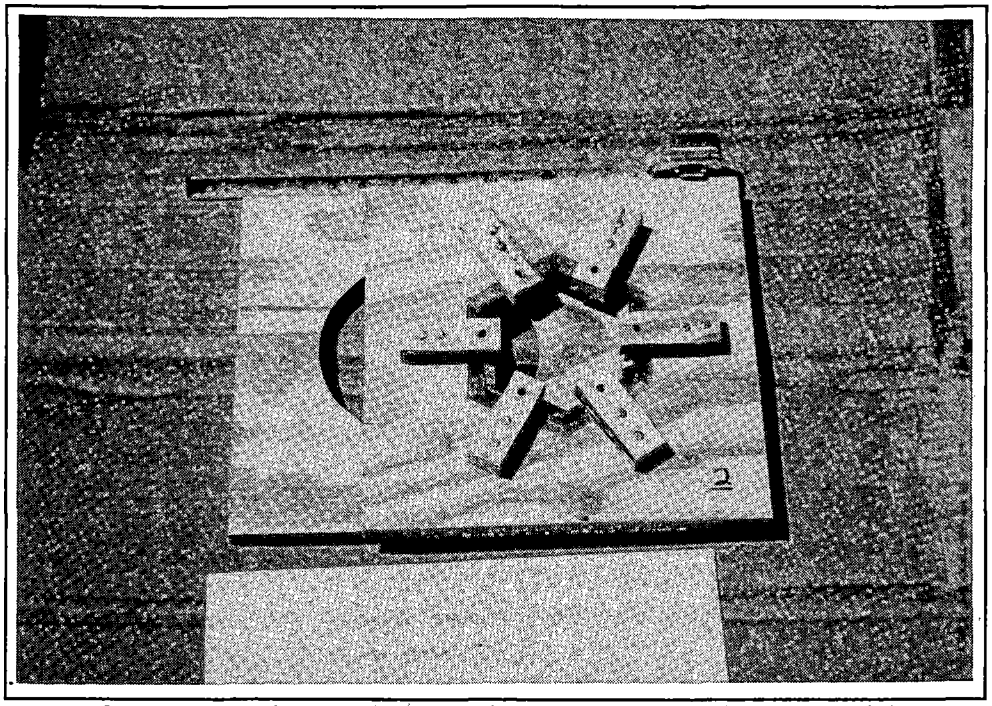

Figure 13. Plywood Jig and Stand-off Block Used with Hexagonal Copper-sheathed Charges

9.1.2.2 Lead-sheathed Charges

Lead-sheathed RDX explosives of 150 gr/ft and 60 gr/ft were used to cut 1/8-inch jacketing material. A field application of the vent and burn procedure would require a section of the tank car jacket to be removed to place the final cutting charge directly on the tank head or shell. A pre-formed explosive charge could be applied to the jacket in the field much more quickly and at less danger to the technician than current jacket cutting techniques. Current jacket removal methods include hand cutting of the jacket with a saw or oxy-acetylene torch.

The flexible lead-sheathed charge was formed into a rough circle and secured on the jacketing with duct tape. The charge stand-off was built into the sheathing. One electric cap, a length of primer-cord, and a non-electric detonator were linked to detonate the charge. The detonator was placed at the location where the charge ends joined.

9.1.2.3 Foam-sheathed Charges

A foam-sheathed RDX explosive of 300 gr/ft also was used to cut 1/8-inch-thick jacketing. DRI suggested that foam-sheathed explosives require about twice the charge of copper or other metallic-sheathed materials due to the characteristics of polystyrene foam.

The foam charge was flexible and attached with duct tape; proper stand-off was built into the sheathing. A single electric blasting cap, placed at the junction of the charge ends, was used to detonate the explosive.

9.2 TEST PROCEDURE

To perform the tests safely, procedures were implemented to protect the personnel and equipment involved in the testing. General entry to the Burn Pit area was restricted during testing by a locked gate at the Hazardous Materials Training area. The Burn Pit is approximately 6 miles north-northwest of this gate.

All personnel at the Burn Pit area were housed in a culvert bunker, located behind a dirt mound approximately 75 yards from the test tank head. Only those applying the explosives to the tank head were permitted into the firing area after pre-test photo-documentation was completed. The final connection of the blasting caps to the explosive charge was performed by certified personnel immediately before detonation. Radio silence was maintained to prevent premature detonation caused by radio frequency interference.

Air space over the test site was closed during the testing period as an additional safety precaution.

Test charges were secured to the tank head with tape. Wire hangers were used to help support the weight of the plywood jigs. Upon clearing the firing range of all but certified personnel, blasting caps, primer-cord, detonators, and det sheet were applied to the charge, as needed, to ensure proper charge initiation. An electrical detonation circuit was used to set off the blasting cap and subsequently the test charge. Figure 14 displays the final installation of a hexagonal charge on the sample tank head.

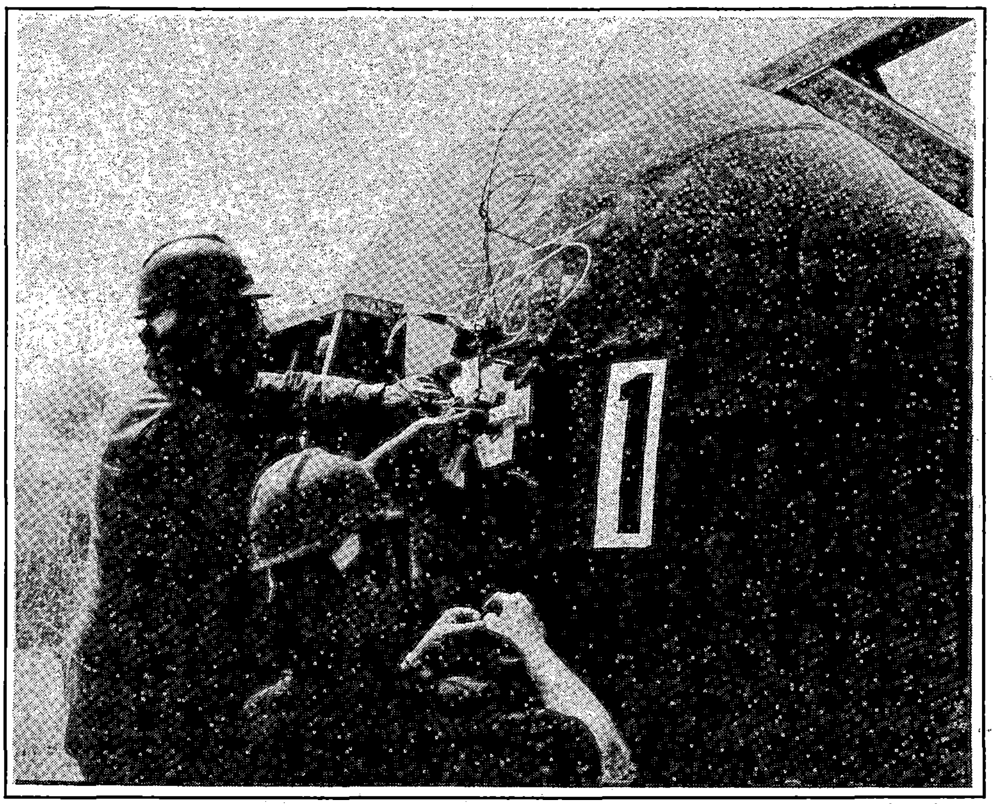

Figure 14. Final Installation of Hexagonal Copper-sheathed Charge on Sample Tank Head

After each test, the test controller and other personnel walked the perimeter of the Burn Pit to look for brush fires or other hazards resulting from test detonation.

9.3 PHOTOGRAPHIC DOCUMENTATION

Video and still photography were used to document the testing effort. One high speed camera, operating at a speed of 500 frames per second (fps), was used on the initial tests. The high speed camera was started by a hand operated switch.

9.4 RESULTS OF TANK HEAD TESTS

Tests at the Burn Pit were conducted on April 27, 1993, and May 21, 1993. Initial tests displayed success in cutting the bare tank head with 1,000 gr/ft and 2,000 gr/ft copper-sheathed charges. The jacketing material was easily cut with 150 gr/ft lead-sheathed and 300 gr/ft foam-sheathed charge. A sample of 60 gr/ft lead-sheathed failed to completely cut the jacketing. Table 7 displays sample tank head results in a matrix. Successful tests are marked with a plus sign (+), while failed results are marked with a minus sign (-); blank cells indicate no test was performed.

Table 7. Results of Tank Head Testing

Test Number	Bare Head	Jacketing	1,000 gr/ft Copper	2,000 gr/ft Copper	60 gr/ft Lead	150 gr/ft Lead	300 gr/ft Foam
1	•		+				
2	•		+				
3	•			+			
4B		•			—		
4A		•				+	
9		•					+

Test 0

Test 0 consisted of detonating a blasting cap to check the continuity of the detonation circuit wiring. This test was successful. The cap detonated approximately 1 second after the detonation circuit was triggered.

Test 1

The purpose of this test was to determine the success of 1,000 gr/ft copper-sheathed RDX explosive in cutting a hole in the 0.609-inch bare tank head. The charge was constructed in a hexagonal form as pictured and sized in Figures 10, 12, and 13. A single layer of det sheet was used below each blasting cap. The angle of the explosive was 90 degrees. See Figure 14 for Test 1 set up.

Test 1 successfully cut a hexagonal-shaped hole 4 7/8 inches by 4 7/8 inches by 5 inches as measured between opposite sides. The explosion produced a curl at the edges of the cut that ranged from 1/16 inch to 1/8 inch into the tank head.

Test 2

The purpose of this test was to replicate Test 1. Test 2 was conducted with the same explosives and stand-off on the sample head. The results of Test 1 were successfully replicated. Figure 15 displays the resultant hole created during Test 2.

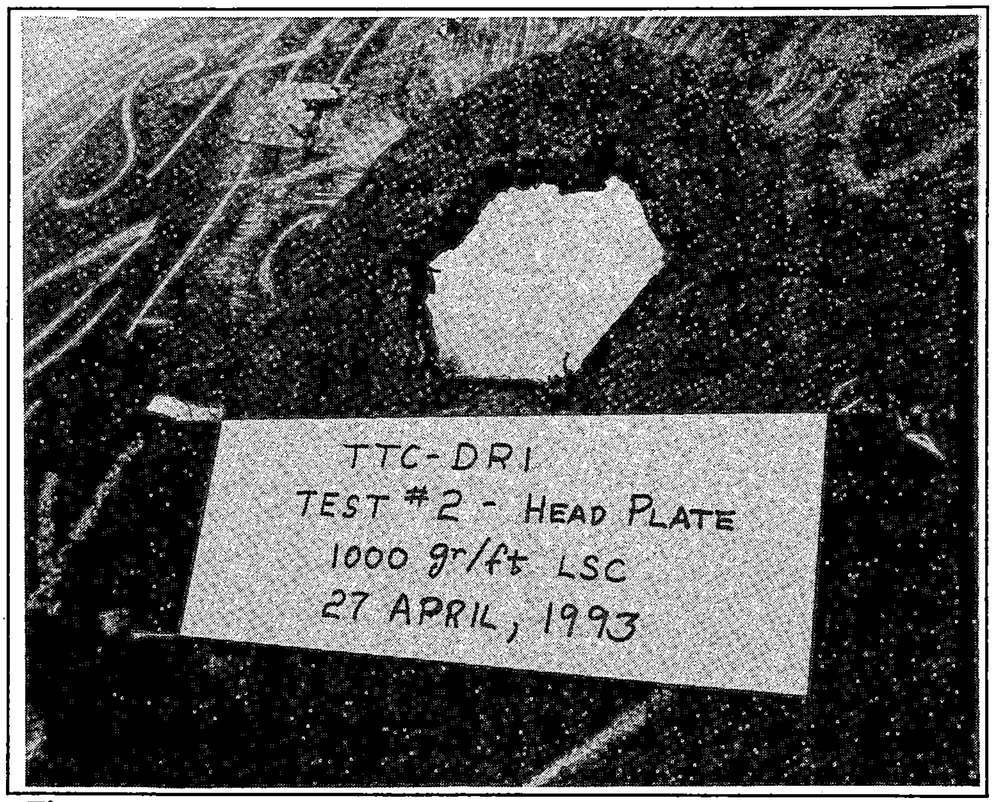

Figure 15. Test 2 Results -- 1,000 gr/ft Copper-sheathed Charge on Bare Tank Head

Test 3

Test 3 was conducted on the same tank head using a copper-sheathed charge of 2,000 gr/ft of RDX explosive. The jet-forming angle was again 90 degrees. This charge was initiated in the same manner as Tests 1 and 2.

The edges of the hole cut with this charge were much more ragged than those cut with the 1,000 gr/ft charges. This hole was also hexagonal-shaped, measuring 4 7/8 inches by 5 inches by 5 1/8 inches between opposite sides of the hole.

Test 4A

The purpose of this test was to cut a large hole in tank car jacket material to gain access to the tank shell. A charge of 150 gr/ft lead-sheathed RDX was placed on 1/8-inch-thick mild steel, typical of tank car jacket material. This jacket material was affixed over the test tank head, backed by 4 inches of fiberglass insulation and 1 inch of ceramic thermal protection, typical of a DOT/TC 105J class tank cars.

This test produced a 9-inch-circular hole, with partial cutting of both the fiberglass and ceramic material. The jacketing was noted to curl inward toward the tank head approximately 1 inch at the edge of the puncture. Figure 16 displays Test 4 set up, including both 4A and 4B.

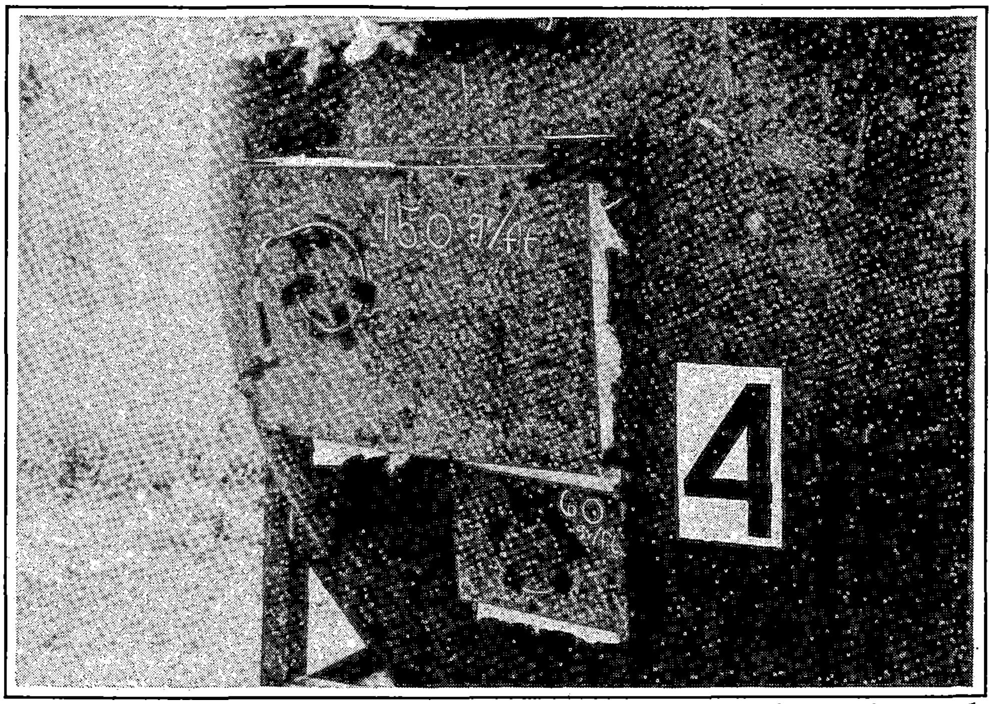

Figure 16. Test 4 Setup -- Jacket Material on Sample Tank Head 150 gr/ft (4A) and 60 gr/ft (4B) Lead-sheathed Charge

Test 4B (conducted at same time as Test 4A)

The purpose of Test 4B also was to find an explosive that would cut an acceptable hole into tank jacket material. The charge was lead-sheathed, 60 gr/ft RDX explosive formed in an 8-inch circle. The jacket was backed by 1 inch thermal protection, simulating a DOT/TC 112/114J tank car.

This test resulted in cutting completely through the jacket material only in intermittent sections around the perimeter of the circle. Approximately 50 percent of the perimeter was not cut. This test was not successful, indicating that a more powerful charge than 60 gr/ft lead-sheathed RDX is required to cut jacket material.

Test 9

Test 9 was conducted on May 21, 1993, using a foam-sheathed RDX explosive of 300 gr/ft to cut a hole in the tank jacket material. The charge was formed into a 7-inch-diameter circle. The jacketing was backed by 4 inches of fiberglass insulation and 1 inch of ceramic thermal protection, the same as in Test 4A.

The explosion cut completely through the perimeter of the jacket coupon, partially cutting the insulation, thermal protection, and scoring the tank head. Test 9 results are pictured in Figure 17.

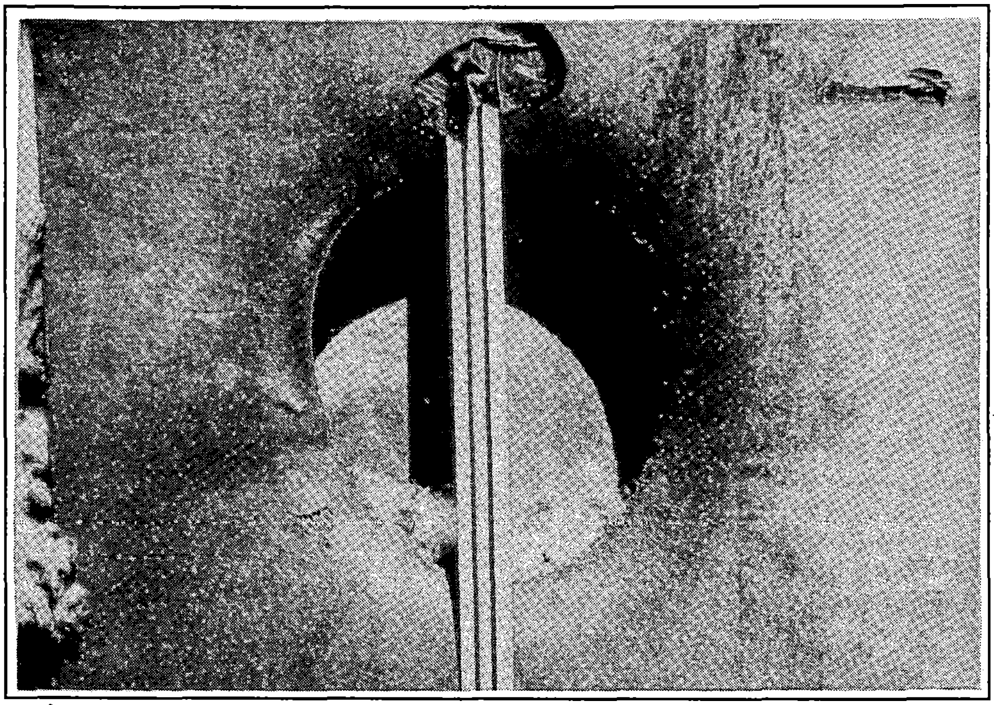

Figure 17. Test 9 Results -- 300 gr/ft Foam-sheathed Charge on Jacket Material

9.5 CONCLUSIONS OF TANK HEAD TESTS

The tank head tests led to the following conclusions.

- 1,000 gr/ft and 2,000 gr/ft copper-sheathed RDX explosive with a 90-degree jet-forming angle, arranged into a segmented hexagonal charge, worked cleanly and consistently to cut a 0.609-inch TC-128B, Grade B normalized steel tank head. The 1,000 gr/ft charge is recommended as providing a cleaner cut with reduced explosive material.
- 150 gr/ft lead-sheathed and 300 gr/ft foam-sheathed RDX explosive successfully cut 1/8-inch mild steel tank jacket material. The 300 gr/ft foam-sheathed charge is recommended because it presents no shrapnel or vapor inhalation hazards.
- Fiberglass insulation and ceramic thermal protection should be removed by hand after the tank jacket is cut. Charges sufficient to cut this material will damage the tank shell surface, further weakening the tank and endangering personnel safety.

10.0 FULL SCALE TANK TESTS

After preliminary tests were successfully conducted on a sample tank head, tests were performed on full scale pressure cars of DOT112T340W specification. These tests were conducted at TTC's Impact Track. Both copper- and foam-sheathed charges were tested. Cutting of exit holes was attempted in the tank vapor space, liquid space, and head shields.

10.1 TEST PREPARATION

10.1.1 Sample Tank Cars

Four full scale pressure tank cars were prepared to simulate a range of actual product conditions. Specifically, the tanks were filled with water to approximately 20-percent outage as would be expected in flammable gas service. Table 8 lists the actual tank car filling levels. Tank fill levels were initially checked by car weight; final outage levels listed in Table 8 are from tank depth measurements and an outage table published with the tank car build sheets. Figure 18 displays tank DUPX 20462 at the test location.

An air compressor capable of pressures up to 250 psi was rented to allow simulation of high pressure vapor within the tank.

The full scale tank cars were constructed of 0.669-inch TC-128B, Grade B normalized steel. They were thus thicker material than the 0.609-inch sample head.

Table 8. **Full Scale Tank Car Preparation -- Water Fill Levels**

Car Number	Percent Outage
DUPX 20462	21
DUPX 26740	14
DUPX 26761	12
DUPX 26770	14

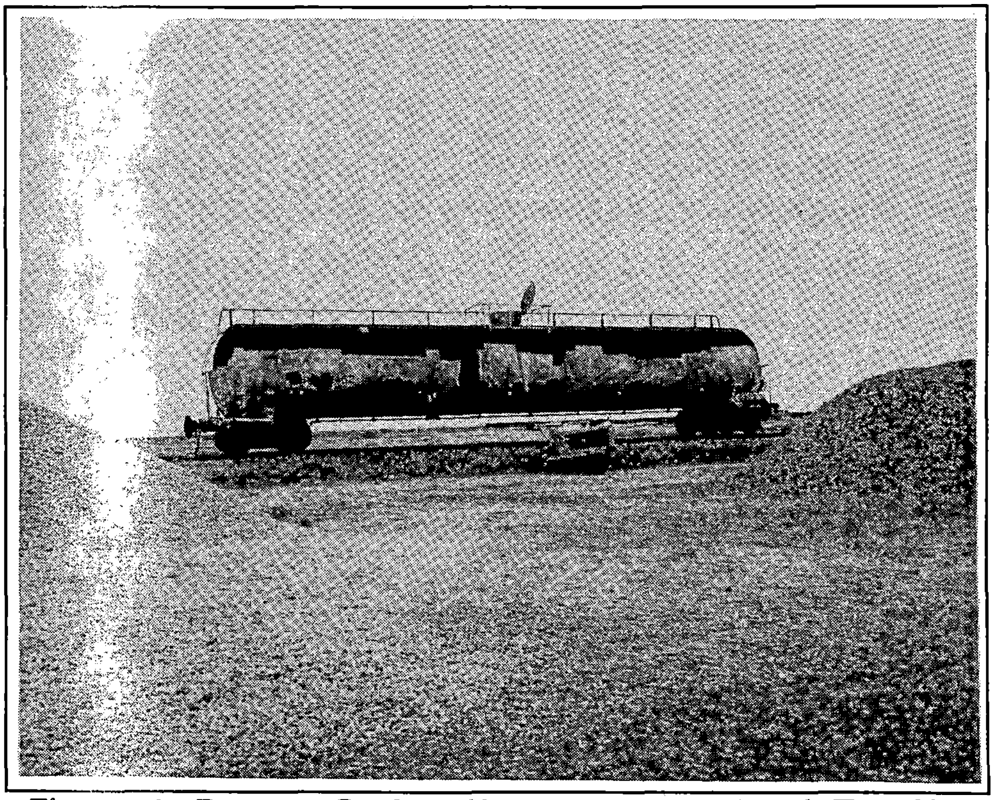

Figure 18. **Pressure Car DUPX 20462 at Impact Track Test Site**

10.1.2 <u>Explosive Charges -- Full Scale Testing</u>

10.1.2.1 Copper-sheathed Charges

DRI supplied 1,200 gr/ft copper-sheathed RDX with a 72-degree jet-forming angle. It was felt that the increased charge power compared to the originally tested 1,000 gr/ft copper-sheathed RDX and more precise 72-degree jet would more than compensate for the increase in material thickness from the 0.609-inch-thick head to 0.669-inch tank. The new copper-sheathed explosives were prepared in the same manner as described during tank head testing. One charge of 1,000 gr/ft, 90 degrees, remained unused after tank head tests.

Electric blasting caps were used in place of the blasting cap, primer-cord, and detonator combination used on the tank head. Det sheet was placed beneath the blasting cap to assure charge detonation.

10.1.2.2 Foam-sheathed Charges

DRI had suggested the use of foam-sheathed explosive as an alternative to the copper. The foam-sheathed explosive was flexible and could be bent into a circular form. Preliminary full scale tank test results with the copper charges indicated explosive power was lost at discontinuities in explosive material and sheathing. A circular formed charge should avoid these problems. A flexible charge could also be made to match the curve of the tank shell.

Foam-sheathed explosives were ordered in strengths of 2,400 gr/ft, 3,600 gr/ft, and 5,400 gr/ft. Especially the 5,400 gr/ft charge was stiff and hard to maintain in a circular shape. Duct tape was used on some tests to hold the charge into a circle, but with unreliable results. The charge would expand from its circular shape or roll away from the tank surface. Charge expansion would result in a gap between charge ends -- no tank shell cutting could take place under this separation. The roll of the charge would cause the explosive's gas jet to strike the surface at a glancing angle and loose cutting strength. Figure 19 depicts the desired normal charge orientation and the undesired rolled orientation. Figure 20 displays a foam charge, banded by tape, installed on the test tank.

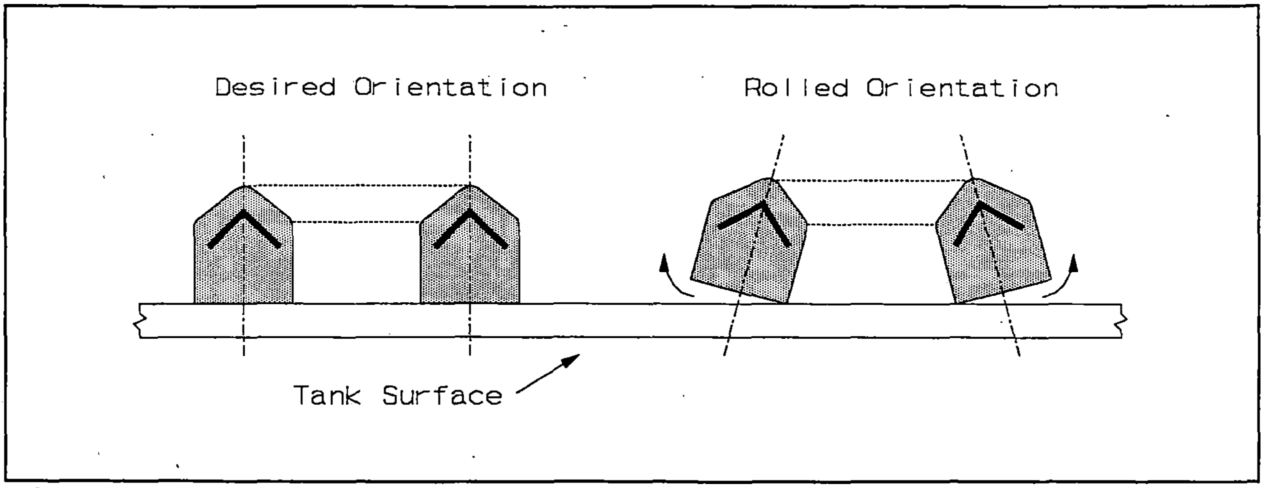

Figure 19. Desired Normal and Actual Rolled Orientation of Taped Charge -- End View

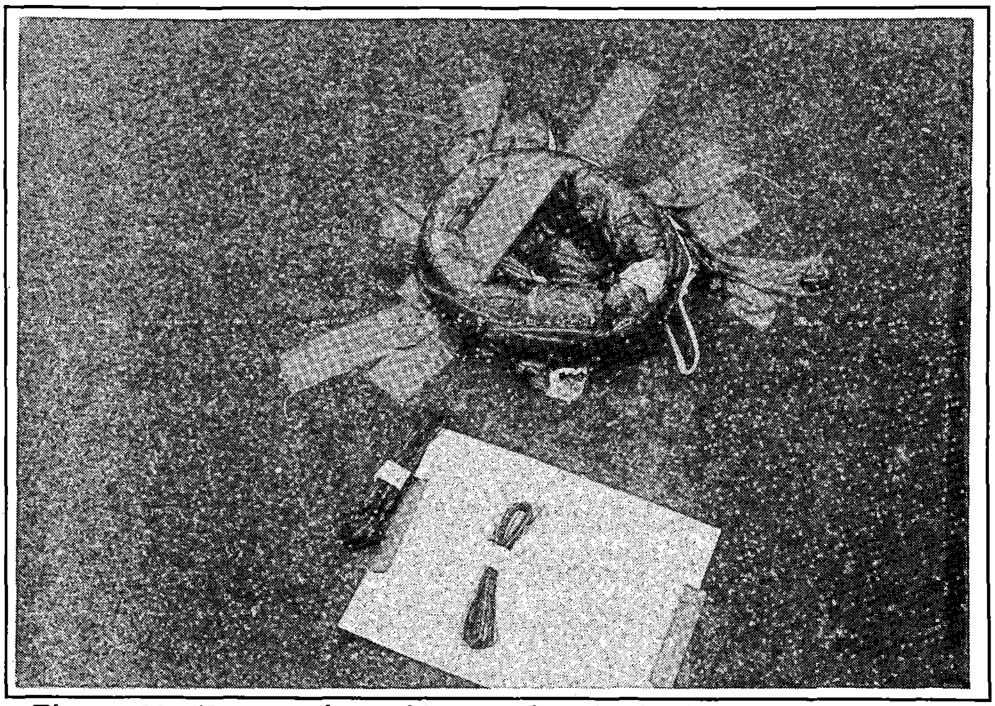

Figure 20. Preparation of Foam-sheathed Charge -- Duct Tape Used to Band Charge into Circular Shape

Metal bands were made to hold the charges in their proper shape and orientation. Bands were constructed of 2-inch-wide, 1/16-inch-thick steel stock, cut in length to the desired charge outer diameter, and tack welded into their circular form. The charge was bent and inserted into the retaining band. The charge was securely held within the banding by friction. Det sheet was added to the charge at the small gap formed between the segment ends, assuring uniform charge detonation. Figure 21 displays a 5,400 gr/ft charge (top view) within a metal band; det sheet can be seen as a triangular wedge within the charge. Figure 22 displays the bottom view of this same charge. The banded charges were secured to the tank surface by a double-faced tape pre-applied to the foam charge (visible in Figure 22). Duct tape and later epoxy adhesive were used to help secure the charge to the tank shell.

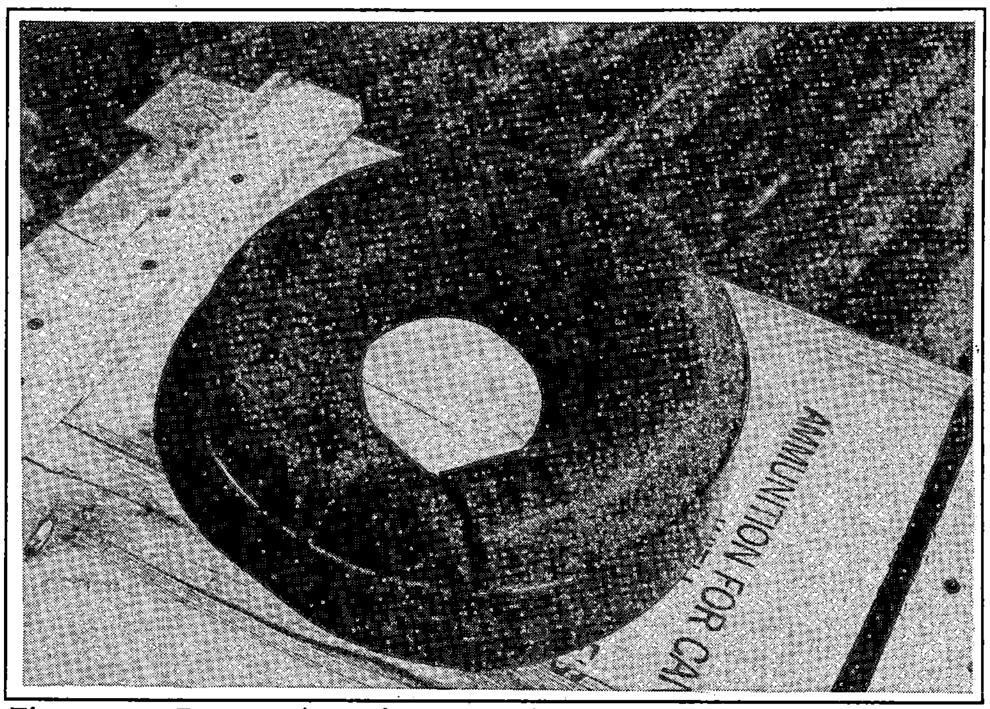

Figure 21. Preparation of a Foam-sheathed Charge -- Metal Band Used to Form Charge into Circular Shape -- Top View

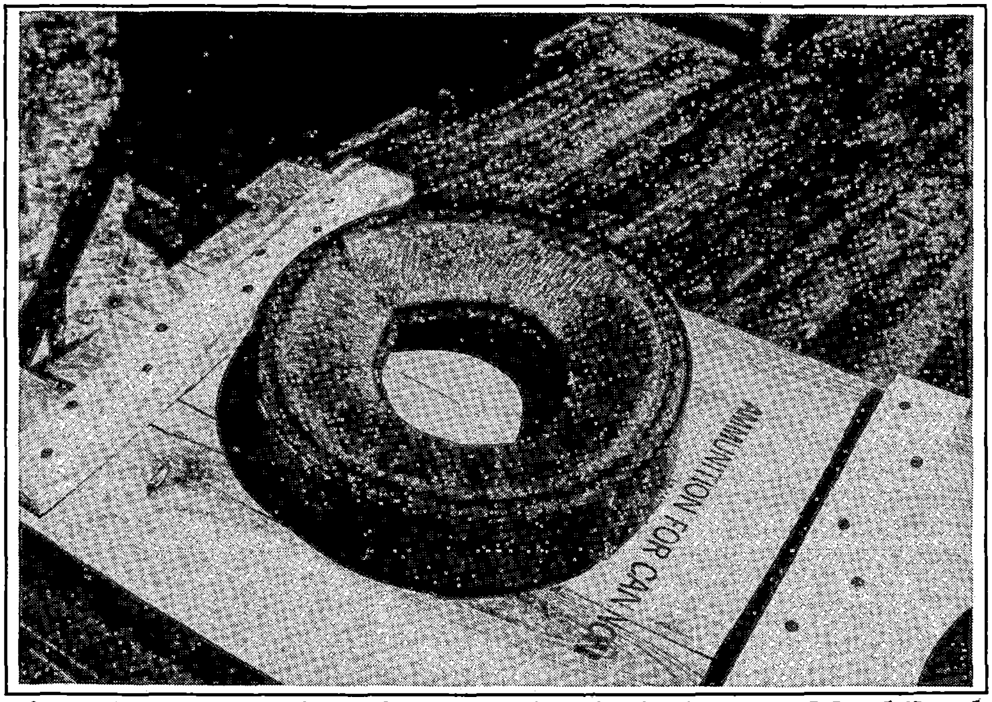

Figure 22. Preparation of a Foam-sheathed Charge -- Metal Band Used to Form Charge into Circular Shape -- Bottom View

Detonation was achieved by two electric blasting caps placed into the RDX near the two ends of the charge. Det sheet was used beneath the caps to assure charge initiation.

10.2 TEST PROCEDURES

Utmost care was taken to observe safety during all phases of the testing. The tanks were placed in an area of track more than 1/2 mile from any above-ground structure. The entrance to the test area was sealed with barricades and a sentry. The support equipment, including cameras and a generator, were protected with shields of plywood or plexiglass. All vehicles were removed from the test site by approximately 50 yards and parked behind ballast piles. A bunker constructed of 2-inch-thick plate steel provided protection for personnel during the firing of the charges. Radio silence was maintained near the charges to prevent premature detonation due to radio frequency interference. Figure 23 shows photo and detonation equipment setup within the bunker.

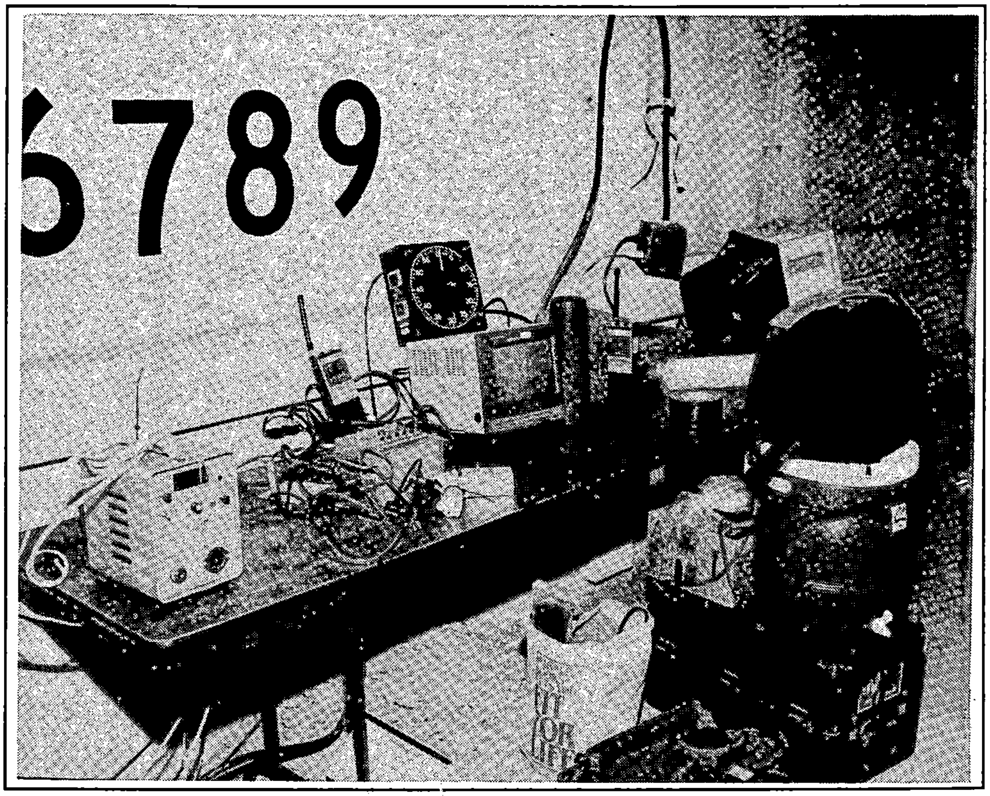

Figure 23. Test Equipment Housed in Protective Bunker

The Test Controller cleared the firing range of personnel before charge detonation. After charge firing, the Test Controller inspected the general area for air borne debris and safety hazards before allowing other personnel out of the bunker. The air space above the test site was closed to all aircraft during the test periods. These periods typically were 2 hours long.

Test charges were secured onto the tank shell with tape or adhesive. Metal rings were used to hold charge shape during some tests. Wooden bracing was used to support some charges on the underside of the tank cars. Certified personnel applied blasting caps and det sheet to the charge, as needed, to ensure proper charge initiation. An electrical detonation circuit was used to set off the blasting caps and subsequently the test charge.

During tests implementing high speed cameras, a timing device was added to the detonation circuit to allow the cameras to attain their desired shutter speed before actual detonation was triggered.

An air compressor was used to apply between 100 psi and 250 psi to the tanks before certain test firings. Air pressure was applied through standard vapor valves on the test car.

10.3 PHOTO DOCUMENTATION

All tests on the actual tank cars were documented with video and still photography. Two high speed motion picture cameras, operating at 500 fps and 5,000 fps, respectively, were used on initial and final tests only. Figure 24 displays the photographic equipment used during testing.

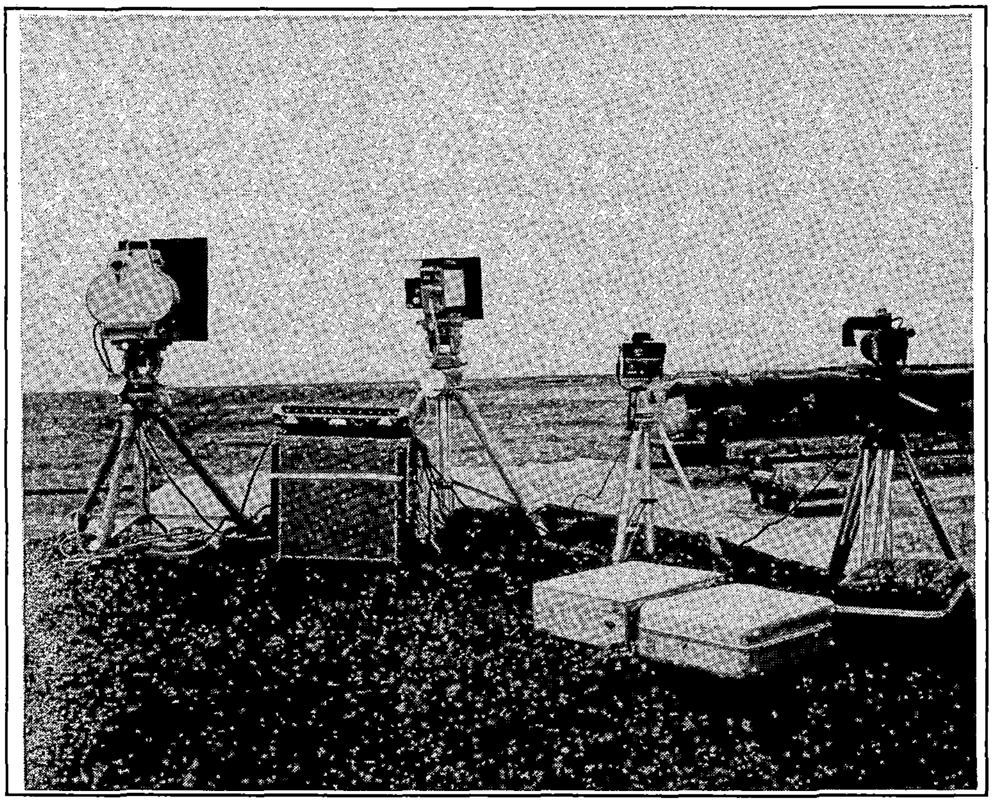

Figure 24. Photo Equipment Used to Document Testing

10.4 RESULTS OF FULL SCALE TESTING

Full scale tank car test results are divided by copper-sheathed charges, foam-sheathed charges, and head shield cutting. Test numbers may not appear in sequential order, but rather are grouped by experiment type.

10.4.1 Copper-sheathed Charges

Testing on the sample tank head had indicated the good probability of successful cutting with the copper-sheathed charges used on full scale tank cars. However, all test with copper-sheathed RDX explosive on full scale tank cars failed. Table 9 presents tests performed in a matrix format; a minus sign (-) indicates test failure and a blank cell indicates no test.

Table 9. Results of Copper-sheathed Charge Testing on Full Scale Tank Car

Test Number	Tank Pressure (psi)	Number of Det Sheets	1,000 gr/ft Copper	1,200 gr/ft Copper
5	250	1		—
6	225	1	—	
7	0	4		—
8	0	8		—

Test 5

Test 5 was conducted on May 11, 1993. The purpose of this test was to determine the type, amount and configuration of explosive required to cut an acceptable vapor vent hole in a tank car simulating loaded conditions with internal vapor pressure. This setup most nearly represented actual conditions expected during field application of Vent and Burn. The test car, DUPX 26761, was pressurized to 250 psi with air.

The charge used in this test was 1,200 gr/ft, copper-sheathed RDX with a 72-degree jet-forming angle, initiated with six blasting caps. A single layer of det sheet was inserted under each blasting cap to ensure uniform detonation. The charge was dimensioned and constructed as indicated in Figures 10, 12, and 13. Stand-off distance was achieved with a 3/4-inch plywood form placed between the charge and the tank surface. The finished charge was duct taped in place on top surface of the tank in a bare metal region.

The charge failed to completely cut the perimeter of the coupon. The coupon remained attached to the tank at 12 locations: at the six corners of the hexagon, and at the centers of the six charge legs, under the installation locations of the blasting caps. The coupon measured 7 inches corner-to-corner. The results of Test 5 are displayed in Figure 25.

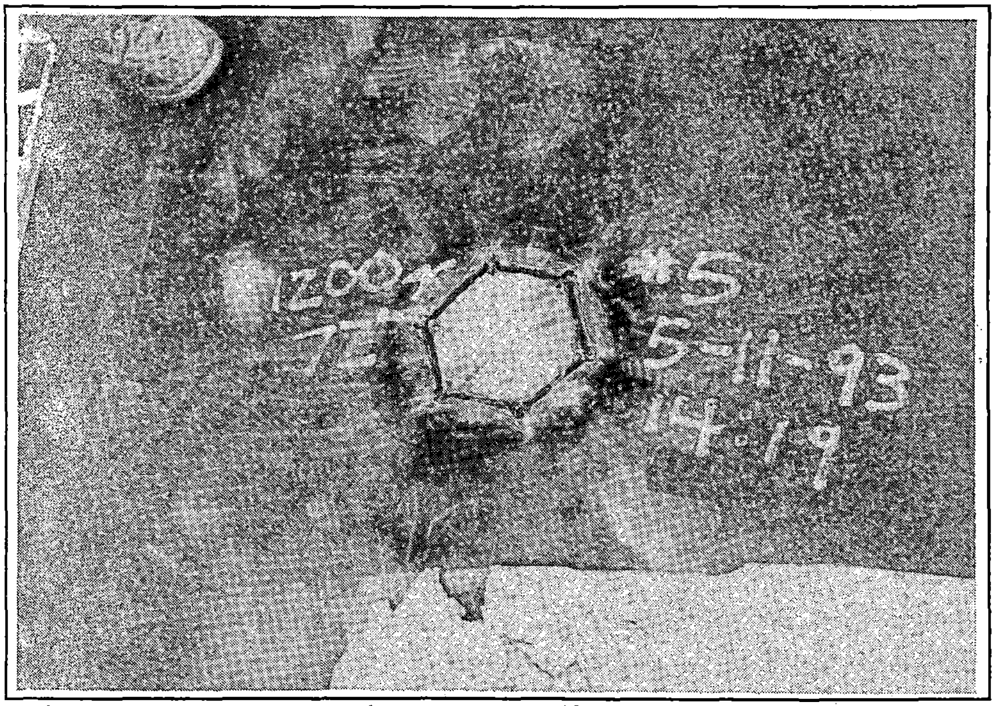

Figure 25. Test 5 Results -- 1,200 gr/ft Copper-sheathed Charge on Pressure Car Vapor Space, 250 psi Internal Pressure

After initiation of the explosion, the time required to vent the 250 psi internal pressure was 8 minutes 30 seconds. Vent time was recorded between detonation and the loss of sound from escaping vapor. Expected vent time was 12.2 seconds with successful cutting of a 31.8 square-inch hole. The true vent area was estimated at 0.625 square inches.

Test 6

Test 6 was conducted on May 12, 1993. The purpose of this test was the same as Test 5; namely, to find the correct type, amount, and configuration of explosive to cut a vent hole in a loaded, pressurized tank car.

DUPX 20462 was pressurized to 225 psi with air and used as the test car. The air compressor could not maintain more than 225 psi on the day of testing.

The charge used in this test was 1,000 gr/ft, copper-sheathed RDX. Test 5 had used a charge of 72-degree cutting angle, untested on the tank head; it was felt that the 90-degree angle, tested previously, would be more likely to produce a continuous and thus successful cut. The charge was taped in place on top of the tank on bare metal.

This test failed to completely cut through three corners and four side-center areas of the coupon. The coupon measured 4 7/8 inches between opposite sides. Vent area was estimated at 1.15 square inches. Vent time was originally estimated at 32.1 seconds for a 20.6 square-inch hole, but was timed at 8 minutes 40 seconds. Time was recorded between detonation and the loss of sound from escaping vapor.

Test 7

Test 7 was conducted May 12, 1993, to successfully cut the full scale tank car. The test was performed on the now unpressurized DUPX 20462.

The explosive used was copper-sheathed, 1,200 gr/ft RDX, with a 72-degree jet-forming angle. This charge was identical to that used in Test 5, except that four layers of det sheet were placed under each blasting cap for additional boost.

This test also failed to achieve the desired results. The explosion failed to cut completely through four corners and four side centers of the coupon. The coupon measured 7 inches between hexagon corners. Figure 26 shows the partially cut coupon resultant from Test 7.

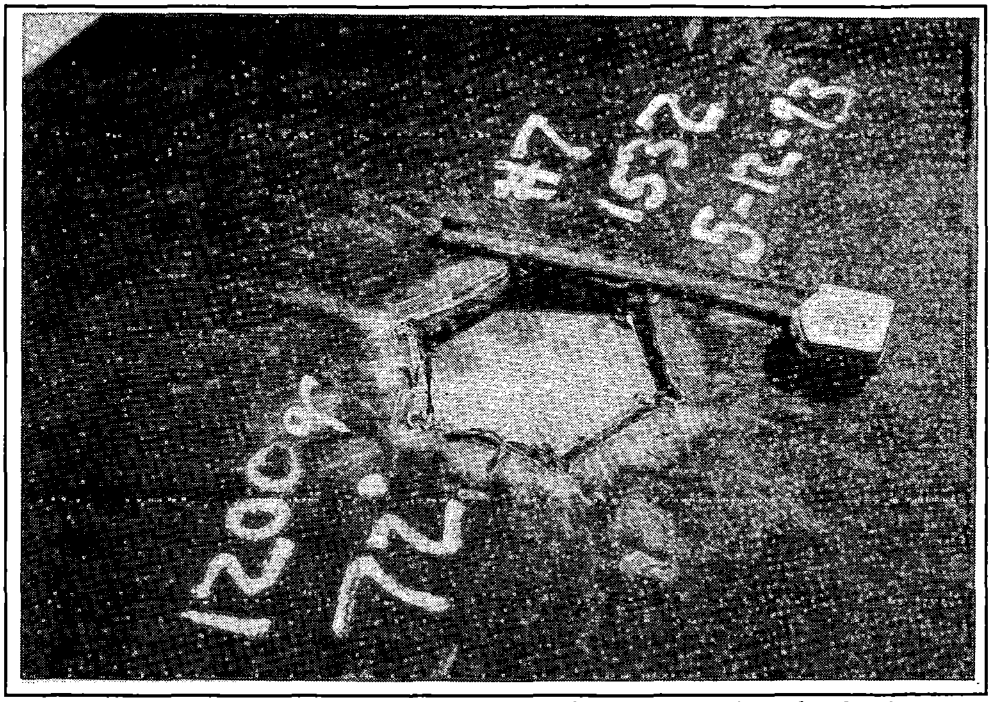

Figure 26. Test 7 Results -- 1,200 gr/ft Copper-sheathed Charge on Pressure Car Vapor Space, No Internal Pressure

Test 8

Test 8 was conducted on May 19, 1993, in a continued effort to successfully cut through the pressure car material. Test car was DUPX 26761, unpressurized.

A 1,200 gr/ft, copper-sheathed, 72-degree charge was used, but with eight layers of det sheet to boost the blasting cap initiation at the centers of each side of the hexagon.

This test also failed to produce acceptable results. All corners and side centers were only partially cut through. The coupon measured 7 inches between hexagon corners.

10.4.1.1 Conclusion, Copper-sheathed Charges on Full Scale Tank

The following conclusions can be drawn as to the applicability linear shaped copper-sheathed RDX explosives to cut a pressure tank car.

- Linear shaped charges of 1,000 gr/ft and 1,200 gr/ft copper-sheathed RDX explosive with jet-forming angles of 90 degrees and 72 degrees, respectively, segmented and arranged into the shape of a hexagon, could not successfully cut 0.669-inch TC-128B, Grade B normalized steel forming the barrel portion of a tank car shell.
- Variations, within available materials, had been made to increase charge strength, cutting angle, and charge initiation. The charges consistently failed to cut at junctions of charge segments and at locations beneath the blasting caps; both regions were marked by the discontinuity in explosive and sheathing material. Focusing of the explosive forces was weakened by the sheathing joints. Breaks in the explosive material could result in non-continuous detonation around the coupon perimeter.
- The segmented charges were by nature flat, but placed on a curved surface. The charge corners have both a discontinuous sheathing and an increased stand-off distance.

10.4.2 Foam-sheathed Charges

DRI suggested the use of flexible foam-sheathed charges for cutting the tank car surface. The charge could be bent into a circular shape to avoid the charge discontinuities seen at the linear charge segment joints. The foam charge could also be molded to the curve of the tank surface, maintaining a constant stand-off distance. Table 10 describes the series of tests undertaken with foam-sheathed RDX explosives; a plus sign (+) indicates a successful test while a minus (-) indicates failure. A blank cell states no test was performed.

Table 10. Results of Foam-sheathed Charge Testing on Full Scale Tank Car

Test Number	Tank Pressure (psi)	Liquid Space	Vapor Space	Spray-on Thermal Protection	3,600 gr/ft Foam	5,400 gr/ft Foam
10	0		•			+
11	0		•			+
12	0		•		—	
13	0	•				+
16*	0	•				+**
17	100		•			+
18	0	•				+
19	100		•			+
20	0		•	•		+
22*	0	•		•		+

* Tests 14, 15, and 21 are documented in Section 10.4.3, Head Shield Tests.
** Partial cut of tank allowed liquid to drain within an acceptable time frame.

Test 10

Test 10 was conducted on May 21, 1993. The purpose of this test was to determine if the foam-sheathed explosive would successfully cut an acceptable vent hole in a tank car. The test car was the unpressurized DUPX 26761.

The explosive used in this test was 5,400 gr/ft foam-sheathed RDX with built-in stand-off of 3/4 inch. The explosive was applied to the top of the tank car on bare metal. The explosive was 2 feet long and bent into a 7-inch-diameter circle with a slight overlap occurring where the charge ends meet. This explosive had a pre-applied adhesive backing, but it was not adequate to hold the charge in a circular shape; duct tape was used to hold the charge in a circular form. The charge was detonated with two blasting caps placed at the overlap -- to initiate the charge from both ends. Det sheet was used to fill-in the slight gap in explosive material at the end joint.

This test was successful. The charge cut an egg-shaped hole approximately 7-inches by 12-inches. There was evidence of tearing at either end of the egg-shaped hole, where the charge was initiated, and where the detonating wave fronts "met" opposite the initiation points.

TEST 11

Test 11 was conducted on August 23, 1993, to replicate the results of Test 10. It was performed on DUPX 26761 with 5,400 gr/ft foam-sheathed RDX explosive. Due to the problems experienced in Test 10 of forming the charge into a circular shape, a metal ring was used to hold the charge in the proper shape. The foam charge's self-sticking adhesive was aided by application of duct tape. The slight gap in the circular explosive charge was filled with det sheet. Figure 27 shows the application of foam-sheathed charge for Test 11.

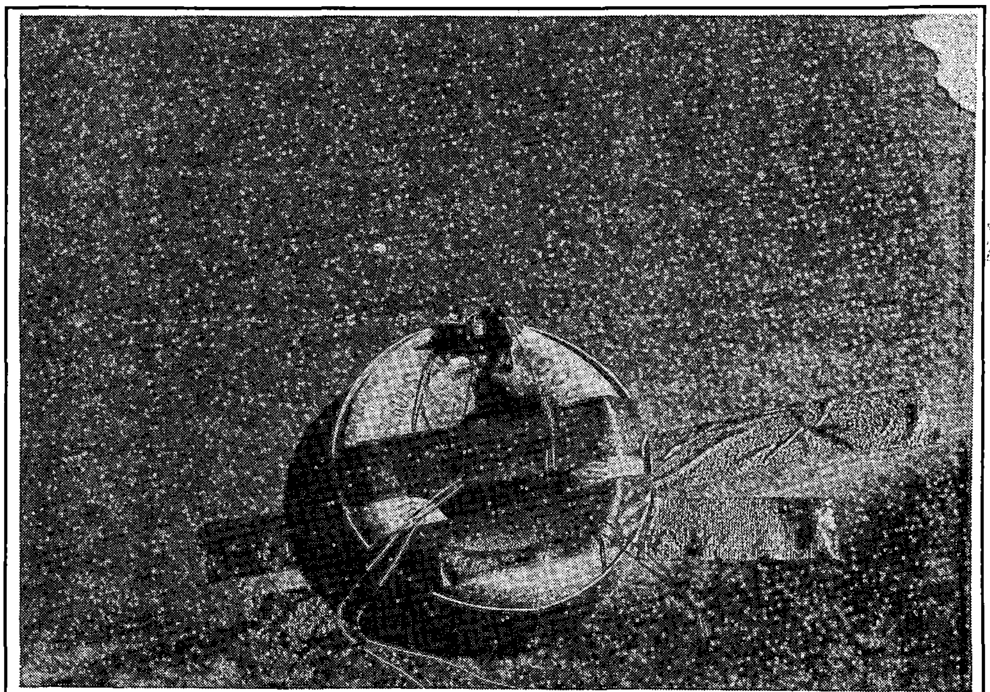

Figure 27. Application of 5,400 gr/ft Foam-sheathed Charge to Tank Vapor Space, Before Test 11

This test was successful, cutting a 7-inch-circular hole, with an approximate 2- by 4-inch triangular tear at the initiation point. There was also a small, thin tear, approximately 1 inch long, directly opposite the initiation point. Figure 28 shows the resultant hole from Test 11; the smaller tear is marked by a white arrow. Figures 27 and 28 were photographed from approximately the same vantage point.

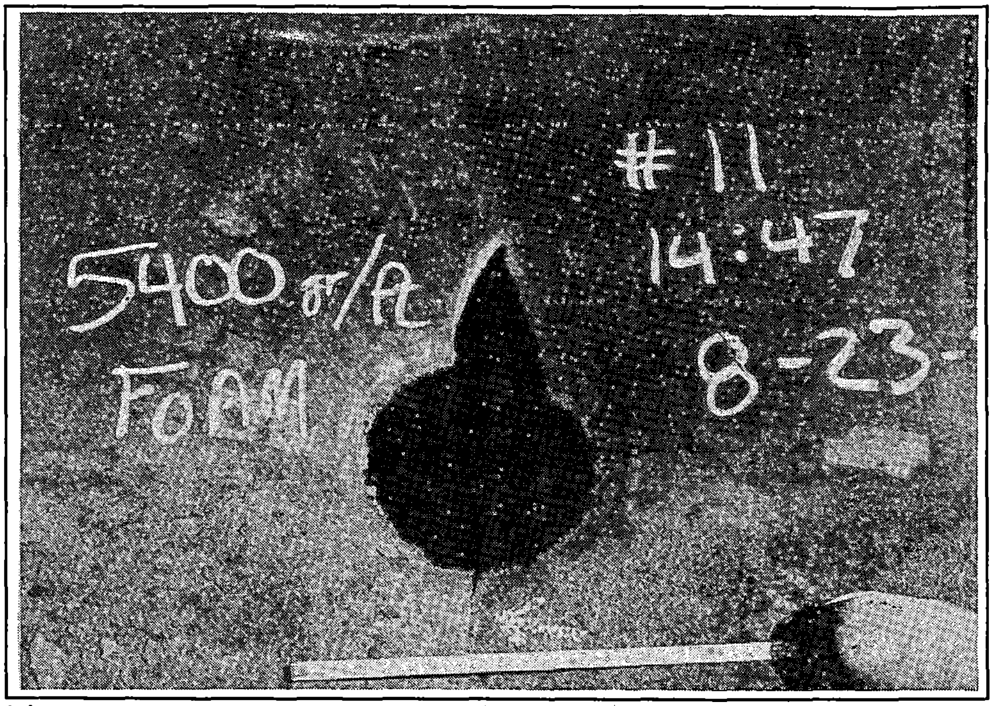

Figure 28. Test 11 Results -- 5,400 gr/ft Foam-sheathed Charge on Pressure Car Vapor Space, No Internal Pressure

TEST 12

Test 12 was conducted on August 23, 1993, to test the ability of 3,600 gr/ft foam-sheathed RDX explosive to cut through the pressure tank car shell. This charge was applied to the unpressurized tank car DUPX 26761. The charge was shaped using a steel ring and applied as mentioned in Test 11. The gap on this charge was also filled with det sheet.

This test was unsuccessful. The metal was fully cut at some portions of the charge perimeter, but elsewhere the surface was only pitted by the cutting jet. Figure 29 displays the results of Test 12. It may be noted that no surface damage occurred under the area of the charge filled with det sheet.

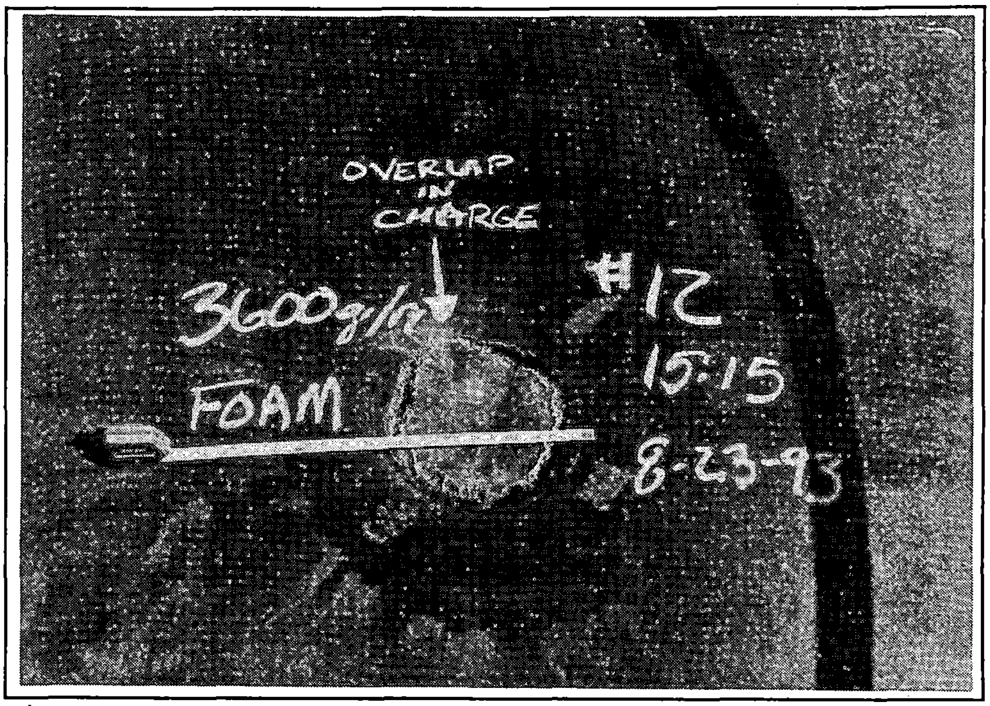

Figure 29. Test 12 Results -- 3,600 gr/ft Foam-sheathed Charge on Pressure Car Vapor Space, No Internal Pressure

TEST 13

Test 13 was conducted on August 23, 1993. Its objective was to test the 5,400 gr/ft foam-sheathed explosive placed on the bottom portion of the tank shell, under liquid (water) head pressure. The test car was DUPX 26761. The charge was applied on a portion of the tank with no sprayed-on thermal protection. A metal band was used to assure charge orientation, as performed with Test 11. Figure 30 displays the explosive charge placed on the liquid space of the tank.

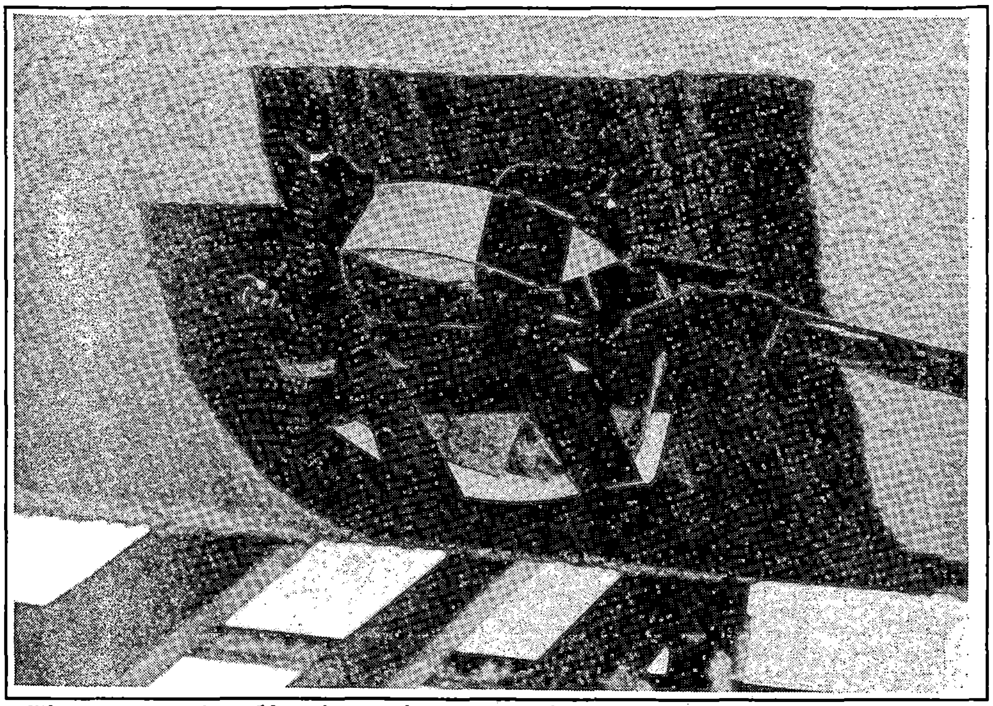

Figure 30. Application of 5,400 gr/ft Foam-sheathed Charge on Liquid Space of Tank, Before Test 13

The test was successful, cutting a 7-inch hole in the tank in the liquid space. There was no significant tearing at the charge initiation point or at a point opposite it, where the two detonating fronts met. Figure 31 presents the resultant puncture hole after tank drainage.

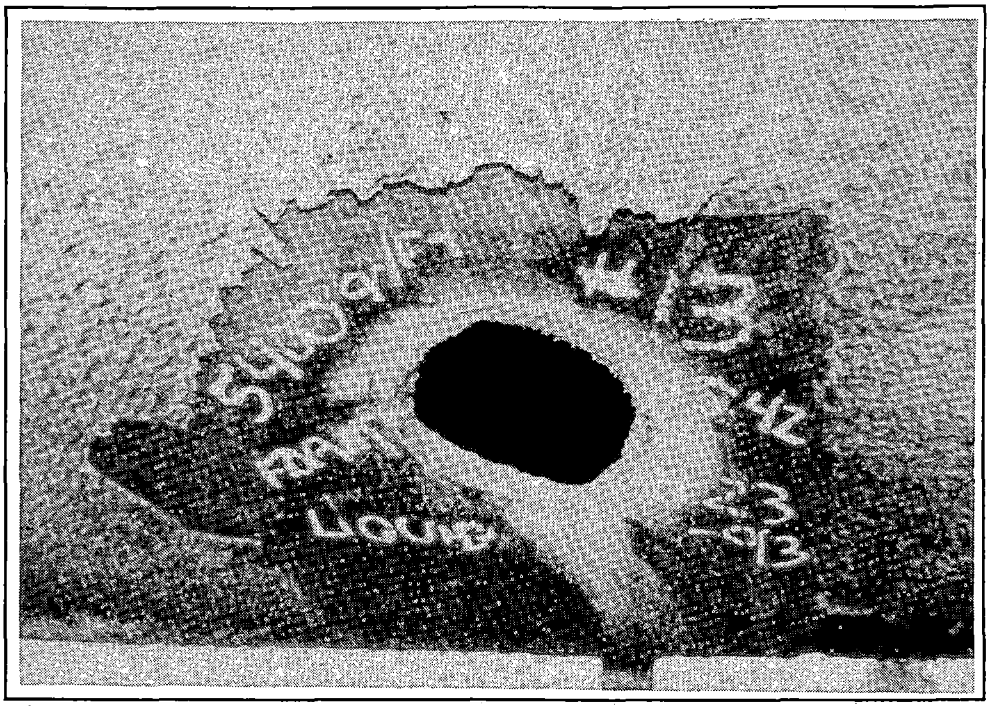

Figure 31. Test 13 Results -- 5,400 gr/ft Foam-sheathed Charge on Liquid Space of Tank

The test tank car's top surface was cut during Test 10, and this hole allowed direct measurement of the tank internal fluid level during tank drainage. Water depth measurements were recorded at various times throughout draining. Fluid level data was later compared to theoretical calculations. All water drained from the tank 52 minutes after detonation. Figure 32 shows water exiting the tank through the cut hole; the water flow rate pictured is approximately 25 gallons per second.

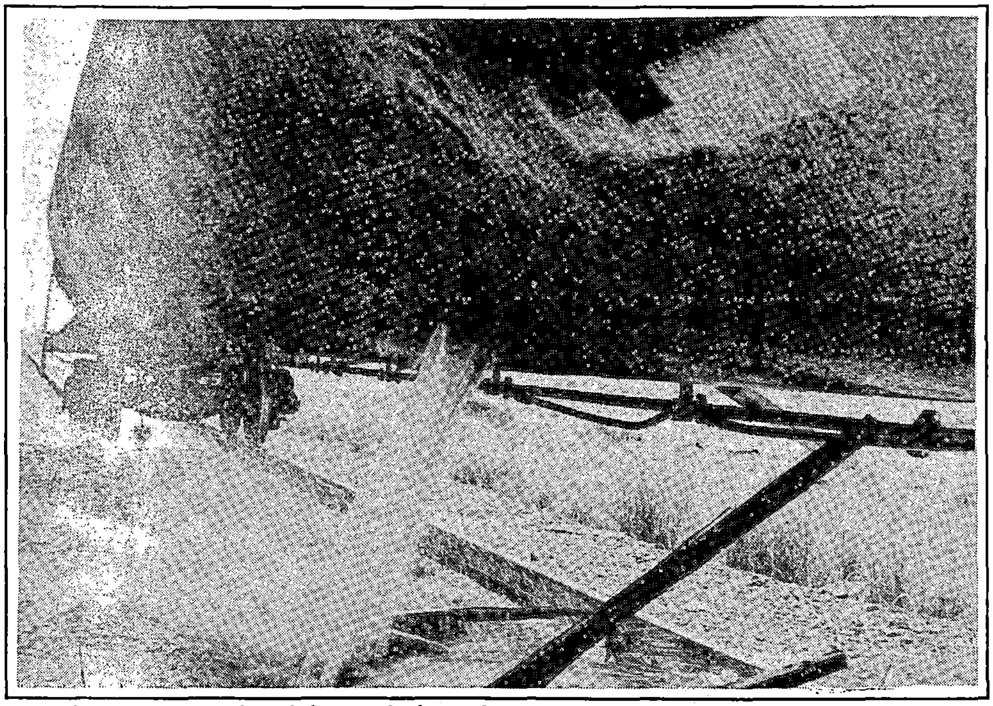

Figure 32. Liquid Draining from Tank Car after Successful Cutting, Test 13

TEST 16

Test 16 was performed on the bottom of the tank car DUPX 20462, under the liquid space, to replicate Test 13. This test provided a second measure of full scale tank drain times for a 33,500-gallon tank. The test date was September 28, 1993.

A 5,400 gr/ft foam-sheathed charge was used, formed into a circular shape. No det sheet was inserted at the junction of charge ends.

Duct tape was used to hold the charge into the desired shape as no metal rings were available. The tape allowed the foam to roll slightly and shift the explosive focus angle away from normal to the tank surface. Wood bracing was used to hold the charge in place.

The detonation failed to cut approximately 2 inches of the coupon perimeter below the det sheet. The freed portion of the coupon was forced into the tank, but was held by the uncut metal and partially blocked the exiting flow. Actual flow area was approximately 21 square inches, 55 percent of the anticipated area.

Internal tank water depth was recorded over the course of tank drainage for comparison to theoretical calculations. Total drain time was slowed due to the smaller exit area. The drainage time during Test 16 was comparable to that recorded during Test 13, however. The final drainage occurred in 1 hour 7 minutes.

Figure 33 displays the resultant liquid drain hole from Test 16. The uncut area of the coupon is marked by a white arrow.

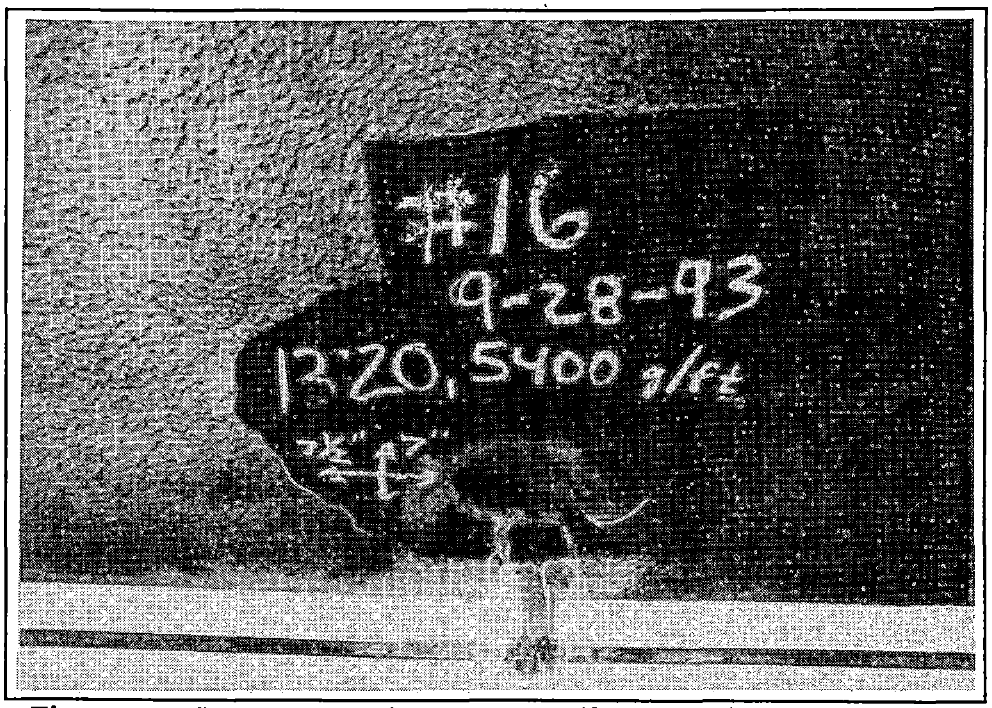

Figure 33. Test 16 Results -- 5,400 gr/ft Foam-sheathed Charge Applied to Liquid Space of Tank Car

TEST 17

Test 17 used 5,400 gr/ft foam-sheathed RDX to cut tank car DUPX 26770 pressurized to 100 psi with air; the charge was placed on top of the tank car over the compressed air space. The foam was bent into a circular form and held to shape with a metal ring. The junction of charge ends was well packed with det sheet to assure uniform detonation around the entire charge. The test date was October 6, 1993.

The explosive successfully cut the tank shell, forming a 8 1/2-inch by 7 1/2-inch elliptical hole. The tank material was torn bluntly under the point of charge initiation and a sharp, thin crack, 3 1/2 inches long was formed on the opposite side of the hole, where the detonation wave fronts met. Figure 34 shows the resultant tank hole from Test 17.

Figure 34. Test 17 Results -- 5,400 gr/ft Foam-sheathed Charge Applied to Vapor Space of Tank Car, 100 psi Internal Pressure

Compressed air discharge time was recorded at between 6.5 and 7.0 seconds. Times were marked between detonation and the loss of sound from venting.

TEST 18

Test 18 was performed on October 6, 1993, with a 5,400 gr/ft foam-sheathed charge applied to the bottom, bare-metal surface of DUPX 26770. The test was designed as a repeat of Tests 13 and 16.

The charge was attached to the tank with an epoxy compound applied to the bottom of the foam. A metal ring was used to hold the charge in the proper shape during epoxy curing, but removed for photographic purposes before detonation. The epoxy cured within about 10 minutes and firmly held the charge in the proper shape and orientation without the metal ring. The charge was well packed with det sheet, approximately 6 square inches at 1/16 inch thickness, as with Test 17.

The charge was mounted on the tank and caps placed within the RDX prior to the detonation of Test 17 on the upper surface of the same tank car. The detonation of the Test 17 charge did not dislodge or detonate the Test 18 charge. This confirmed the ability to place the vapor vent charge and the liquid drain charge on the tank at the same time, reducing the safety risk to the explosives technicians.

The charge successfully cut the tank shell in a 7-inch by 7 3/4-inch elliptical shape. A small area of metal tear occurred under the point of charge initiation, but followed the general elliptical perimeter shape.

Internal tank water depth was recorded periodically during tank drainage for comparison to theoretical drain rates.

TEST 19

Test 19 was performed on car DUPX 26740, in a re-creation of Test 17. The tank was pressurized to 100 psi with air over a 19-percent outage of water. The test date was October 6, 1993.

A 5,400 gr/ft foam-sheathed charge was prepared, well-packed with det sheet (again, near 6 square inches of 1/16-inch-thick material), and placed on the top surface of the tank shell. A metal ring was used to assure charge shape and orientation relative to the tank.

The charge cut a 7 1/2-inch-round hole in the tank shell. No surface tearing occurred around the hole perimeter; the cut was generally very clean.

The compressed air vented in between 7.2 and 7.4 seconds. Times were marked between detonation and the loss of sound from venting.

<u>TEST 20</u>

Test 20 was used to verify the ability to explosively cut through spray-on insulation. A 5,400 gr/ft foam-sheathed charge was placed on the side of car DUPX 20462 over spray-on thermal protection approximately 1/8 inch thick. The tank was empty.

Epoxy was used to secure the charge to the thermal protect. The epoxy held firmly on the rough surface.

The charge successfully cut the tank surface through the thermal protection. A rough 7 1/2-inch-round hole was formed, with a 6 1/2-inch by 4-inch by 6 1/2-inch triangular tear formed under the point of charge initiation. The spray-on thermal protection near the hole was separated from the tank and hung loosely. Figure 35 displays the results of Test 20.

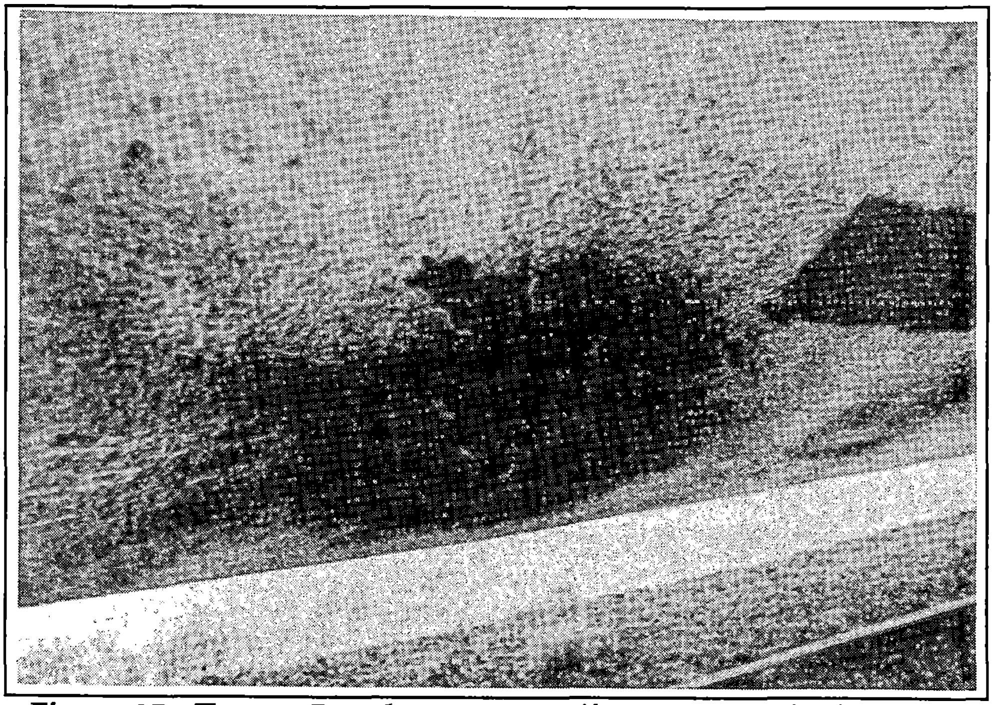

Figure 35. Test 20 Results -- 5,400 gr/ft Foam-sheathed Charge Applied to Vapor Space of Tank Car, over Spray-on Thermal Protection

Test 22

Test 22 was performed on October 22, 1993, with a 5,400 gr/ft foam-sheathed RDX charge applied to the bottom surface of DUPX 26740. The charge was separated from the tank shell by 1/8-inch spray-on thermal protection.

The charge was attached to the tank with an epoxy compound applied to the surface of the foam. A metal ring was used to hold the charge in the proper shape. Duct tape was used to help secure the ring to the tank during epoxy curing. The charge had been cut to minimize the gap at the charge end junctions; det sheet was well-packed at this smaller junction. The charge was detonated by two electrical caps placed near the charge ends.

The charge successfully cut the tank in 6 1/2-inch by 7-inch elliptical-shaped hole. A small region of metal tearing occurred under the point of charge junction, but it was smaller in size than the area of tearing seen after Test 18. A small, thin tear formed opposite the point of charge initiation, as seen during Tests 11 and 17.

Internal tank water depth was recorded periodically during tank drainage for comparison to theoretical drain rates.

10.4.2.1 Conclusions, Foam-sheathed Charges on Full Scale Tank

The following conclusions can be drawn as to the applicability of using foam-sheathed RDX explosives to cut a pressure tank car.

- 5,400 gr/ft foam-sheathed RDX explosive, formed into a circular shape, was successful in cutting 0.669-inch TC-128B, Grade B normalized steel forming the barrel portion of a tank car shell.
- The 5,400 gr/ft charge was unaffected by internal vapor pressures, internal liquid pressures, or spray-on thermal protection up to 1/8 inch thick.
- 3,600 gr/ft foam-sheathed RDX explosive did not successfully cut a pressure tank car.

- Careful attention must be paid to the installation and orientation of the explosive charge. It is recommended that the charge be applied to the tank with a layer of epoxy adhesive (weather permitting) to assure thin, uniform attachment. A metal or hard plastic retaining ring is recommended to prevent expansion or rolling of the charge.
- Large quantities of det sheet or other explosive booster compound need to be applied to regions of discontinuity in explosive material. Poor continuity may result in tank material tearing or cutting failure.
- The vapor vent charge and liquid release charge may be placed on the tank car at the same time, reducing the safety risk to the explosives technicians. The detonation of the vapor charge will neither detonate nor displace the liquid release charge if it is secured properly.

10.4.3 Tests on Head Shields

Some tank car orientations resulting from derailments may present the tank head as the most convenient point of entry into the tank car. Tests were undertaken to determine the correct charge to cut a tank car head shield to gain access to the actual tank surface. Table 11 presents the test results. Positive test results are marked by a plus sign (+), a minus sign (-) indicates test failure, and a blank cell represents no test.

Table 11. Results of Head Shield Cutting Tests

Test Number	Spray-on Thermal Protection	2,400 gr/ft Foam	3,600 gr/ft Foam	5,400 gr/ft Foam
14	•	—		
15	•		—	
21	•			+

TEST 14

Test 14 was conducted on September 27, 1993, on the 1/2-inch-thick half head shield at the A end of DUPX 20462. The shield was completely coated with spray-on thermal protection, 1/8 inch thick. A 2-foot section of 2,400 gr/ft foam-sheathed RDX explosive was formed into a circular shape and attached to the head shield with two-way tape. Two blasting caps were used to initiate the charge; det sheet was used as a filler at the meeting point of the circular charge.

This test was not successful. The detonation scarred the head shield over the entire perimeter of the charge, but full cutting occurred only in small, localized areas.

TEST 15

Test 15 was also conducted on the A-end head shield of DUPX 20462 on September 27, 1993. The charge for this test was 3,600 gr/ft foam-sheathed RDX explosive. The adhesive on this charge was not strong enough to hold the charge in place; duct tape was used to hold the charge in a circular form and attach the explosive to the head shield. No metal retaining ring was used and the foam material wanted to roll away from the head shield. The charge was re-taped to reduce this rolling effect.

This test failed to make a complete circular cut. The majority of the coupon perimeter was cut and pushed in toward the tank head. However, one side of the coupon remained attached to the head shield. Figure 36 shows the results of Test 15.

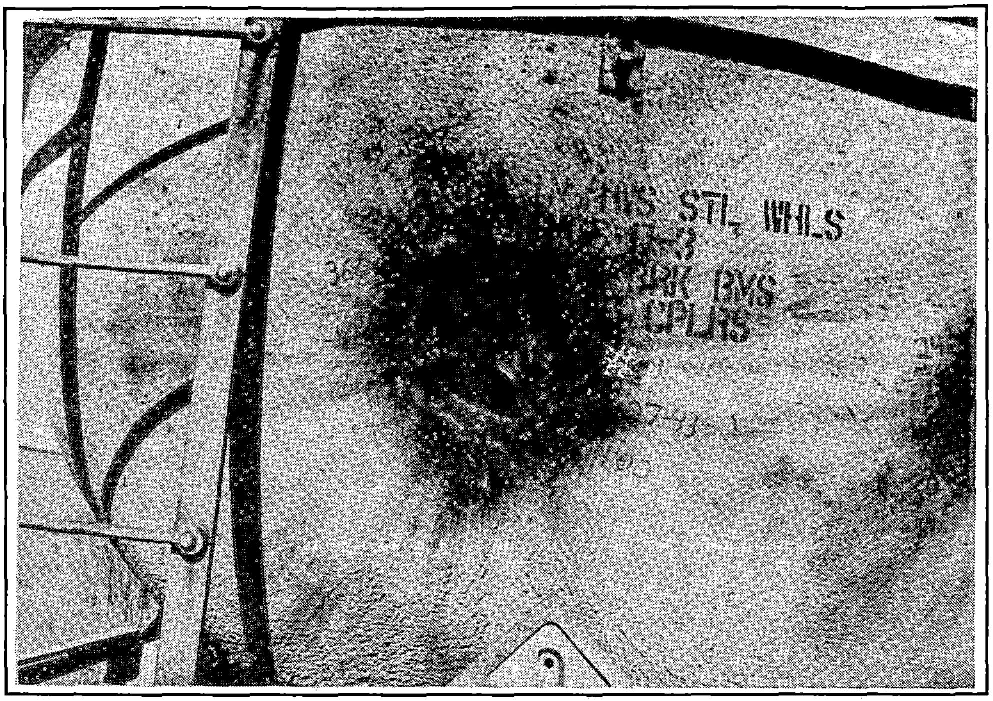

Figure 36. Test 15 Results -- 3,600 gr/ft Foam-sheathed Charge Applied to Half Head Shield, over Spray-on Thermal Protection

<u>Test 21</u>

Test 21 was conducted on October 22, 1993. A charge of 5,400 gr/ft foam-sheathed RDX was used to cut through the A-end head shield of DUPX 20462. The head shield was completely coated in 1/8-inch spray-on thermal protection.

A 4-foot-long section of charge was formed into a circular shape and banded by duct tape. The charge was long enough and bending gradual enough that no significant charge rolling was encountered. Tape had sufficient strength to hold the charge in a circular shape without the assistance of a metal ring. The charge was held on to the head shield by a combination of pre-applied tape, epoxy, and duct tape. Det sheet was placed at the charge junction; two electrical blasting caps were used to detonate the explosive.

The test successfully cut the head shield and dislodged a 15-inch by 16 1/2-inch elliptical-shaped coupon. The coupon perimeter was cut by the explosive gas jet; once freed, the body of the coupon was forced against the tank head. The rough cut coupon edges were visibly deformed from hitting the tank head and the head itself was dented up to 1 inch inward by this impact. The coupon rebounded and flew away from the tank head, striking the ground 13 1/2 feet from the tank head. The coupon skipped and came to rest 23 feet from the tank head.

The tank head showed minor pitting formed by the explosive cutting jet. These pits were localized to one corner of the coupon perimeter. The tank head showed only superficial marks due to the impact of the coupon edges. The total force of the explosion caused a smooth denting of the tank inward, up to 1 inch.

The head shield had a small region of metal tearing under the point of charge initiation; it was roughly trapezoidal in shape, 1 1/2 inches wide (along perimeter) and 1/2 inch high (away from coupon center). A narrow tear, 1 1/2 inches long, occurred opposite the point of charge initiation. The perimeter of the coupon cut was bent into the tank 2 to 3 1/2 inches. The thermal protection was loosened from the head shield near the area of cutting. Figure 37 shows the resultant cut of Test 21.

Figure 37. Test 21 Results -- 5,400 gr/ft Foam-sheathed Charge Applied to Half Head Shield, over Spray-on Thermal Protection

10.4.3.1 Conclusions, Testing on Head Shields

The following conclusions can be drawn as to the applicability of using foam-sheathed RDX explosives to cut a tank head shield.

- 5,400 gr/ft foam-sheathed RDX explosive, formed into a circular shape, was successful in cutting 1/2-inch-thick steel forming the tank head shield. Spray-on thermal protection, 1/8 inch thick, did not prevent cutting. Damage to the tank head behind the explosive charge was minor.
- The hole cut in the head shield must be a minimum of 15 inches in diameter to allow placement of a second cutting charge on the tank head through the cut hole. This requires approximately 4 feet of explosive material.
- Cutting the head shield could compromise severely damaged tank cars, causing premature or even uncontrolled release of product.
- Due to the excessive explosive material requirements and potential risks, it is recommended that the head shield not be cut during field response. All cutting charges should be placed directly on the barrel portion of the tank car shell.

10.5 CUSTOM EXPLOSIVE CHARGES

Explosive charges that were successful during preliminary tank head tests did not work successfully on barrel portion of the full scale tank car shell. This unexpected result prompted DRI to invite a representative from Francis Associates Ordnance Company of Denver, Colorado, to observe testing. Cutting failure occurred at regions of charge or sheathing discontinuity, namely the insertion points of the blasting caps and the segment joints. It was proposed that Francis Associates Ordnance Company could fabricate a copper-sheathed RDX charge in the shape of a continuous, seamless circle. The product, to be in the range of 1,400 to 1,800 gr/ft and 72- to 90-degrees angle, was thought to hold great promise in providing a solution to tank car cutting.

Francis Associates Ordnance Company was thus contracted to deliver six custom charges for testing at TTC. Francis encountered unforeseen technical difficulties in charge development and could not provide working charges within the resource constraints of this project.

10.6 COMPARISON OF ACTUAL VERSUS PREDICTED VENT TIMES

Vapor discharge was timed during Tests 5, 6, 17, and 19. Actual venting was assumed to occur between the sound of detonation and the loss of sound of vapor discharge. No instrumentation could be placed near the explosive charge to monitor vapor release quantitatively.

Post-test estimates of expected vent times were calculated with the model described in Section 8.2. For Tests 5 and 6, internal tank air temperature was estimated to be 80°F; the temperature was estimated to be 60°F for Tests 17 and 19. The barometric pressure was estimated to be 13.0 psia for all tests (TTC is roughly 4,800 ft above sea level).

Tests 17 and 19 provide the best record of vent times; both tests vented 100 psi of air through 50- and 44-square-inch holes, respectively. Test 17 vent time was estimated by the model at 6.8 seconds for 14 percent vapor space, within the range of recorded vent time (6.5 seconds to 7.0 seconds). The loss of noise from the venting was hard to mark and thus was recorded as a range of times. Test 19 vent time was estimated at 7.8 seconds for 14 percent vapor space. The recorded time was between 7.2 and 7.4 seconds. The vapor exit velocity will decrease near the end of venting and the noise will quiet significantly. The recorded vent times are likely to be shorter than actual due to the inaccuracy of the measurement technique. Table 12 summarizes actual and modeled (estimated) vent times.

Table 12. Comparison of Estimated to Actual Vapor Vent Times

Test Number	Actual Vent Time (seconds)	Post-test Estimate (seconds)
17	6.5 to 7.0	6.8
19	7.2 to 7.4	7.8

Tests 5 and 6 vented 250 psi and 225 psi, respectively, through partially cut vent holes. The exit area for Test 5 was approximated to be 0.625 square inches; the exit area for Test 6 was approximated to be 1.15 square inches. Vent time for Test 5 was modeled to be 10 minutes 22 seconds as compared to a recorded time of 8 minutes 30 seconds. Vent time for Test 6 was modeled to be 9 minutes 35 seconds as compared to a recorded time of 8 minutes 40 seconds. The discrepancy in times can be accounted for with a vent area measurement error of less than 20 percent or a prematurely recorded loss of vent noise.

10.7 COMPARISON OF ACTUAL VERSUS PREDICTED LIQUID DRAIN RATES

Data was recorded during Tests 13, 16, 18, and 22 to document the internal tank fluid level over time as the water drained from the tank. A time history of the actual fluid level could be compared to theoretical predictions.

The drain model described in Section 8.3 is only valid for fluid filling the entire exit hole area. Actual tank car drain holes were cut some 3 to 10 inches above the tank bottom. "Drain times" could not be recorded during field experiments due to an inability to detect the water level reaching the top of the exit hole. Instead, a final drain time can be interpolated from the time history plots of in-tank water levels. The slope of the time history plot will change suddenly as the water level reaches the top of the drain hole and exiting fluid can no longer fill the entire hole area. The exit area decreases, and with it, the tank drain rate.

Test 13 drained DUPX 26761 through a 38.5-square-inch (7-inch diameter) hole from an initial outage of 20 1/2 inches (12 percent). The coefficient of discharge was found to be approximately 0.63. Final drain time was marked at 27 minutes.

Test 16 drained DUPX 20462 through a partially cut hole from an initial outage of 29 1/2 inches (21 percent). The exit area was estimated from measurements of the tank car to be approximately 21 square inches. The coefficient of discharge was found through data regression to be approximately 0.55. Final drain time was then interpolated to be 51 minutes. Figure 38 compares actual to theoretical water levels for Test 16.

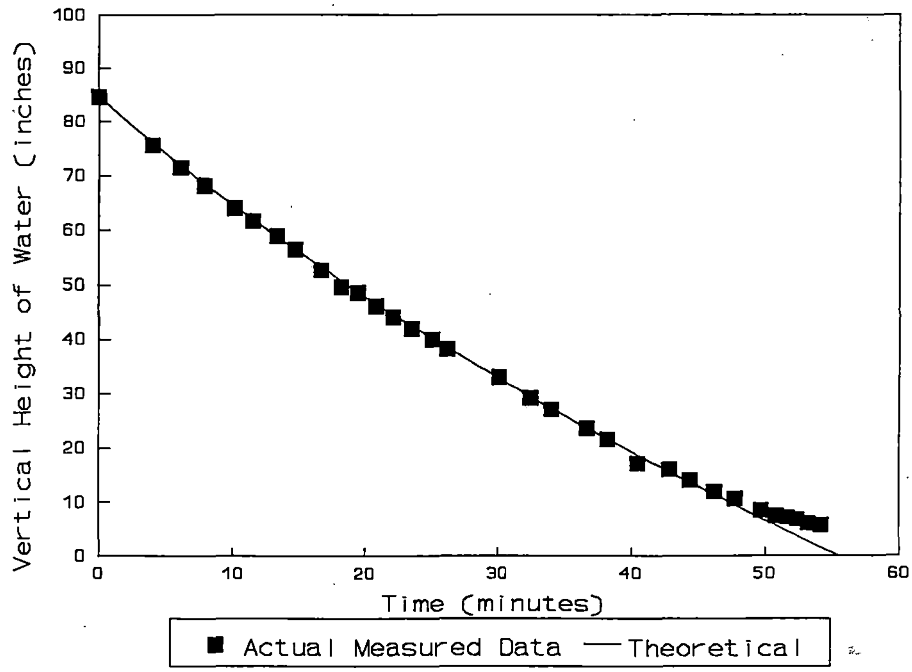

Figure 38. Comparison of Actual Liquid Drain Time History to Theoretical Predictions, Test 16

Similar data was recorded for Test 18 on DUPX 26770. Initial tank outage was 22 1/2 inches (14 percent). Exit area was measured to be 41.3 square inches (7 1/4-inch diameter). The coefficient of discharge was found to be 0.55. Final drain time was interpolated at just over 27 minutes.

Test 22 drained DUPX 26740 through a 35.8-square-inch hole (6 3/4-inch diameter). Initial tank outage was 22 1/2 inches (14 percent). The coefficient of discharge was found to be 0.58. Final drain time was found to be 31 minutes. Figure 39 compares actual to theoretical water levels for Test 22.

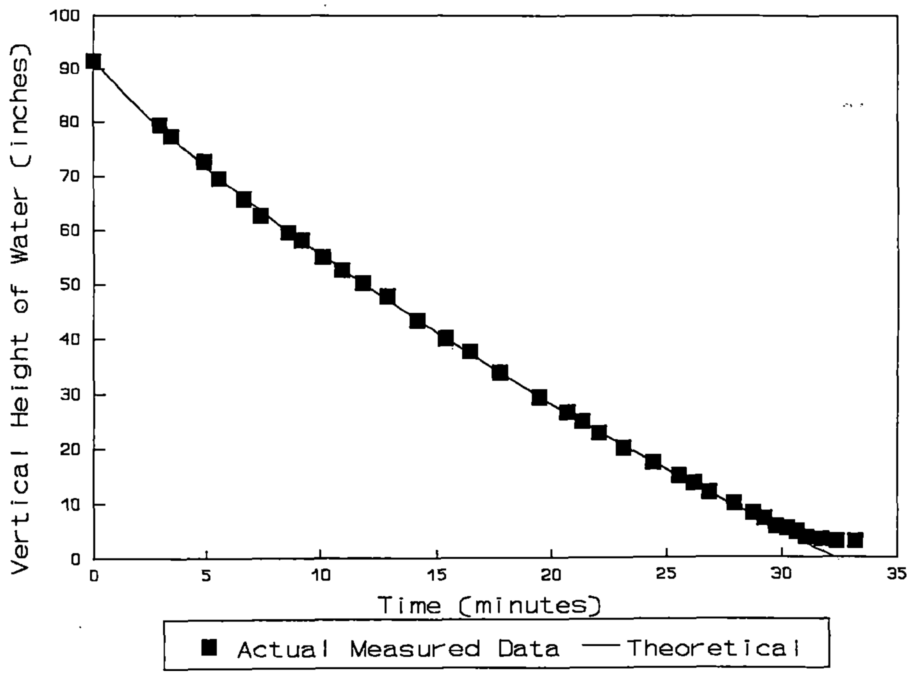

Figure 39. Comparison of Actual Liquid Drain Time History to Theoretical Predictions, Test 22

A departure from theoretical time histories was noted below 15 inches standing water in both of the above graphs. The fluid flow rate is sufficiently low at this point for the roughness of the exit hole to have a significant effect. The coefficient of discharge begins to decrease, reflecting the metal curl at the hole edge. Once the water level passes below the top of the exit hole, effective exit area is dramatically altered and deviance from theoretical drainage is expected. The plateaus seen in Figures 38 and 39 indicate that the fluid level has reached the bottom of the exit hole and drainage has practically stopped.

The average coefficient of discharge was found to be 0.587 for Tests 13, 18, and 22, during which clear tank cutting was achieved. Including Test 16, the average coefficient of discharge was found to be near 0.58.

In fluid drain tests, the theoretical fluid levels matched actual field measurements with great accuracy. Pre-test estimates could be made of final drain time based on a coefficient of discharge of 0.62 and a tank bottom exit hole of 7-inches diameter. Post-test estimates could be made based on actual exit areas, coefficients of discharge, and height of the top of the exit hole. Table 13 compares pre-test, post-test, and actual (interpolated) drain times.

Table 13. Comparison of Estimated to Actual Drain Times

Test Number	Pre-test Estimate (minutes:seconds)	Actual Drain (minutes)*	Post-test Estimate (minutes:seconds)
13	28:42	27	26:54
16	26:59	51	50:24
18	28:18	27	26:36
22	28:18	31	30:40

* Times approximated from time history plots.

11.0 HANDBOOK FOR FIELD APPLICATION OF VENT AND BURN

The AAR has produced a handbook entitled "Field Product Removal Methods for Tank Cars," under Task E of FRA Task Order 31. This document currently describes the general procedures recommended for the application of Vent and Burn method of field product removal.

Current testing has quantified actual procedures and explosive charges for use during Vent and Burn. The conclusions and recommendation of this program have been documented in a procedural guide entitled "Handbook for Vent and Burn Method of Field Product Removal," report DOT/FRA/ORD-94/18.

12.0 CONCLUSIONS

The following conclusions can be drawn from the course of this test program:

- Vent and Burn is an inherently dangerous process. It should be considered only as a final option of field product removal and then only under the strict adherence to product applicability and procedural guidelines.
- The vapor vent explosive cutting charge should be placed on the highest point of the barrel portion of the tank shell, avoiding any structural reinforcements.
- The liquid release explosive cutting charge should be placed on the lowest point of the barrel portion of the tank shell, avoiding any structural reinforcements or eduction pipes.
- The liquid discharge hole should be targeted at 7-inches diameter. A hole this size should drain the tank before dangerous heating and product expansion could occur to compromise the tank.
- The vapor vent hole should be targeted at 7-inches diameter. This will reduce responder inventory to one size of explosive charge while providing sufficient discharge area to (1) quickly vent tank internal pressure, and (2) equalize tank internal pressure during liquid drainage.
- Tank car jacket material should be cut with 300 gr/ft foam-sheathed RDX explosives. Jacket holes should be 15 to 18 inches in diameter. Detonation should be achieved with a minimum of one blasting cap and det sheet. The charge should be secured to the tank with a thin adhesive, tape, magnets, or external bracing -- the stand-off distance should not be altered. Weather conditions may affect charge attachment.
- All fiberglass insulation and/or ceramic thermal protection material must be removed by response personnel before placement of the final charge on the tank shell. All types of spray-on thermal protection should be removed, if possible. Thicknesses up to 1/8 inch were not seen to affect the charge cutting ability.
- Tank car shell materials up to 25/32 inches thick should be cut with a 5,400 gr/ft foam-sheathed RDX explosive. Detonation should be achieved with a minimum of two Number 6 Engineering Special (or better) blasting caps. All discontinuities in explosive material must be joined with explosive booster such as det sheet.

- Explosives suppliers must be consulted for the availability of charges able to cut tank car materials between 25/32 inches and 1 1/4 inches thick; 5,400 gr/ft is currently the strongest foam-sheathed explosive manufactured by NAX. Such charges should be applied in a similar manner to the 5,400 gr/ft foam-sheathed RDX.
- Epoxy is recommended to bond the charge to the tank surface. Tapes tend to become fouled and may not provide consistent, continuous adhesion. Other bonding compounds may increase the stand-off distance beyond an effective range. External bracing may be needed to hold the charge in place depending on weather and tank surface conditions.
- A metal or hard plastic ring is recommended to hold the charge in a closed, circular form. Such a ring also prevents the charge from rolling away from a normal orientation to the tank surface.
- The vapor vent charge and liquid release charge may be placed on the tank car at the same time, reducing the safety risk to the explosives technicians. The detonation of the vapor charge will not detonate or displace the liquid release charge if it is secured properly.

Foam-sheathed explosives are easy to work with, achieve the desired results, and are not exorbitantly expensive. They have a shelf-life of approximately 5 years. According to the manufacturer, these explosives can be used effectively within a wide-range of temperatures, and can even be applied and used under water. They require a minimal amount of configuration and application time, thus reducing the time a technician is exposed to a hazardous situation.

13.0 RECOMMENDATIONS FOR FURTHER RESEARCH

The following recommendation are made to continue research related to Vent and Burn procedures.

- NAX should be contacted in regards to the manufacture of a seamless, circular-shaped foam-sheathed RDX explosive charge. Such a charge could be pre-sized to the desired 7-inch-diameter hole size. The foam rolling problem would be avoided and the chance of partial tank cutting or tearing would be reduced. Charge application would be simplified and detonation could be performed with one blasting cap and minimal det sheet.
- To further quantify Vent and Burn procedure, it should be performed on an actual tank car filled with actual product such as propane. Such a test would confirm the conclusions of this report under field conditions.

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DEFINITION OF TERMS

Blasting Cap -	A small, sensitive explosive device designed to initiate/detonate larger, stable explosive charges. It is ignited by an electrical current or by a physical fuse.
Combustible Liquid -	By U.S. Department of Transportation definition, it is a liquid that has a closed cup flash point between 100°F (38°C) and 200°F (93°C).
Compressed Gas -	A material that meets one or more of the following criteria: (1) it is a gas at 68°F (20°C) or less at 1 atmosphere of pressure; (2) it exerts 41 psig at 68°F; (3) it has a boiling point of 68°F or less at 1 atmosphere of pressure.
Corrosive -	A material that has a destruction rate of 1/4 inch per year on steel or aluminum at a test temperature of 131°F (55°C).
Cutting Jet -	A high velocity jet of material formed from the detonation of an explosive material. This jet heats and displaces the target material, cutting it.
Detonation Sheet -	An explosive material designed to aid a blasting cap initiate a larger charge or to enhance detonation across a seam in explosive material. Made as a flexible sheet of various thicknesses ranging from 0.04 inch (1 millimeter (mm)) up to 0.333 inch (8 mm). It is referred as "det" sheet.

DEFINITION OF TERMS (continued)

Flammable Liquid -	A liquid with a closed cup flash point of less than 100°F (38°C).
Grains per foot (gr/ft) -	The amount of explosive material, measured by weight in grains, found in a linear foot of manufactured explosive charge. 7000 grains = 1 pound.
Inhibitor -	An agent added to a material to prevent rapid chemical reaction of that material with itself under normal conditions. May lose effectiveness with temperature.
Insulation -	A material used to slow the transfer of heat energy. Typically a blanket material applied to the outside of a container to help maintain its temperature.
Jacket -	The sheet metal used to hold the insulation/thermal protection in place against the tank car.
Jet forming angle -	The orientation angle of two faces of explosive material within a shaped charge.
Linear shaped charge -	A shaped explosive charge arranged in a straight line.
Oxidizer -	A compound that does not burn itself, but releases oxygen to support combustion if the material is heated or mixed with an organic material.

Poison-Inhalation Hazard -	A material that is known to be so toxic through inhalation by humans as to pose a hazard to health during transportation (DOT), or presumed to be toxic to man based on laboratory animal tests.
Polymerization -	Reaction of a compound with itself, uncontrollably forming heat and pressure.
RDX -	An explosive composed of Cyclonite (cyclo-1,3,5-trimethylene-2,4,6-trinitramine), Trimethylentrinitramine, and Hexagene.
Shaped Charge -	Explosive material arranged in a specific geometry to enhance the force of detonation. Allows deeper and more precise cutting with a limited amount of explosive material.
Stand-off -	The distance from the leading edge of the explosive material to the target. The stand-off allows the explosive forces to focus and to form an optimal cutting jet at the target surface.
Tank Shell -	The actual structure of the tank car that holds the material in the car. The shell is the tank car body.

APPENDIX

Derivation of Tank Discharge Models

1.0 INTRODUCTION

The Federal Railroad Administration tasked the Association of American Railroads (AAR), Transportation Test Center (TTC) Hazardous Materials Training Center, Pueblo, Colorado, to research and develop safe, reliable operating procedures for the Vent and Burn method of field product removal, and to define when or if this procedure should be used in the event of tank car derailments involving hazardous materials. The Vent and Burn procedure uses explosive charges to cut holes in the damaged tank car to relieve internal vapor pressure and subsequently drain the liquid product from the car for destruction.

This document was prepared as a preliminary step to the Vent and Burn test program, to evaluate the theoretical vapor and liquid discharge rates. The relief of high pressure vapor and liquid through a rough, explosively cut hole is an extremely complex flow environment. To simplify and narrow the scope of this text, assumptions were made during model development; these assumptions are noted within the text. During field application, large variations from theoretical predictions should be expected due to environmental and product variability.

2.0 OBJECTIVE

The objective of this document is to mathematically model theoretical vapor and liquid discharge rates to be encountered during execution of the Vent and Burn emergency field product removal procedure.

3.0 IDEALIZED RAIL TANK CAR

True rail tank cars vary greatly in size, shape, and construction. The main storage volume is usually a cylinder capped with parabolic tank heads, typically of a radius twice the head depth. However, for the sake of this paper, the tank car is assumed to be a right cylinder with flat ends. Its diameter will be called D_t and it length L_t. Tank volume, V_t, is thus $\pi(D_t/2)^2L_t$. Figure A-1 shows the idealized tank used throughout this paper.

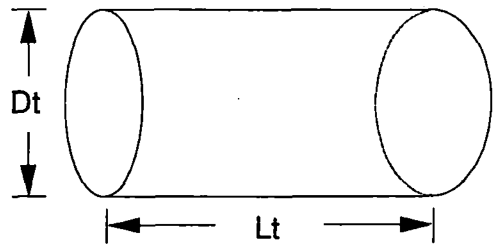


Figure A-1. Idealized Tank Car

4.0 CANDIDATE PRODUCTS

Vent and Burn is intended for some compressed gases and some flammable or combustible liquids. The physical and thermodynamic properties of each candidate product vary greatly. Each product must be researched before it can be specifically modeled.

During revenue service, tank cars may experience temperatures between of -40°F and 120°F, which may be above the nominal boiling point of many candidate products. Tank internal vapor pressure will hold these products in a liquid state during transport. Between 4- and 20-percent outage space is provided within the tank car to help account for temperature expansion of compressed gases; between 2 and 5 percent outage is maintained for liquid products.

The vapor pressure will change with tank temperature. Product-specific vapor pressure tables can be used to determine the tank internal pressure at any given tank temperature. Typically, internal tank pressures encountered during rail transport vary from 0 psi to 250 psi. Table A-1 lists vapor pressure by temperature of four candidate products.

Table A-1. Vapor Pressure by Temperature

Tank Shell Temperature (°F)	Vapor Pressure (psig)			
	Propane	Butane	Isobutane	Vinyl Chloride
70	109.7	16.5	23.9	35.3
100	173.4	36.9	48.0	NA
105	NA	NA	NA	75.3
115	213.0	50.3	63.8	90.3
130	258.4	66.0	82.3	114.3

Data from *Handbook of Compressed Gases*.[1]

Tank temperature most accurately can be found by placing a thermometer on the tank shell at a shaded location. If this is not practical, as a rule of thumb, an uninsulated tank will assume the average temperature it has been exposed to over the last 24 hours; an insulated tank will average temperatures over the last 72 hours.

5.0 CONTINUITY EQUATIONS

Vapor and liquid release from a tank car are physical systems best modeled by thermodynamics. Classical thermodynamics is governed by a set of continuity equations, conditions that must hold throughout any process. Simply, these include conservation of mass, momentum, and energy.

Of most interest to tank relief is the conservation of energy. Energy may be added to a tank by (1) the addition of heat due to proximate fires or air temperature, (2) the addition of mass, or (3) external work. Energy may be removed from a tank by (1) loss of heat to the surroundings, (2) loss of mass, or (3) external work. Lastly, the tank may store or lose energy in the form of internal temperature and pressure. Written in differential form, conservation of energy may be written as:

$$\dot{E}_i + \frac{d'Q}{dt} + \frac{d'W}{dt} = \left(\frac{dE}{dt}\right)_\sigma + \dot{E}_e \qquad (1)$$

where $\dot{E}_i$ and $\dot{E}_e$ represent energy transport per unit time into and out of the tank, respectively. $\frac{d'Q}{dt}$ and $\frac{d'W}{dt}$ are the heat addition and external work per unit time, respectively. Finally, $\left(\frac{dE}{dt}\right)_\sigma$ represents the increase in internal energy within the tank. Equation (1) will be manipulated for both vapor venting and liquid drainage.

6.0 SIMPLE VAPOR DISCHARGE

Vapor release from the tank car can be modeled by compressible, high speed flow. Conservation of energy will be used to determine the vapor exit velocity. However, gas internal energy levels are dependent on temperature, pressure, and density. The ideal gas law and an assumption of system energy gain will be used to help define gas conditions.

6.1 IDEAL GAS

The ideal gas law will be used to relate product vapor temperature, pressure, and density. State conditions for each potential Vent and Burn product should be defined in gas tables by the product manufacturer. However, to avoid excessive research, it is helpful to use the ideal gas law, PV = mRT, which relates pressure (P), volume (V), mass (m), gas constant (R), and temperature (T). It is accurate during reversible processes for most gases under 150 psi and thus is appropriate for evaluation of starting and ending gas conditions. R is the product specific gas constant found from $\mathcal{R}$, the universal gas constant and M, the gas molecular weight: R = $\mathcal{R}/M$. Gas density, ρ or m/V, also can be found from the ideal gas law.

6.2 SPECIFIC HEAT

Specific heat, a measure of a product's ability to absorb or dissipate heat energy, plays an important roll in gas expansion; two specific heat values are needed for each gas species. C_p is the constant pressure specific heat and C_v is the constant volume specific heat. γ, the ratio of C_p/C_v, is often used with gas equations. The specific heat values can typically be found in chemistry or hazardous materials handbooks. An important ideal gas assumption relates C_p to γ, meaning only one of these two values is needed. For hydrocarbons, γ is typically about 1.1:

$$C_p = \frac{\gamma R}{\gamma - 1}$$

6.3 ADIABATIC EXPANSION

The rapid, compressible expansion of gas as it leaves a tank is a non-reversible process. The ideal gas law does not hold during expansion, but only at the starting or ending conditions. However, by assuming one of the gas's physical parameters is held constant during expansion, it is easy to relate beginning and ending conditions. For gas discharge, adiabatic expansion will be assumed -- that is, no heat is gained or lost by the gas during expansion. This assumption is supported by the fact that gas specific heats are relatively low and the time required to expand each group of gas molecules is quite short.

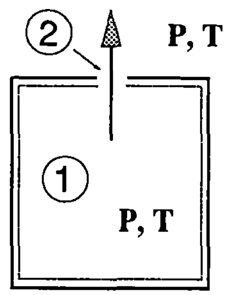
Adiabatic processes relate starting temperature and pressure (subscript 1) to ending temperature and pressure (subscript 2) as follows:

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{(\gamma-1)/\gamma}$$

$$\frac{T_2}{T_1} = \left(\frac{\rho_2}{\rho_1}\right)^{\gamma-1}$$

6.4 EXIT VELOCITY

Conservation of energy is now used to find the vapor exit velocity. Vapor release must assume quasi-steady flow, steady state ($\left(\frac{dE}{dt}\right)_\sigma = 0, \dot{m}_i = \dot{m}_e$), no external work ($\frac{d'W}{dt} = 0$) and no heat transfer into the system ($\frac{d'Q}{dt} = 0$). $\dot{E}$ is a measure of the gas internal energy, pressure, volume, and kinetic energy. The gas within the tank will contain energy mostly as internal energy, pressure, and volume; this is referred to as enthalpy or h. The exiting vapor stream will have significant energy in the form of molecular kinetic energy. The average gas stream velocity is referred to as $\overline{V}$. Equation (1) can be simplified to find:



$$\dot{E}_i = \dot{E}_e$$

$$\dot{m}_i\left(h_i + \frac{\overline{V}_i^2}{2g_c}\right) = \dot{m}_e\left(h_e + \frac{\overline{V}_e^2}{2g_c}\right)$$

$$h_1 + \frac{\overline{V}_1^2}{2g_c} = h_2 + \frac{\overline{V}_2^2}{2g_c}$$

where g_c is 32.17 lbm ft/lbf s^2.

$\overline{V}_1$ is nearly zero for discharge from a fixed tank. Solving for $\overline{V}_2$ yields

$$\overline{V}_2 = \sqrt{2g_c(h_1 - h_2)}$$

Values of h vary by gas species, temperature, and pressure; true values can come only from laboratory work. This may be simplified by the ideal gas assumptions; for an ideal gas:

$$h_1 - h_2 = C_p(T_1 - T_2)$$

Substituting for h gives

$$\overline{V}_2 = \sqrt{2g_c C_p(T_1 - T_2)}$$

Substituting for T_2 during adiabatic expansion gives

$$\overline{V}_2 = \sqrt{2g_c C_p T_1\left[1 - \left(\frac{P_{throat}}{P_{tank}}\right)^{(\gamma-1)/\gamma}\right]} \qquad (2)$$

where P_{throat} and P_{tank} are the stagnation (stopped) gas pressures in the exit hole throat and tank, respectively.

6.5 CHOKED FLOW

Equation (2) indicates that $\overline{V}_2$ is a function of the pressure difference existing between the conditions within the tank and the conditions within the throat of the exit hole of the tank. But $\overline{V}_2$ will approach a limiting value -- the local speed of sound. At this speed, exit hole geometry and shock waves hold the exit velocity constant regardless of increased pressure differential between the tank and atmosphere. This condition is known as choked flow; a complete explanation can be found in any thermodynamics textbook.

The speed of sound, c, is defined as:

$$c = \sqrt{\gamma g_c R T} \tag{3}$$

where T is the flow stream temperature. The speed of sound in the throat of the exit hole must be found from adiabatic expansion relations. Initial conditions are simply the tank internal temperature and pressure. The ending pressure is the exit hole throat stagnation pressure; for the calculation of the speed of sound, this pressure is always equal to the atmospheric pressure. If a varying P_{throat} were used during the formulation of c, a circular definition would be created that does not reflect the physical flow conditions.

The mach number, M, is the ratio of the exit stream velocity $\overline{V}_2$ to the speed of sound c. At the throat, two types of flow can thus exist: (1) $M < 1$ and (2) $M = 1$. For conditions of $M < 1$, equation (2) will dictate exit velocity. However, for $M = 1$, $\overline{V}_2$ becomes constant, equal to the speed of sound; equation (2) instead specifies P_{throat}.

6.6 MASS FLOW RATE

Once the exit velocity is known, it is easy to calculate the rate at which mass leaves the tank. Mass flow rate, $\dot{m}$, is related to vapor density, exit area, and exit velocity as follows:

$$\dot{m} = C_d \rho A \overline{V}_2 \tag{4}$$

where C_d is the coefficient of discharge, a measure of flow restriction caused by converging exit flow through a shaped orifice. Due to the size of the vent holes used in this program, C_d is assumed to be 1.0.

All quantities used in equation (4) must be evaluated at throat conditions. $\overline{V}_2$ was defined in equation (2) for natural flow and defined by equation (3) for choked flow. Throat pressure is atmospheric pressure for natural flow and defined by equation (2) for choked flow. Throat temperature is found from adiabatic expansion using tank internal conditions as reference. Throat density can be found by using the ideal gas law, $\rho = P/RT$.

6.7 SOLVING FOR TIME OF DISCHARGE

The ideal gas law can be used to calculate the mass required to exit the tank to produce a fixed internal tank pressure decrease. Assuming this mass exits the tank at a steady rate, the time required to lower tank internal pressure a finite amount can be found. If appropriately small pressure steps are used, the time required discharge the entire tank vapor pressure can be found. Gas will exit until internal tank pressure equals atmospheric.

Steady state discharge is assumed to exist over a short time period for each set of tank and throat conditions. The mass expelled during this period is

$$dm = \dot{m}\,dt \tag{5}$$

This change in mass affects the internal tank pressure by the ideal gas laws:

$$dP = \frac{RT}{V}dm \tag{6}$$

Combining equations (4), (5) and (6), dt is found in terms of dP:

$$dt = \frac{V}{C_d RT\rho A\overline{V}_2}dP \tag{7}$$

where V is the tank vapor volume, T is exit flow temperature at the throat, ρ is the vapor density at the throat, and A is the throat area. For conditions where M = 1, choked flow exists and $\overline{V}_2$ is held at c as defined by equation (3). When M < 1, natural flow exists and $\overline{V}_2$ is defined by equation (2).

The time required to vent the tank is found by integrating equation (7). But the complexity of the relations of ρ and T to P do not allow an analytical solution. Instead, numerical integration is used. The quantity *dP* can be found by appropriately stepping the internal tank pressure from initial tank pressure, P_0, to atmospheric pressure, P_{atm}. Fifty pressure steps were used for actual modeling; "i" is used to denote successive steps:

$$t_{vent} = \int_0^{t_{vent}} dt = \sum_{i=0}^{i=50} dt_i = \sum_{i=0}^{i=50} \frac{V}{C_d R T_i \rho_i A \overline{V}_{2i}} dP_i \tag{8}$$

The tank internal pressure is stepped appropriately down until no more mass leaves the tank. The time to vent the tank is the sum of the short steady state flows required to discharge all tank pressure.

6.8 VARIATION OF DRAIN TIME BY SYSTEM PARAMETERS

The above vapor flow model is complex and can be simplified by indicating the effects of individual variables on the vapor exit time. However, influences of tank internal pressure, temperature, and ambient temperature cannot be concisely stated. The exit area and coefficient of discharge do have well defined effects on vent times.

6.8.1 Exit Hole Size

Equation (8) indicates that t is inversely proportional to the exit area, a function of 1/A. The vent time can be corrected for a new area by multiplying the reference time by the factor A-reference/A-corrected. A time found for A = 28 in^2 can be corrected to A = 40 in^2 by multiplying the time by 28/40 or 0.70.

6.8.2 Coefficient of Discharge

Equation (8) indicates that t is a function of $1/C_d$. The vent time can be corrected for a new C_d by multiplying the reference time by the factor C_d-reference / C_d-corrected. A time found for a C_d = 1.0 can be corrected for a C_d = 0.90 by multiplying the time by 1.0/0.90 or 1.11.

6.9 PRACTICAL CONSIDERATIONS

The escaping vapor will be cooled dramatically by the exit velocity. Temperatures of -100°F should be expected near the exit hole surface. If the tank is actually cooled to this point, the metal may become brittle and crack more easily under the internal vapor pressure.

Alternatively, a vapor flare will heat the tank surface to over 1300°F, at which point the metal's yield strength is decreased.[2] The metal would be more likely to tear under internal pressure at this temperature.

Discharge holes should be cut in a rounded shape to avoid stress concentrations that would further promote tank cracking. Multiple holes adding to the desired exit area are acceptable.

6.10 RESULTS OF SIMPLE VAPOR DISCHARGE ANALYSIS

The following conclusions can be drawn about the release of compressed vapor from a tank car.

- Sizing of the discharge hole can be used to control the initial vapor exit velocity during natural flow conditions. During choked flow conditions, discharge velocity is held constant by exit hole geometry and vapor product physical characteristics. The vapor mass flow rate can never be held steady -- it will continually decrease unless the tank contents are affected by heat expansion.
- Vapor vent times can be found by use of numerical integration of steady-flow conditions evaluated over discrete pressure steps. Good model resolution is maintained in calculations by using 50 or more integration steps.

- The effect of a variation in a model input parameter can be seen by use of time correction factors rather than recalculating vent times. The dependence of vent drain times on exit hole size and coefficient of discharge was determined.

7.0 BOILING VAPOR DISCHARGE

Depending on accident scene temperature and barometric pressure, most compressed gases and some candidate liquid products will be held above their nominal boiling temperature by tank internal pressure. With the loss of this pressure during vapor venting, the liquid product will boil. Boiling will both cool the liquid and add significantly to the vapor volume to be vented; boiling will continue until the remaining liquid product cools to its nominal boiling boil or all product is vaporized.

With the initiation of the vapor release hole, the standing pressure above the liquid product is decreased. The liquid will spontaneously boil until the pressure is replaced or the remaining liquid is cooled to the new equilibrium temperature/vapor pressure point. Thus, for a finite loss of tank pressure, a small amount of liquid will boil to replace the lost vapor pressure. The vent time required to decrease the tank internal pressure by a finite amount will be extended to allow this additional vapor to vent -- extended by the ratio of actual, boiling-enhanced vapor mass to initial, volume-indicated vapor mass. Extending this reasoning to the entire venting process, the total tank vent time will be extended by a ratio of actual vapor vent mass to initial vapor mass.

7.1 ADDITIONAL VAPOR LOSS

Returning to the continuity equations and differential energy balance presented above, boiling is a process that balances internal energy change with the exit of mass from the system. Simplifying equation (1):

$$0 = \dot{m}_e h_e + \left(\frac{dU}{dt}\right)_\sigma$$

where h is enthalpy per unit mass and U is system internal energy. The system is defined as the entire tank contents, both liquid and vapor regions. By separation of variables, the energy balance becomes

$$\int \dot{m}_e h_e dt + \int dU = 0$$

For the relatively small temperature ranges considered during cooling, fair accuracy can be found by using an average enthalpy, $\overline{h}_e$. System energy, U, is replaced by unit mass energy, u, and system mass, m. Integrating from time 1 to time 2, the energy balance now becomes

$$\overline{h}_e(m_1 - m_2) + m_2 u_2 - m_1 u_1 = 0 \tag{9}$$

Tank conditions at time 1 are saturated vapor at the initial tank temperature. Tank conditions at time 2 are saturated vapor at the boiling point temperature. Specific values of gas properties can be found in product-specific gas tables.

Due to the mixed state (liquid and vapor) system, m and u must be expanded in equation (9). Here, x is introduced as the quality, or mass ratio of vapor within the tank. V is tank volume and v is product specific volume, the inverse of density. Subscript g is used for gaseous properties and subscript f for liquid. Listed below then are the needed relations:

$$\overline{h}_e = \frac{h_{g1} + h_{g2}}{2}$$

$$m_1 = m_{f1} + m_{g1} + \frac{V_{f1}}{v_{f1}} + \frac{V_{g1}}{v_{g1}}$$

$$x_1 = \frac{m_{g1}}{m_1}$$

$$u_1 = (1 - x_1)u_{f1} + x_1 u_{g1}$$

$$m_2 = \frac{V}{v_2} = \frac{V}{(1 - x_2)v_{f2} + x_2 v_{g2}}$$

$$u_2 = (1-x_2)u_{f2} + x_2 u_{g2}$$

From the appropriate product gas tables, values for v_{f1}, v_{g1}, u_{f1}, u_{g1}, h_{g1}, v_{f2}, v_{g2}, u_{f2}, u_{g2} and h_{g2} can be found. Using the above equations, only one unknown remains -- x_2. It can be solved for by substitution algebraically from equation (9):

$$x_2 = \frac{m_1 v_{f2}\left(u_1 - \bar{h}_e\right) + V\left(\bar{h}_e - u_{f2}\right)}{V(u_{g2} - u_{f2}) - m_1(v_{g2} - v_{f2})\left(u_1 - \bar{h}_e\right)} \tag{10}$$

The final tank quality can be used to solve for the final mass:

$$m_2 = \frac{V}{(1-x_2)v_{f2} + x_2 v_{g2}}$$

Total mass lost from the tank then becomes

$$m = m_1 - m_2 \tag{11}$$

The increase to vent time will be

$$t_{actual} = \frac{m}{m_1} t_{no\,boiling}$$

The total mass of gas exiting the tank during venting can be significantly more than the mass of vapor initially present. Additional vapor loss due to boiling and product cooling is a very real and significant process that may occur during Vent and Burn pressure release.

7.2 PREDICTED VAPOR LOSES FOR REAL PRODUCTS

Experimental study of specific products is required to compile gas tables to accurately define values of enthalpy and specific volume at various temperatures. Appropriate research was found for propane, published by Sallet and Wu.[3]

Sallet and Wu only list values of specific volume and enthalpy, but equation (10) is solved in terms of internal energy u. The definition of enthalpy is used to find u:

$$h = u + pv, \text{ or } u = h - pv$$

where enthalpy is taken as per unit mass; p is the saturation pressure, and v is the specific volume.

Modeling inputs included initial tank temperature, percentage out, and tank volume as parameters. However, useful results were compiled that are independent of tank volume. Table A-2 provides example findings for propane.

Table A-2. Estimations of Boiling Vapor Release Upon Venting Propane to Atmosphere

Temp. (°F)	Initial Outage (percent)	Exit Mass per Unit Tank Volume (lbm/ft^3)	Ratio of Final to Initial Gas Exit Mass	Final Outage (percent)
40	2	7.61	514.1	32.4
60	2	9.17	454.6	39.2
80	2	10.64	392.6	45.9
40	20	6.32	42.7	44.8
60	20	7.64	37.9	50.3
80	20	8.42	24.9	58.6

The total mass of product leaving the tank is listed as a function of the tank interior volume. Thus, the mass that must be boiled off can be calculated for any specific tank. As an example, a 30,000-gallon tank initially at 20-percent outage will discharge 7.64

pounds of propane for each cubic foot of tank volume. This will total (30,000 gallons)(0.13368 ft^3/gallon)(7.64 lbm/ft^3) or 30,640 pounds of propane, about 30 percent of the tank volume.

The ratio of final to initial gas exit mass (m/m_1 from Section 7.1) is useful in calculating the additional time required to vent the tank, as indicated above. The 30,000 gallon tank with an initial 20-percent outage of propane will take 37.9 times longer to vent than initially indicated by the model developed in Section 6.0.

Lastly, the final percent outage of the tank was included. This will give a physical sense of how much product is truly boiled away upon venting the tank.

The results are quite startling. At 60°F, a 30,000-gallon tank carrying propane at an initial 20-percent outage will vent nearly 31,000 pounds of propane; the tank will have a final outage of 50 percent. This compares to 800 pounds of vapor that would be expected to escape if no boiling occurred. Remembering that the tank is constantly warmed by the wind and the burning of escaping vapor, it could be expected to boil away the entire contents of the car.

It is important to note that the results presented in Table A-2 have been computed based on fundamental equations of thermodynamics and the physical properties of propane as defined by Sallet and Wu. These results have not been verified by actual experiments on railroad tank cars.

7.3 RESULTS OF BOILING VAPOR DISCHARGE ANALYSIS

The following conclusions can be drawn about the release of additional vapor mass created by boiling liquid product in a tank car.

- The total mass of vapor exiting the tank due to product boiling is dependent on the thermodynamic properties of each individual product. It is possible to boil and vaporize the entire contents of the tank car.
- Vapor vent times will be extended by the ratio of total exit mass to the initial in-tank vapor mass.

8.0 SIMPLE LIQUID DISCHARGE

Vent and burn involves the release of tank vapor pressure followed by the release of the remaining liquid within the tank. The liquid flow rates are calculated from theories of incompressible fluids under zero external pressure. It is assumed the fluid is open to atmospheric pressure at all times during draining.

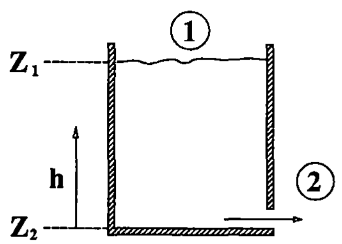
The energy continuity can be manipulated to allow calculation of the exit velocity of liquid from a tank. Assuming no heat transfer, external work, or internal energy change (railcar tank volumes are so big, negligible energy changes can take place over the time spans considered), equation (1) can be shown to reduce to Bernoulli's equation, relating fluid kinetic and potential energies.

8.1 EXIT VELOCITY

To use Bernoulli's equation, three assumptions must be made (1) quasi-steady flow (nearly steady), (2) inviscous liquid (negligible viscosity or frictional effects -- valid for all but thick or sludgy products), (3) incompressible (valid for all liquids). The equation is stated

$$P_1+\tfrac{1}{2}\rho_1\overline{V}_1^2+\rho_1 g z_1 = P_2+\tfrac{1}{2}\rho_2\overline{V}_2^2+\rho_2 g z_2 \qquad (12)$$

Incompressibility assures constant density ($\rho_1 = \rho_2$). Further, if the tank is exposed to atmospheric air both at the top vent hole and exit discharge hole, as proposed by the Vent and Burn procedure, then P_1 equals P_2. Manipulating equation (12), we arrive at:



$$\tfrac{1}{2}\overline{V}_1^2+g z_1 = \tfrac{1}{2}\overline{V}_2^2+g z_2 \qquad (13)$$

As the liquid exits the tank, the surface level at 1 decreases at a rate of $\overline{V}_1$. From mass continuity, the mass exiting at 2 must also "exit" 1; thus $\dot{m}_1 = \dot{m}_2$, or $\rho\overline{V}_1 A_1 = \rho\overline{V}_2 A_2$, or $\overline{V}_1 = \overline{V}_2 A_2/A_1$. Inserting into equation (13), we arrive at the following:

$$\overline{V}_2 = \sqrt{\frac{2g(z_1 - z_2)}{1 - \left(\frac{A_2}{A_1}\right)^2}}$$

For the range of hole sizes expected ($A_2 < 0.44$ ft^2 or 9-inch diameter) and the tank areas encountered ($A_1 > 63$ ft^2 for all but a few inches of height), it is a fair assumption to set $A_2/A_1 = 0$. Renaming the quantity $(z_1 - z_2)$ to h (vertical height of liquid above exit hole), the equation defining liquid exit velocity becomes

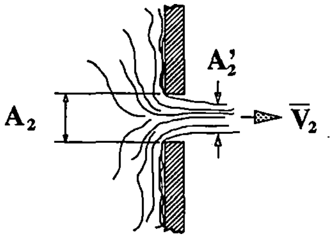
$$\overline{V}_2 = \sqrt{2gh} \tag{14}$$

where g is the acceleration of gravity (32.17 ft/s^2).

This derivation shows that the exit velocity of the liquid is a function of vertical fluid height only. This vertical fluid is often referred to as head pressure. All inviscous fluids under zero external pressure will exit at the same rate for a given height.

8.2 CORRECTION FOR DISCHARGE HOLE GEOMETRY

The above derivation assumes that the exit flow fills completely the exit area. This is not the case for the high exit velocities expected. The exit stream must converge to an orderly flow to exit the tank; flow turbulence will be created by the cut metal edge through which the fluid must pass. As depicted below, the actual discharge area will be a fraction of the physical opening.



$$A_2' = C_d A_2 \tag{15}$$

where C_d is the coefficient of discharge of the exit hole. This value will vary between about 0.4 for inward curling hole perimeters and 0.98 for well-formed outward curling hole perimeters. A value of 0.62 was listed in the *Fire Protection Handbook*,[4] for a circular, square edged orifice. Actual data from tank drainage shows 0.58 to be more representative of explosively-cut tank car material.

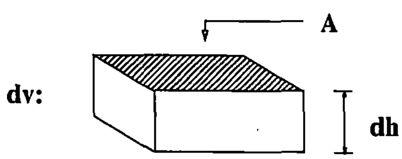
8.3 TIME TO DRAIN TANK

Conservation of mass is used to relate vertical liquid height h to time t; the time required to drain the tank will thus be the time which allows h to decrease to 0.

By conservation of mass, the mass flow rate at the top liquid surface must equal the mass flow rate at the exit: $\dot{m}_1 = \dot{m}_2$. The mass flow rate is defined as $\dot{m} = \rho\overline{V}A$. The volume flow rate is defined as the change in volume over time or $\dot{V} = \overline{V}A$. Thus, conservation of mass can be rewritten as: $\rho\dot{V}_1 = \rho\dot{V}_2$. Remembering incompressibility, this simplifies to

$$\dot{V}_1 = \dot{V}_2$$

The volume flow rate at the top liquid surface will be defined as



$$dV = A\,dh$$

$$\dot{V}_1 = \frac{dV_1}{dt} = A_1\frac{dh}{dt}$$

The volume flow rate at the exit hole will be defined with help of equations (14) and (15) as

$$\dot{V}_2 = -A_2 \overline{V}_2$$

$$\dot{V}_2 = -C_d A_2 \sqrt{2gh}$$

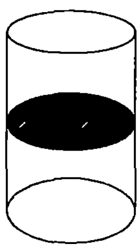
Combining the two flow rate definitions to achieve conservation of mass,

$$A_1 \frac{dh}{dt} = -C_d A_2 \sqrt{2gh} \qquad (16)$$

where A_1 is a constant or a function of h.

8.4 EXIT TIME, CONSTANT CROSS SECTIONAL AREA

Equation (16) can be solved for a constant tank cross sectional area to relate vertical fluid height to time.



In the case of a vertical tank, the top of the fluid will always take the shape of a circle of diameter D_t as h varies from H_{max} (vertical height of tank) and 0.

The differential equation (16) can be solved by separation of variables to give

$$h = \left(-\frac{C_d A_2 \sqrt{2g}}{2A_1} t + c \right)^2$$

Using the known boundary condition (t = 0, h = H_{max}) shows that c = $\sqrt{H_{max}}$. Substituting

$$h = \left(-\frac{C_d A_2 \sqrt{2g}}{2A_1} t + \sqrt{H_{max}} \right)^2 \qquad (17)$$

The tank will empty when h = 0. Thus, the time required to drain the tank can be found from equation (17) by setting h = 0. Rearranging equation (17) gives

$$t = \frac{A_1\sqrt{2H_{max}}}{C_d A_2 \sqrt{g}} \tag{18}$$

Equation (18) is an analytical solution defining the time required to drain liquid from a shell-full tank of constant cross sectional area. It is only valid for incompressible, inviscous flow, with no external pressure differential between the top fluid surface and the exit stream. The fluid top surface area should be greater than 10 times the exit area.

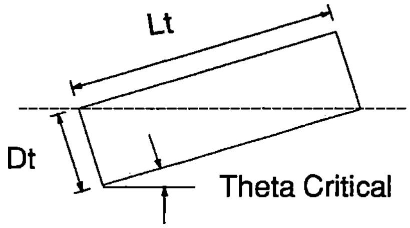
8.5 EXIT TIME, VARIABLE CROSS SECTIONAL AREA

The above formulation of time is valid only for constant cross sectional areas; e.g., a vertical ideal tank car, an extremely rare orientation during derailment. The model must be extended to include an inclined tank to be more realistic.

In this model, theta was defined to be the angle of incline of the tank. Under normal shipping, the tank is horizontal and theta is 0. During derailment, it is likely for theta to vary from 0 to 30 degrees or more.

As liquid drains from the tank, A_1 will take the shape of a horizontal plane within the tilted cylinder. For a vertical tank (theta = 90 degrees), this area will be a circle. For a horizontal tank (theta = 0 degrees), the area will be rectangles of varying width. As theta varies between 0 and 90 degrees, the cross sectional area will be full or partial ellipses.

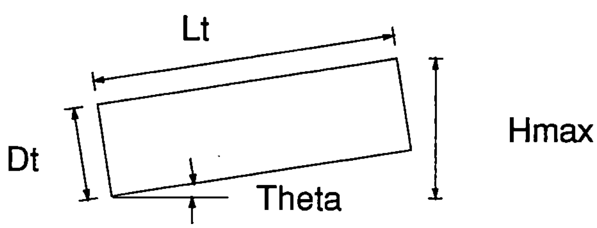
The slanted tank (0 degrees < theta < 90 degrees) is unfortunately pertinent to real world applications. One angle is of extreme importance in this range: the point at which the top of one tank end is exactly the height of the bottom of the second. At this point, the shape of the fluid surface changes and a new formulation of area A_1 must be made. From trigonometry, this θ_{crit} is



$$\theta_{crit} = arctan\left(\frac{D_T}{L_T}\right)$$

where D_T is the tank diameter and L_T is the tank length. θ_{crit} ranges between 8 and 12 degrees for the tanks under consideration within this project.

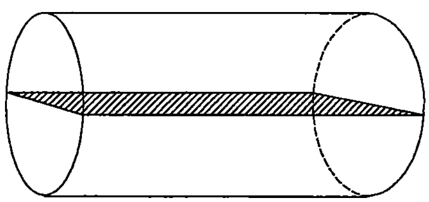
It was shown in Section 8.1 that fluid flow depends only on vertical height of the fluid column. Thus, it is important to know the starting height of fluid within an angled tank. The maximum height will be at the upper tank corner or

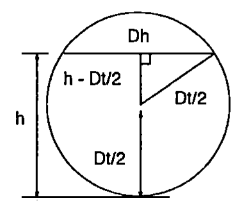


$$H_{max} = D_T \cos\theta + L_T \sin\theta$$

8.5.1 Horizontal Tank

Liquid drains from a horizontal tank and forms a top cross sectional area of a rectangle length L_T and width D_h.





Using the Pythagorean theorem and simplifying, D_h is found to be

$$D_h = 2\sqrt{D_T h - h^2}$$

for all values of h. Formalizing the cross sectional area of the tank, A_1 equals

$$A_1 = 2L_T\sqrt{D_T h - h^2} \tag{19}$$

For a horizontal, ideal tank, the top surface area of the liquid becomes a simple function of fluid vertical height. Thus, the change in tank fluid volume over time can be related to the change in fluid height.

$$\dot{V}_1 = \frac{dV_1}{dt} = A_1\frac{dh}{dt}$$

$$\dot{V}_1 = \frac{dV_1}{dt} = 2L_T\sqrt{D_T h - h^2}\frac{dh}{dt}$$

Substituting into equation (16), the conservation of mass is now seen to be

$$2L_T\sqrt{D_T h - h^2}\frac{dh}{dt} = -\, C_d A_2\sqrt{2g\,h}$$

Solving by separation of variables results in

$$h = D_T - \left(\frac{3C_d A_2\sqrt{2g}\,t}{4L_T}\right)^{2/3}$$

The time required to drain is found by setting h = 0 and rearranging algebraically to find

$$t = \frac{4L_T D_T^{2/3}}{3C_d A_2\sqrt{2g}} \tag{20}$$

Equation (20) is the analytical solution to the time to drain a horizontal tank from shell full configuration for incompressible, inviscous fluids under no external pressure.

A more practical solution is found through numerical integration. Such a solution can be customized for partial outage by varying the range of h. Equation (19) defined A_1 as a function of h for all h, H_{max} to 0. Rearranging equation (16) to separate variables, it becomes obvious that even though t is not easily solved, dt can be solved as

$$dt = \frac{A_1 dh}{-C_d A_2 \sqrt{2gh}}$$

Numerically integrating for successive values of h, indicated by the summation index i, the tank drain time for a horizontal, ideal tank is found to be

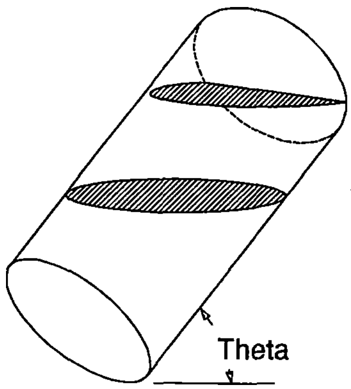
$$t_{drain} = \int_0^{t_{drain}} dt = \sum_{i=0}^{i=50} dt_i = \sum_{i=0}^{i=50} \frac{2L_T \sqrt{\left(D_T h_i - h_i^2\right)} dh_i}{-C_d A_2 \sqrt{2gh_i}} \qquad (21)$$

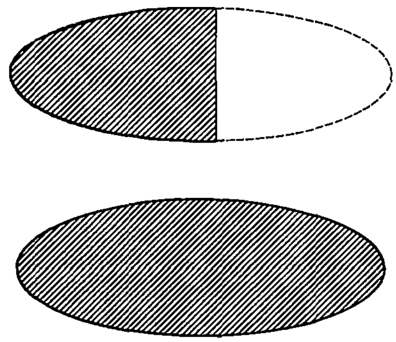
as h is suitably stepped from H_{max} to 0. During program modeling, 50 equal steps of h were used.

The numerical integration technique was compared to the analytical solution for accuracy; less than a 0.8 percent error was found. This model was extended to 200 steps (0.3 percent error) for prediction of field test results.

8.5.2 Tank Above Theta Critical

Consider an infinite cylinder, angled away from vertical; a horizontal fluid surface will trace out an ellipse within this tube. As h varies, the ellipse will simply move along the center line of the tube, holding a constant shape. Now consider a finite cylinder. The fluid level will trace out an ellipse at the midheight of the tube. As h is increased or decreased, this ellipse will move along the tube until it strikes the end wall. At this point, the fluid will continue to form an ellipse, but one truncated by the end wall. The width of the ellipse at the point of truncation will be D_h, the width of the tank end wall -- a function of fluid height. These two area conditions are depicted below.





Two regions are created, each with unique area calculations: (1) upper and lower "triangles," the full height of the tank ends, where area is a partial ellipse; and (2) a center region where area is a constant ellipse. To check continuity as theta approaches 90, the angled tank must become nearly equal to the vertical tank configuration; the two triangular regions become very short and inconsequential and the elliptical cross section of the central tank region becomes increasingly circular in shape. Indeed, if theta equals 90, we return to the condition solved in Section 8.4. Alternately, as theta approaches theta critical, the triangular regions dominate and the constant-area region disappears. At theta critical, only the two triangular regions exist.

Due to the angle of the tank ends, D_h no longer depends on h but $h/\cos\theta$ (projection of h onto tank end). D_h is found to be

$$D_h = 2\sqrt{D_T \frac{h}{\cos\theta} - \left(\frac{h}{\cos\theta}\right)^2}$$

for all values of h over which the top fluid surface touches the tank ends.

The elliptical cross section can be defined parametrically. X is assumed to be longitudinal on the tank, and Y spans the width of the tank.

$$\frac{x^2}{\left(\frac{D_T}{2\sin\theta}\right)^2}+\frac{y^2}{\left(\frac{D_T}{2}\right)^2}=1$$

Solving for x and integrating x dy from y_1 to y_2 gives the area of a full or partial ellipse:

$$A=\frac{1}{\sin\theta}\int_{y_1}^{y_2}\sqrt{\frac{D_T^2}{2}-y^2}\,dy$$

The area of a full ellipse becomes simply

$$A=\frac{\pi D_T^2}{4\sin\theta}$$

Evaluation of a partial ellipse can be performed through trigonometric substitution in the above integral or, in the case of this study, numerically by trapezoidal approximation (saves computer time while sacrificing only minor accuracy).

As shown, A_1 can be defined as a function of h for all h, H_{max} to 0. But due to the complex relation of A_1 to h, it is not practical to solve this analytically. Instead, by choosing arbitrary values of h, $A_1 dh$ can be evaluated. Numerically integrating for successive values of h, indicated by the summation index i, the time to drain a slanted, ideal tank is found to be

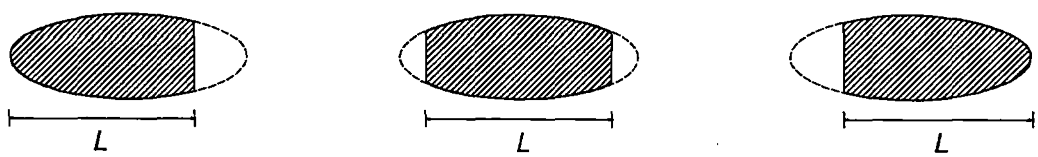
$$t_{drain}=\int_0^{t_{drain}}dt=\sum_{i=0}^{i=50}dt_i=\sum_{i=0}^{i=50}\frac{A_{1i}dh_i}{-C_d A_2\sqrt{2gh_i}}$$

as h is suitably stepped from H_{max} to 0. The three regions of tank geometry were each modeled by 50 equal steps of h.

As a check to this formulation, the time to drain the tank at theta = 89.9 degrees must be approximately equal to the analytical result of theta = 90 degrees. Indeed, the two times matched within a few seconds or 0.1 percent error.

8.5.3 Tank Below Theta Critical

Tank orientation below theta critical is very similar to that for the tank above theta critical. Again two triangular regions exist as h nears $H_{\max}$ or 0. But instead of having a region of constant area between, it is a region of constant length. As the upper triangle lowers and stretches across the tank upper surface, it will encounter the lower tank end while still truncated by the upper tank end. The tank ends, being parallel, will form a region of constant length. When the upper triangle first encounters the lower tank end, the fluid surface will be a truncated ellipse spanning from $x = -x_{\max}$ to $x = -x_{\max} + L_T/\cos\theta$ (length of fluid surface). It will become a doubly truncated ellipse with ends width $D_{h upper}$ and $D_{h lower}$ -- upper and lower indicating upper and lower tank end widths, respectively. At the start of the lower triangle, the ellipse will return to a single truncation, spanning now from $x = x_{\max} - L_T/\cos\theta$ to $x = x_{\max}$. The figures below depict the movement of this constant length region across the ellipse.



Numerical integration by trapezoidal approximation was used to find the fluid surface area A_1 as a function of h. The time required to drain the tank was again found through numerical integration.

To check the formulation of the time to drain the tank for angles below theta critical, two angles were compared: theta = 0 degrees and theta equal to theta critical. The numerical solution matched the analytical formulation within 0.2 percent at theta = 0 degrees. At theta critical, the two numerical techniques differed by up to 1 percent. Trigonometric functions take on extreme values at this angle and the error should be expected. This error is less than 15 seconds for a 30,000-gallon tank drained through a 6-inch hole.

8.6 VARIATION OF DRAIN TIME BY SYSTEM PARAMETERS

The tank draining model derived above depends on tank geometry, exit hole area, coefficient of discharge, and tank angle. The possible variations in these parameters are to diverse to present every possible solution here. Instead, the effect of each parameter has been analyzed and normalized. This allows the correction of a tank drain time for a change in one or more parameters. For example, the drain time of a 30,000-gallon tank can be corrected for a 40-in^2 exit hole rather than the original 28-in^2 hole.

8.6.1 Exit Hole Size

Equation (21) indicates that t is inversely proportional to the exit area, a function of $1/A_2$. The drain time can be corrected for a new A_2 by multiplying the reference time by the factor A_2-reference/A_2-corrected. A time found for a $A_2 = 28$ in^2 can be corrected to a $A_2 = 40$ in^2 by multiplying the time by 28/40 or 0.70.

8.6.2 Coefficient of Discharge

Equation (21) indicates that t is a function of $1/C_d$. The drain time can be corrected for a new C_d by multiplying the reference time by the factor C_d-reference/C_d-corrected. A time found for a $C_d = 0.62$ can be corrected for a $C_d = 0.58$ by multiplying the time by 0.62/0.58 or 1.07.

8.6.3 Tank Angle

Sections 8.5.2 and 8.5.3 outlined techniques to find the time required to drain a tank at various angles of inclination. These calculations are too laborious to be carried out in the field at the site of the Vent and Burn procedure. Instead, a correction factor can be found to shorten drain times for inclined tanks. Figure A-2 indicates how tank drain times must be corrected for non-horizontal tank angles. As an example, the horizontal tank drain time for a 30,000-gallon tank volume would be multiplied by 0.74 to correct for a 5-degree incline.

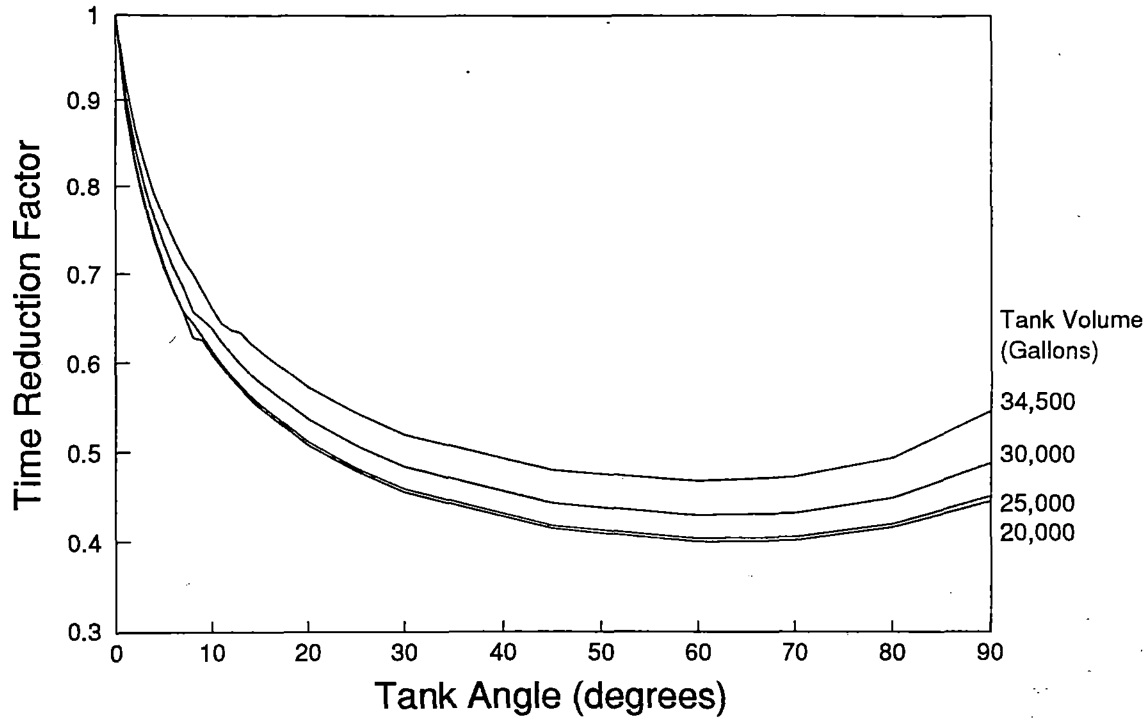


Figure A-2. Time Correction Factors to Calculate Liquid Drainage from an Inclined Tank

8.6.4 Partial Outage

The effect of partial outage can be calculated easily for a horizontal tank, as outlined in Section 8.5.1. Multiplying the horizontal tank partial outage time by a tank angle correction will roughly approximate an angled tank partial outage drain time.

Fluid flow rate is proportional to vertical fluid height; tank drain time is a function of flow rate and tank cross sectional area by fluid height. The drain times for identical tanks filled to differing partial outages are not related by the ratio of outages, but rather by the ratio of the initial fluid heights that correspond to these partial outage levels. As an example, consider a 30,000-gallon tank of 114.5-inch internal diameter. A 20-percent outage corresponds to 30 inches of vertical vapor space or 84.5 inches of liquid lading; 10-percent outage corresponds to 17-inches vapor or 97.5 inches liquid product. If the drain time for the 20-percent-outage tank was compared to the 10-percent-outage tank, the drain time would be reduced by 97.5/84.5 or 0.87. Figure A-3 plots relative tank product height as a function of percent outage.

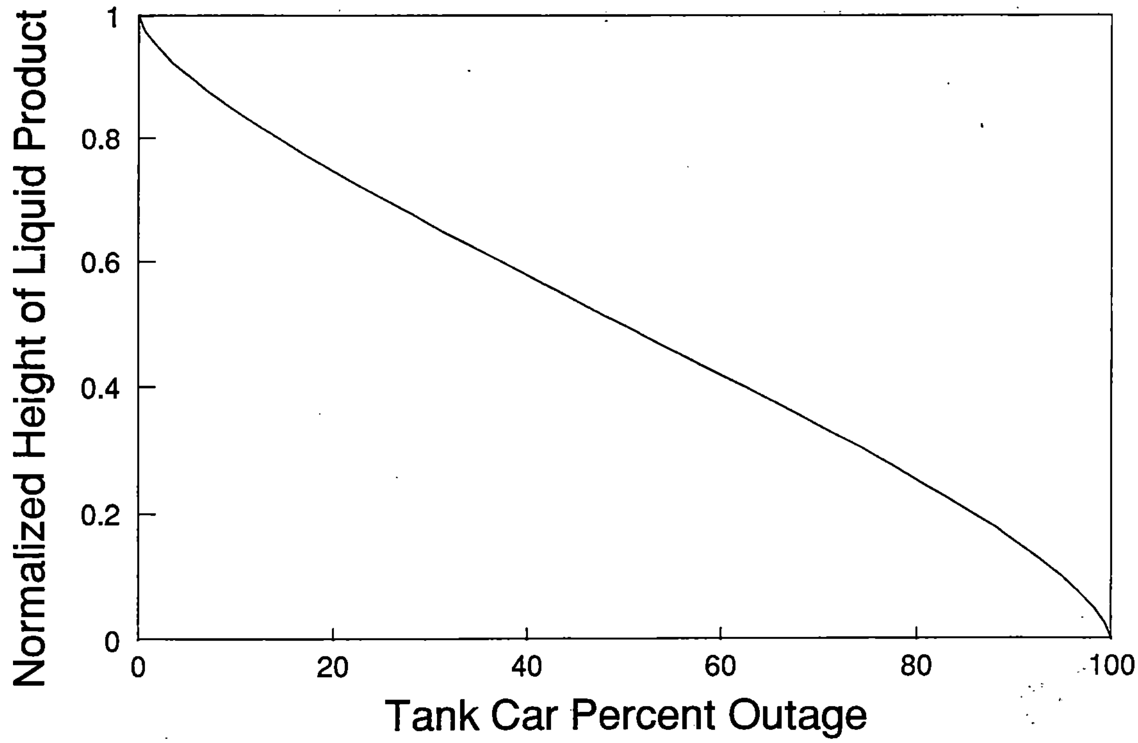


Figure A-3. Relation of Relative Product Height to Tank Percent Outage (Idealized Tank)

8.7 RESULTS OF FLUID FLOW ANALYSIS

The following conclusions can be drawn about the fluid drainage from a tank car.

- If the vapor pressure within the tank car is maintained at atmospheric during liquid drainage by a vent hole, the fluid flow rate is dependent only on vertical height of the fluid column.
- Sizing of the discharge hole can be used to control the initial discharge rate and total time of discharge. The flow rate can never be held steady -- it will continually decrease unless the tank contents are affected by heat expansion.
- Fluid drain times can be solved analytically for a tank of constant cross sectional area assuming inviscous, incompressible flow. The fluid must be exposed to atmospheric pressure.

- Fluid drain times can be solved analytically for a horizontal, right cylindrical tank filled initially to a shell full configuration. The fluid must be inviscous, incompressible, and exposed to atmospheric pressure.
- Fluid drain times can be found by use of numerical integration for non-constant cross sectional areas and partial outage tank configurations. Reasonable accuracy is maintained in calculations by using 50 or more integration steps.
- The effect of a variation in a model input parameter can be seen by use of time correction factors rather than recalculating drain times. The dependence of fluid drain times on various model parameters was charted.

9.0 TRUE LIQUID DISCHARGE

Liquid drainage should be started after all vapor pressure has been released from the tank car and the tank internal pressure is returned to atmospheric. However, boiling product or other considerations may make this timing impractical. By following a similar derivation as in Section 8.1 (re-applying Bernoulli's equation), a vapor pressure applied to the surface of the liquid product can be accounted for in the fluid exit velocity.

Recall Bernoulli's equation in its full form as presented in equation (12):

$$P_1+\tfrac{1}{2}\rho_1\overline{V}_1^2+\rho_1 g z_1 = P_2+\tfrac{1}{2}\rho_2\overline{V}_2^2+\rho_2 g z_2 \tag{12}$$

Incompressibility assures constant density ($\rho_1=\rho_2$). Under a standing vapor pressure, the tank internal pressure (P_1) does not equal the atmospheric pressure (P_2). Let P_I be the tank internal gage pressure, $P_I = P_1 - P_{atm}$. Because $P_2 = P_{atm}$, $P_I = P_1 - P_2$. P_I has two helpful features: (1) tank shippers will usually quote internal pressure as the gage pressure P_I; and (2) it substitutes directly into equation (12) during simplification. Manipulating equation (12), we arrive at

$$\frac{2P_I}{\rho}+\overline{V}_1^2+2g z_1 = \overline{V}_2^2+2g z_2$$

Substituting for $\overline{V}_1$ as in Section 8.1, $\overline{V}_2$ can be found. Remembering the restrictions of A_1 versus A_2, A_2/A_1 can be set to zero. Final, renaming $(z_1 - z_2)$ to h, $\overline{V}_2$ is found to be

$$\overline{V}_2 = \sqrt{2gh + \frac{2P_I}{\rho}}$$

Substituting this new value for $\overline{V}_2$ into equation (16), the equation becomes

$$A_1\frac{dh}{dt} = - C_d A_2\sqrt{2gh + \frac{2P_I}{\rho}}$$

Rearranging to separate variables, it becomes obvious that though t can't be solve for easily, dt can be found by

$$dt = \frac{A_1 dh}{-C_d A_2\sqrt{2gh + \frac{2P_I}{\rho}}}$$

Numerically integrating dt for successive values of h, indicated by the summation index i, the time to drain an ideal tank with non-atmospheric internal pressure is found to be

$$t_{drain} = \int_0^{t_{drain}} dt = \sum_{i=0}^{i=50} dt_i = \sum_{i=0}^{i=50} \frac{A_{1i} dh_i}{-C_d A_2\sqrt{2gh_{1i} + \frac{2P_{Ii}}{\rho_i}}}$$

as h is suitably stepped from $H_{\max}$ to 0. No modeling was actually performed for internal tank pressure, but a minimum of 50 equal steps of h is recommended.

Standing vapor pressure will increase the initial fluid discharge rate, but as the fluid level drops, the internal volume available for the vapor increases as well. With no vent hole to equalize the internal pressure, P_I will decrease, potentially to a vacuum hindering fluid flow and potentially capable of collapsing the tank structure.

The minimum internal pressure required to allow fluid release without a vapor vent hole can be found from the ideal gas law. Assume initial conditions of $P_1 = P_I$ and V_1 = tank percent outage and final conditions of $P_2 \geq 14.7$ psi (standard atmospheric pressure) and $V_2 = 100$ percent outage.

$$P_I \geq \frac{14.7psi}{percentoutage}$$

10.0 CONCLUSIONS

The following conclusions can be drawn about the derivation of mathematical models to predict compressed vapor release and liquid product drainage from a rail tank car:

- A mathematical model was made to find the time required to release a compressed vapor from a rail tank car. The model used numerical integration of steady-state flow conditions evaluated at successive, finite pressure increments. Model parameters included tank volume, tank percent outage, tank temperature and pressure, ambient temperature and pressure, exit hole area and roughness, and product molecular weight and specific heats. Assumptions included inviscous vapor, adiabatic expansion, ideal gas, steady state, no external work, and no heat transfer into the system.
- The addition of compressed vapor due to product boiling was also modeled. Vapor vent times were corrected to include discharge of the additional vapor mass. Model parameters included tank volume, tank percent outage, tank temperature and pressure, product-specific thermodynamic energy data. Assumptions included a perfectly insulated tank car and a near linear relationship of enthalpy to product temperature.
- A mathematical model was made to find the time required to drain liquid product from a rail tank car. Analytical solutions were found for a vertical and horizontal tank filled to shell-full configurations. A numerical integration model calculated

drain time by use of steady flow conditions evaluated at successive fluid heights. Model parameters included tank length and diameter, percent outage, tank incline, and exit hole area and roughness. Assumptions include inviscous fluid, no tank internal gage pressure, no external work, and no heat transfer into the system. The fluid top surface area should be greater than 10 times the exit hole area.

- A model correction for liquid release under pressure was formulated. It used the same model parameters as did the simple fluid flow model with the addition of internal tank pressure. The assumptions were the same as with the simple fluid model.

APPENDIX

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