Comparative analysis of documented damage to tank cars containing denatured alcohol or crude oil exposed to pool fire conditions

A White Paper
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I. Summary

This paper is a comparative analysis of documented damage to tank cars exposed to pool fire conditions following a derailment of trains consisting partially or entirely of tank cars containing denatured alcohol and crude oil. The purpose of the analysis is to understand the relative hazards of denatured alcohol and crude oil and their potential to cause catastrophic failure of tank cars in pool fire conditions. Much has been made of the effect of volatility of crude oil on hazards, especially crude oil from the Bakken shale play in the Williston Basin. An important safety policy question currently under debate is whether the increased volatility renders crude oil involved in a derailment more explosive than other flammable liquids[1]necessitating special classification and packaging.

FRA has developed and implemented procedures to carefully document damage to each tank car involved in derailments. The fruit of this effort is a catalog of damage to tank cars, specifically DOT 111 specification tank cars transporting flammable liquids, which can be mined to understand the behavior/performance of protective design features. Further, vulnerabilities of the specification can be identified and design enhancements evaluated. Data, in the form of photographs, assessment forms and narrative descriptions of damage to all tank cars (containing denatured alcohol and crude oil) involved in derailments and exposed to pool fire conditions was organized and evaluated. First the damage was evaluated relative to tank car vintages and features to determine if damage could be attributed to these features. Then damage was evaluated relative to the commodity to provide a qualitative relative hazard of the commodities under consideration.

The overall conclusion from this analysis is that (i) there was no discernable correlation between design features of the tank cars and the damage to the tank cars exposed to pool fires and (ii) denatured alcohol poses a similar, if not greater, risk as (Bakken) crude oil when released from a tank car failing catastrophically and resulting in a large fireball type of fire with or without an explosion.

II. Introduction

The annual number of shipments of denatured alcohol began to increase from less than 100,000 in 2005 to a maximum near 360,000 originations in 2011. The number of originations has dipped slightly since but remains steady and is projected to remain steady for the foreseeable future. In 2012, the number of crude oil shipments began to increase at a significant rate. In 2013, the number of originations of crude oil exceeded 480,000 (Figure 1). The rate of increase in originations of crude oil is expected to increase over the next few years and remain steady afterwards[2].

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[1] Class 3 (flammable liquid) is defined in 49 CFR 173.120.

[2] The Energy Information Administration (EIA) indicates the growth, long-tern production stability, and ultimate longevity of tight oil (oil from a uniform sponge layer, not a shale product) are linked to resource assumptions. Uncertainties in these assumptions include geologic dependencies in well development, effects of improved technology on well productivity, and the effect on an incremental recovery factor.

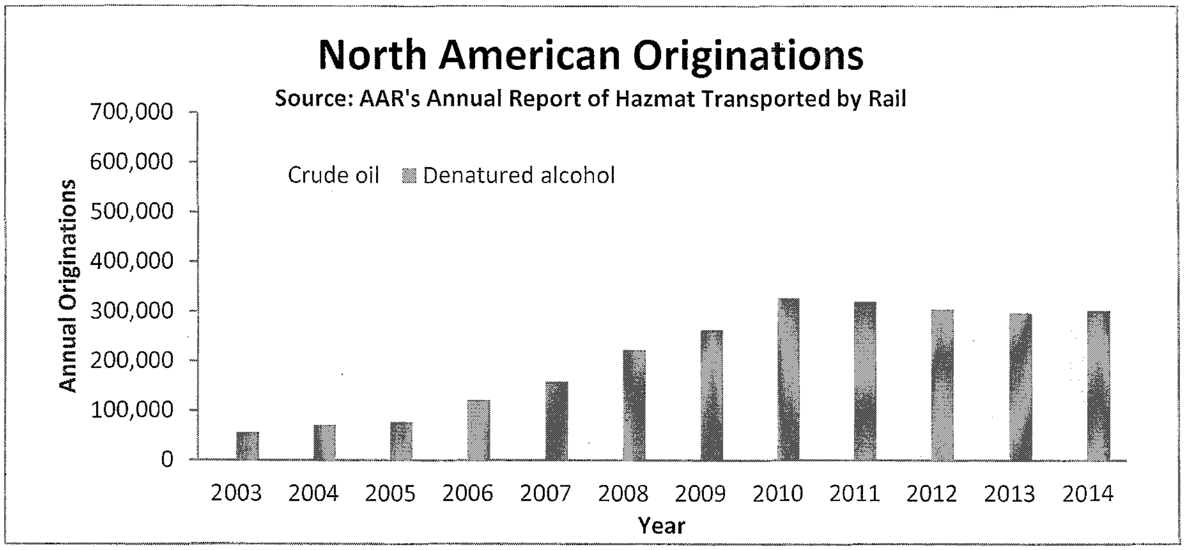

Figure 1: Denatured alcohol and crude oil originations since 2005. (2014 data is projected based on 20% growth in crude oil originations and a five –year average for denatured alcohol)

Description of tank cars involved

Based on the Hazardous Materials Table (172.101) the bulk packaging requirements for denatured alcohol (denatured alcohol) and crude oil are found in 173.243 (PGI) and 173.242 (PG II and III). § 173.243 permits the use of Class DOT 103, 104, 105, 109, 111, 112, 114, 115, or 120 fusion-welded tank car tanks; and Class 106 or 110 multi-unit tank car tanks. Section 173.242 permits the use of Class DOT 103, 104, 105, 109, 111, 112, 114, 115, or 120 tank car tanks; Class 106 or 110 multi-unit tank car tanks and AAR Class 206W tank car tanks. In all of the recorded incidents of a thermal tear or separation of the tank shell the cars were built to a DOT 111A100W1 specification.

In 179.201-1 Individual Specification Requirements indicate the minimum allowable thickness of the tank shell and head material is 7/16". The allowable carbon steel plate in § 179.200-7 for use in the fabrication of the shell and heads of DOT111A100W1 tank cars is either AAR TC-128 Grade B or ASTM 516 Grade 70. All of the tank cars that experienced a thermal tear or separation of the tank shell were constructed to TC-128 B steel. In four of the cars the steel was normalized. The Hazardous Materials regulations have no requirement for a jacket, insulation or thermal protection[3,4].

The volumetric capacity of the tank cars are all approximately 30,000 gallons. These tank cars are optimized for materials with a specific weight of 6.63 pounds per gallon at 115°F. For the purpose of this assessment a tare weight of 66,000 lbs, a gross weight on rail of 263,000 pounds, liquid full capacity

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[3] Insulating material must meet a performance standard requiring thermal conductance at 60 °F that is not more than 0.225 Btu per hour, per square foot, per degree F temperature differential. Thermal protection must have sufficient thermal resistance so that there will be no release of any lading, except lading released through the pressure release device, when subjected to either a pool fire for 100 minutes or a torch fire for 30 minutes. The federal regulations do not require thermal protection for general purpose tank cars (DOT 111A100 specification).

[4] Research summarized by Abassi et al. indicate the following (see Footnote 7).
(i) Using only the steel jacket provides thermal protection as it behaves as an effective radiation shield. In these tests, the jacket was found to cut the wall heating rate to approximately half of an unprotected wall (53 °C/min versus 24.5 °C/min) assuming that there is an air gap between the wall and the jacket.
(ii) Thermally protecting the tank wall with a steel jacket and a blanket of 13mm ceramic insulation provides substantial thermal protection. The fully protected tank may reduce the wall heating rate to approximately 1/10th of an unprotected wall (53 °C/min versus 5 °C/min).

30,000 gallons and a minimum outage of 1 percent are assumed. If new requirements are included with an additional 1/8" thickness in the tank shell, an 11-gage jacket, and ½" full head shields the additional weight would be 22,500 pounds. This would be compensated for by allowance to operate at a gross rail load of 286,000 pounds.

There are two requirements for settings of pressure relief devices. Section 179.15(b) states that a reclosing pressure relief valve must have a minimum start-to-discharge pressure equal to the sum of the static head and gas padding pressure and the lading vapor pressure at 46 °C (115 °F) for non-insulated tanks. Moreover, § 179.15(b)(2)(i) states that the start-to-discharge pressure of a pressure relief device may not be lower than 5.17 Bar (75 psig) or exceed 33 percent of the minimum tank burst pressure (165 psi for the DOT 111A100 specification tanks cars). The start to discharge pressure of the reclosing pressure relief valves on all the cars involved in the incidents referred to in this paper was either 75 psi or 165 psi.

Accident/Incident Data

Transportation of these materials by rail has taken the form of unit trains or trains with large blocks of tank cars containing these materials. With the increase in the number of originations there has been a commensurate increase in the number of derailments. Since 2006, there have been 15 derailments involving unit trains or trains with large blocks of tank cars containing flammable liquids (Table 1). Of these derailments, eight have resulted in catastrophic failure of the tank car tanks (Table **2**).

Table 1: Derailments of large block or unit trains of denatured alcohol or crude oil

Incident	Date	Tank Cars Derailed	Material
LaSalle, CO	May-14	5	Crude Oil (unit)
Lynchburg, VA	May-14	17	Crude Oil (unit)
Vandergrift, PA	Feb 2014	21	Crude Oil, LPG
New Augusta, MS	Jan 2014	11	Crude Oil (unit)
Plaster Rock	Jan 2014	9	LPG, Crude Oil
Casselton, ND	Dec 2013	20	Crude Oil (unit)
Aliceville, AL	Nov 2013	26	Crude Oil (unit)
Lac-Megantic	July 2013	63	Crude Oil (unit)
Plevna, MT	Aug 2012	17	Denatured alcohol
Columbus, OH	July 2012	3	Denatured alcohol
Tiskilwa, IL	Oct 2011	10	Denatured alcohol
Arcadia, OH	Feb 2011	31	Denatured alcohol (unit)
Rockford, IL	June 2009	19	Denatured alcohol (unit)
Luther, OK[5]	Aug 2008	8	Crude Oil (PG III)
Painesville, OH	Oct 2007	7	Denatured alcohol
New Brighton, PA	Oct 2006	23	Denatured alcohol (unit)

The properties of the flammable liquids and handling of the cars in large blocks or unit trains presents a unique hazard, in that if released and ignited the fire will affect adjacent cars (which will likely, if not certainly in the case of a unit train, contain the same flammable liquid) and result in release of more flammable liquid through the pressure relieve valve or a catastrophic failure of the tank. A catastrophic failure involved either a tear in the tank or a violent rupture that nearly or completely separated

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[5] Luther, OK occurred in 2008. The crude oil in the tank cars was classified as a Class 3, PG III material. The information related to this incident was not included in the analysis because it was pre-Bakken. The information is included in an Appendix B to this paper.

portions of the tank. Accompanying these failures have been the resulting fireball type fire (deflagration) and, in some cases, blast wave (explosion) effects. See Figure 2.

Figure 2: Photographs of explosions at recent derailments; Arcadia, OH (denatured alcohol); Casselton, ND (crude oil), and Plevna, MT (denatured alcohol).

The data analyzed below relates to the performance of the tank cars that experienced catastrophic failure by way of thermal damage in the form of tears or separations[6,7] (completely or nearly breaking into pieces). These damages were caused as a result of exposure to pool fire conditions in derailments involving denatured alcohol or crude oil. The analysis below has considered the flammable liquid contained in the tank. This analysis is intended to address the safety policy question of whether the volatility of crude oil poses a greater risk to safety than other flammable liquids, like ethanol, when operated in unit trains or large blocks of cars and involved in a derailment and pool fire. The following is an evaluation of the observed damage relative to the flammable liquid in the tank and the tank specification. No claims are made regarding the properties of the materials involved[6,7].

Table 2: Summary of Incidents in catastrophic failure due to exposure to a pool fire was observed

Incident	Date	Total cars	Speed (mph)	Temp.	Thermal Tear[8]	Separation[9]	Commodity
Arcadia, OH	2/11	31	46	11°F	2	3	Denatured alcohol
New Brighton, PA	10/06	23	37	-	1	0	Denatured alcohol
Luther, OK[10]	8/08	14	unknown	-	3	0	Crude Oil
Plevna, MT	8/12	17	25	92°F	4	2	Denatured alcohol
Tiskilwa, IL	10/11	19	34	-	3	0	Denatured alcohol
Columbus, OH	7/12	17	23	-	2	0	Denatured alcohol

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[6] Information regarding each tank car that experienced thermal damage is provided in Appendix A to this paper. The information includes a photograph of the damage as a summary of attributes of each tank car.

[7] A summary of observations from derailments of trains of tank car containing crude oil and denatured alcohol is provided in Appendix C to this paper.

[8] A thermal tear is typically a longitudinal failure that occurs in the portion of the shell surrounding the vapor space of the tank following exposure of the tank to pool fire conditions. The tank shell fails when the pressure in the tank (and resulting tensile or hoop stress) exceeds the tensile strength of the shell material that is diminishing with time of exposure to the pool fire. The length of thermal tears measured during FRA investigations ranged from 2-16 feet. The length of the tear may be a function of the volume of vapor escaping through the failure, flaws in the shell material, and the existence of crack arresters such as welds or stronger, non-heat effected steel.

[9] A separation occurs when a thermal tear propagates circumferentially from each end of the tear and result in the tank completely or nearly fragmenting into multiple pieces.

[10] See Appendix B.

Aliceville, AL	11/13	26	26	-	5	0	Crude Oil
Casselton, ND	12/13	20	38	-	3	0	Crude Oil
Lac Megantic,	7/6/13	63	~65	-	4	0	Crude Oil

Denatured alcohol provides a basis for a relative consequence analysis for crude oil. Like crude oil, denatured alcohol is often transported in a unit train or in trains containing large blocks of tank cars. The annual number of originations in 2013 (297,000) was second only to crude oil (485,000). Denatured alcohol also provides an interesting comparison based on the properties. Denatured alcohol is classified as a flammable liquid in packing group II (flash point <73°F and boiling point greater than 95°F). Crude oil is also a flammable liquid but is assigned a packing group I (initial boiling point less than 95°F). Industry experts and the Department have questioned whether the volatility/vapor pressure of certain crude oil grades make the material more hazardous (flammable or explosive) than other packing group I flammable liquids when transported in tank cars by rail.

Table 3 provides a comparison of the consequences observed in trains transporting crude oil and denatured alcohol. The data suggests that denatured alcohol may pose a greater risk of explosion than crude oil. As such, using vapor pressure as a metric to identify potential hazards may not prove effective when considering real world accident conditions involving tank cars loaded with flammable liquids.

Table 3: Comparison of consequences of derailments of denatured alcohol and Bakken crude oil

	Crude Oil	Denatured alcohol
Incidents involving loss of containment (tank cars involved)	8 (172)	7 (110)
Incidents involving pool fire (tank cars involved)	4 (126)	7 (110)
Tank cars experiencing thermal tears (Footnote 3)	12	12
Tank cars experience complete or near separation of tank shell (Footnote 4)	0	5
Rate of thermal failure in pool fire (failures per 100 cars)	9.5	15.5%

III. Possible failure modes and mechanisms

The tank car exposure as well as failure modes and mechanisms are provided below.

- Tank cars are exposed to a pool fire
- Tanks are damaged
  - Dented decreasing volume
    - Modeling has demonstrated that decreasing the outage in a tank decreases the time until failure.
  - Scored decreasing the integrity of the tank (FRA has not observed a thermal tear along damage resulting from the derailment.
- Temperature of lading increases
- Pressure in tank increases
- Lading expelled through pressure relief device
- Lading is a heat sink keeping the temperature of the steel relatively low
- Temperature of steel increases at an increasing rate as lading is expelled
- As the temperature of steel increases the mechanical properties of the steel change
  - Tensile strength decreases
  - Ductility increases
- Increase in pressure increases hoop stress

- The steel, under tension, begins to stretch and thin
- The steel of the shell continues to thin (much like putty as it is stretched) until the capacity of the shell in tension (tensile strength) is reached by the hoop stress caused by the increasing pressure in the tank.
- Thermal tear originated in vapor space of tank shell.
- Release of pressure is always straight up
- In most cases the damage is limited to a thermal tear
- In some cases the thermal tear extends circumferentially (as a mechanical – no thinning observed- tear) and results in near or complete a separation of segments of the tank.

IV. Data Analysis and Discussion

The analysis below compares the potential underlying reasons for the differences in thermal failure of tank cars carrying denatured alcohol and crude oil. Table **3** contains a comparison of the consequences of a derailment involving tank cars containing denatured alcohol and crude oil service. The data suggests that denatured alcohol poses a greater risk to safety than more volatile grades of crude oil (Bakken). Next, the attributes of the tank cars were compared to determine if the consequences were affected by the differences in design/specification. Specifically, a comparison was made of the material of construction and thickness of the tank shell, start to discharge pressure and flow capacity of the pressure relief valve (PRV), and age of the tank car. Additionally, the locations of each car experiencing a thermal failure in the train consist and derailments were considered.

Table **4** is a summary of the materials of construction for the cars that were involved in derailments and experienced thermal failures. All of the tank car tank shells were constructed of TC-128 Grade B steel. This speaks to the abundance of tank cars constructed of this materials rather than the susceptibility to thermal damage.

Table 4: Relationship between materials of construction, thermal damage

Material	Thermal Tear	Separation
TC 128	24 (4 normalized)	5
ASTM 516-70	0	0

Table **5** is a summary of the age of the tank cars experiencing specific types of thermal damage and the commodity involved. Most of the cars are less than 10 years old. This is logical given fleet sizes were increased to accommodate the growth in transportation of denatured alcohol and crude oil over the last 10 years

Table 5: Relationship between age of tank car, thermal damage and commodity

Lading (outcome)	0-5 years	6-10 years	11-15 years	16-20 years	21-25 years	26-30 years
Denatured alcohol (thermal tear)	7	4	1	0	0	0
Denatured alcohol (separation)	2	0	0	2	0	1
Crude Oil (thermal tear)	5	6	1	0	0	0
Crude oil	0	0	0	0	0	0

(separation)	

Table **6** is a summary of the relationship between start to discharge pressure of the pressure relief device (PRD) and the damage sustained by the tank car. It is noteworthy that the most energetic events occurred in the tanks with a PRD with a lower set pressure. This chart does not account for the possibility that the PRD was damaged during the derailment, which could potentially prevent proper operation.

Table 6: Relationship between start to discharge pressure and thermal damage

Start to Discharge Pressure	Thermal Tear	Separation
165 psi	9	1
75 psi	14	4

Table 7 summarizes the relationship between the flow capacity[11] of the PRD and the type of thermal damage. Fourteen of the twenty-four thermal tears occurred in tank cars equipped with a PRD having a low flow capacity. It is worth noting that the PRD was below the liquid line of the lading in 26 of the 29 tank cars experiencing thermal damage. Additionally, most of the tank cars experiencing a high energy thermal event (separation) were equipped with a PRD with a high flow capacity. As liquid is expelled through the PRD, there is less material to absorb the heat of the fire and the steel shell heats up faster. As the steel heats it tensile strength decreases and the internal pressure will be sufficient to cause hoop stress larger than the plastic yielding stress resulting in a tear of the tank shell.

Table 7: Relationship between pressure relief valve flow capacity and thermal damage

Flow Capacity	Thermal tear	Separation
20,464	2	0
20,520	2	0
20,555	1	0
20,605	3	0
21,602	6	1
33,808	0	1
35,608	1	0
35,660	0	2
38,902	9	1

Table 8 summarizes the relationship between the location of the tank car experiencing thermal damage in the derailment and the commodity. The data indicates that thermal damage occurs in cars through the derailments.

Table 8: Relationship between location in derailment of the releasing tank car and commodity

Lading	1st third	2nd third	3rd third
Denatured alcohol	9	5	3
Crude Oil	5	2	5

Table 9 summarizes the relationship between the location of the first tank car in the train that derails and the commodity. In all derailments in which tank car experienced thermal damage the first car to derail was in the first third of the train.

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[11] The rated flow capacity is based on standard cubic feet per minute of air.

Table 9: Relationship between location of first car to derail and commodity

Lading	1st third	2nd third	3rd third
Denatured alcohol	5	0	0
Crude Oil	3	0	0

VI. Conclusion

The data does not indicate any causal relationship between the attributes of the tank car, PRV, location in train, or other attributes indicated above and the occurrence of the thermal damage that would suggest something other than the commodity would explain the observed thermal damage. Denatured alcohol provided the basis for a relative risk analysis of crude oil. Like denatured alcohol, crude oil is transported in large block trains or unit trains and is classified as a flammable liquid. Denatured alcohol is a packing group II material. Crude oil can be a packing group I, II or III. Crude oil from the Bakken shale play is typically a packing group I material. The available evidence does not suggest that the relatively higher volatility of crude oil (Bakken) has any meaningful impact on the thermal damage that occurs to tank cars during derailments. The documented performance of the tank cars containing these materials involved in derailments and exposed to pool fire conditions provides an objective means to compare the effects of certain properties of these commodities on the survivability of tank cars exposed to pool fire conditions.

- The separations (higher energy events) occurred in tank cars containing denatured alcohol.
- The same number of thermal tears occurred in tank cars containing denatured alcohol as cars containing crude oil.
- The number of cars involved in derailments in which thermal tears and separations were encountered was nearly equal for denatured alcohol (107) and crude oil (109).
- A variety of factors that could have influenced the likelihood of thermal damage were analyzed, including steel specification, start to discharge pressure, age of car, lading, flow capacity of PRV, location of cars in derailment, location in train of first car to derail.

There is little evidence supporting the position that crude oil (especially that extracted from the Bakken region) poses a heightened risk of a high energy or explosive event when tank cars containing the material are exposed to pool fire conditions. In fact, the failure rate (due to thermal damage) of tank cars containing denatured alcohol is 1.5x greater than that of a tank cars transporting crude oil.

Appendix A – Summary of individual derailments with photos of each car experiencing a thermal tear or separation.

Arcadia

Car number	Location in derailment	Location in consist	Shell material	thickness	normalized	Build date	PRV number	Flow	Req'd flow	STDP
ADMX30837	5	9	TC-128	7/16"	No	10/1/07	1	21,602		75
ADMX30917	7	11	TC-128	7/16"	No	9/1/07	1	21,602		75
ADMX30107	10	14	TC-128	7/16"	No	2/7/91	2	35,660	20,613	75
UTLX211623	14	18	TC-128	7/16"	No	4/1/08	1	38.902		165
ADMX29420	31	35	TC-128	7/16"	No	11/20/84	2	35,660	20,545	75

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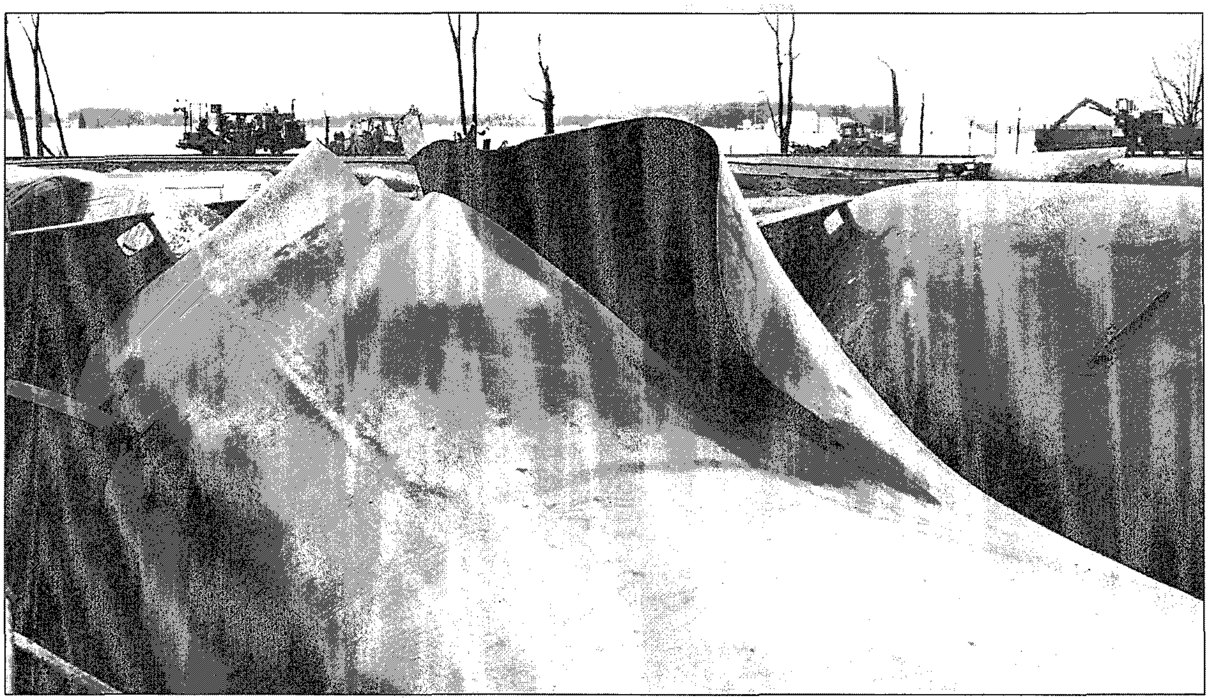

Figure 1: Arcadia, OH derailment ADMX30837

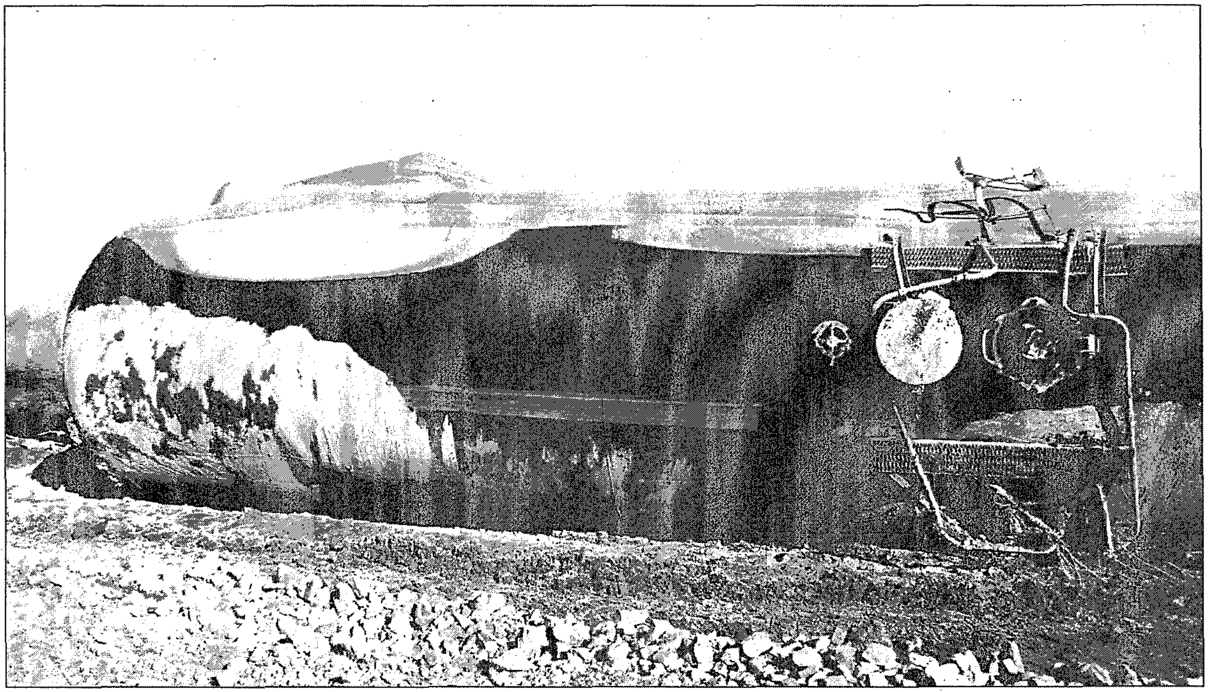

Figure 2: Arcadia, OH derailment ADMX30917

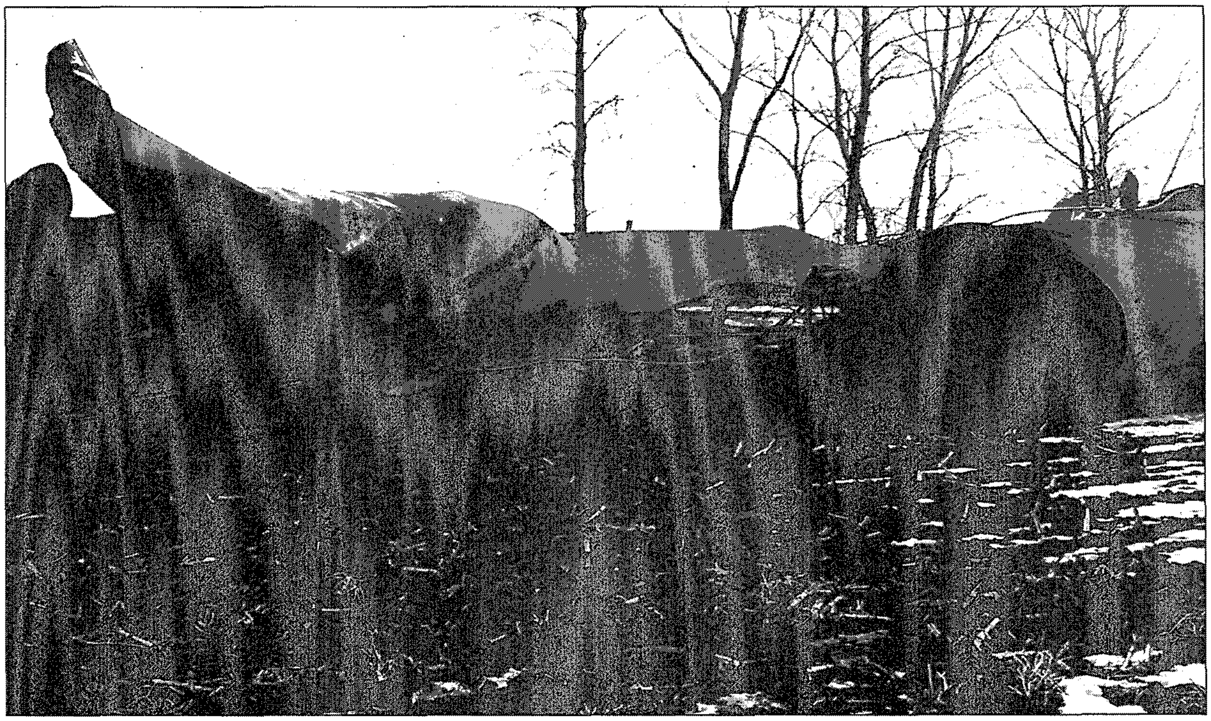

Figure 3: Arcadia, OH derailment ADMX30107

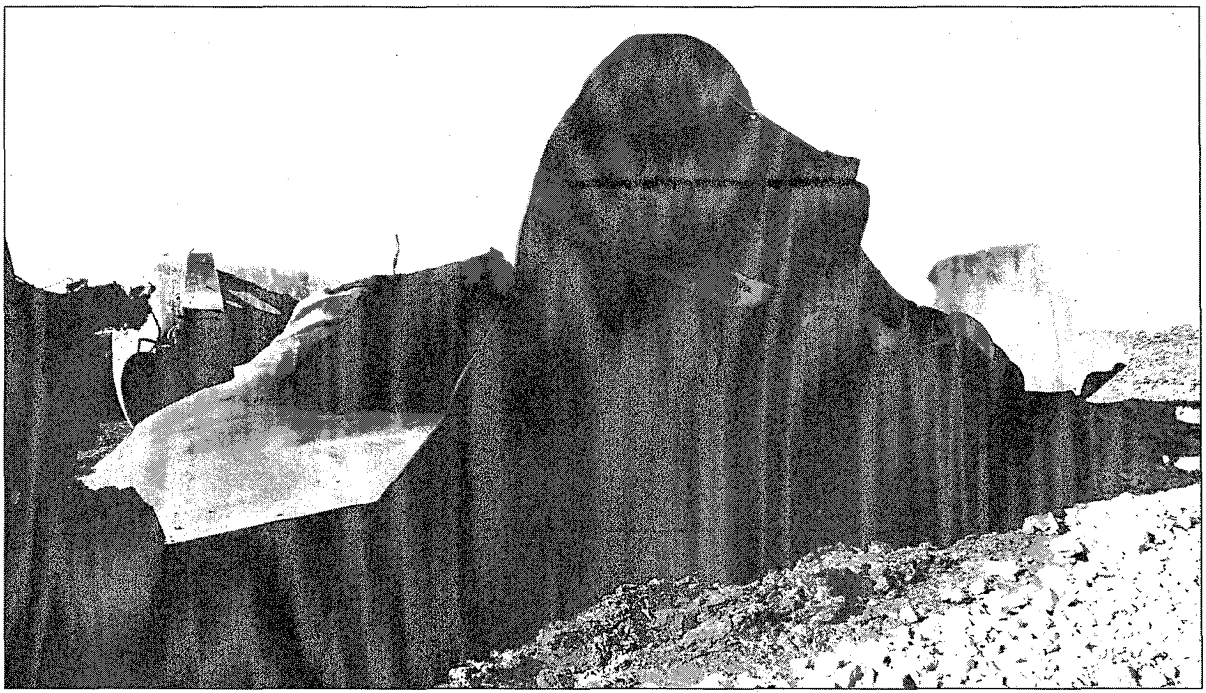

Figure 4: Arcadia, OH derailment UTLX211623 ("dance floor")

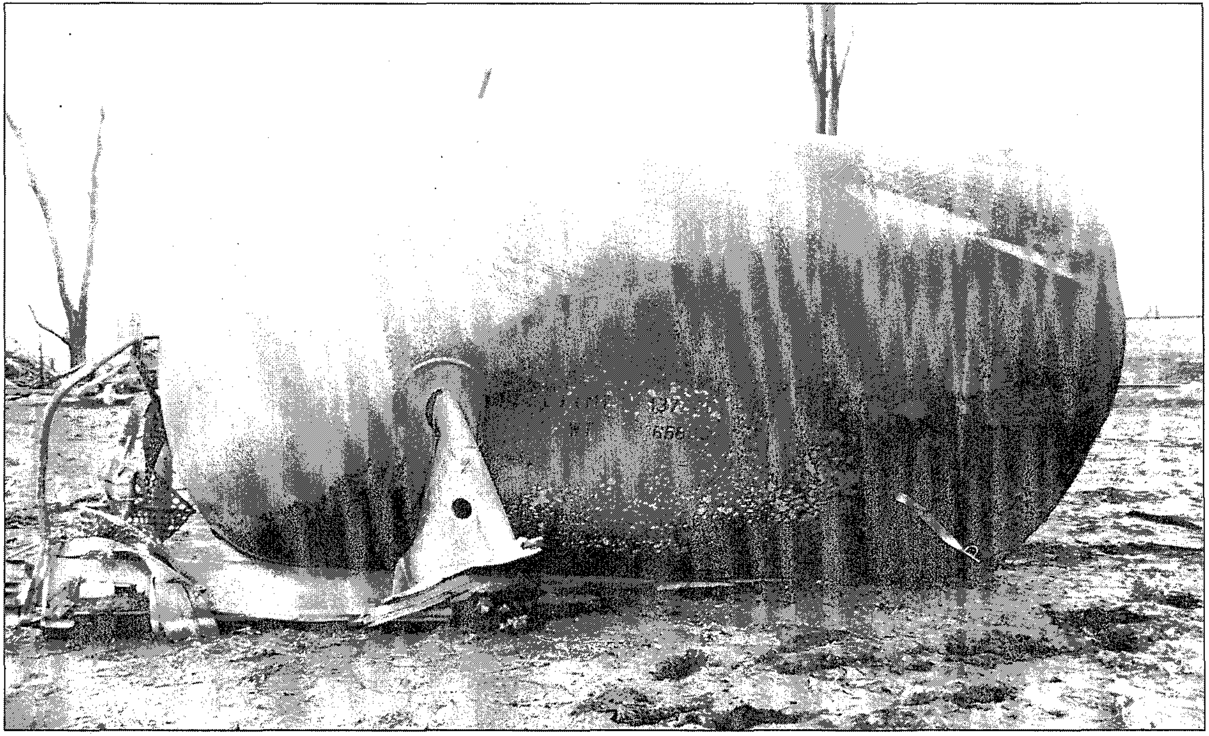

Figure 5: Arcadia, OH derailment UTLX211623 ("rocket" landed approximately 100 yards from "dance floor")

Figure 6: Arcadia, OH derailment ADMX29420 ("dance floor")

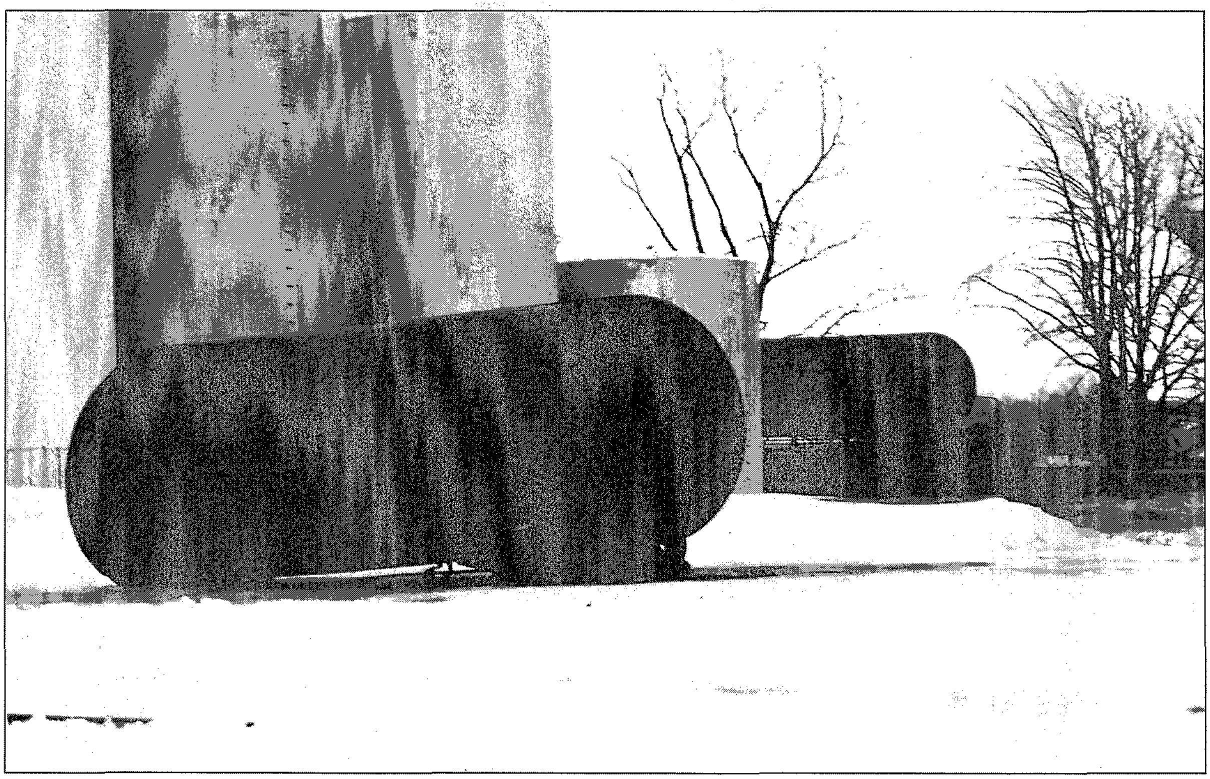

Figure 7: ADMX29420 (" rocket" landed approximately 300 feet from "dance floor")

New Brighton

Car number	Location in derailment	Location in consist	Shell material	thickness	normalized	Build date	PRV number	Flow	Req'd flow	STDP
SHPX206699	6	28	TC-128	7/16"	No	9/30/03	1	20,555	20,420	75

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Figure 8: New Brighton, PA derailment SHPX206699

Plevna

Car number	Location in derailment	Location in consist	Shell material	thickness	normalized	Build date	PRV number	Flow	Req'd flow	STDP
UTLX204772	2	21	TC-128B	7/16"		1/21/05	1	38,902	26,292	165
UTLX203411	8	27	TC-128B	7/16"		7/13/01	1	38,902	26,586	165
UTLX211777	11	30	TC-128B	7/16"		10/22/07	1	38,902	26,292	165
ACFX200416	1	20	TC-128B	7/16"		2/22/96	2	33,808	20,546	75
GATX200855	14	33	TC-128B	7/16"		11/21/03	1	21,602	10,846	75
NATX303405	13	32	TC-128B	7/16"	yes	12/6/06	1	35,608	11,120	165

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Approximately 90 minutes after the derailment around 4:30 PM, the fire chief reported that a tank car (GATX 200855) experienced a heat induced tear which separated the tank car into 3 parts. 2/3 of the tank car (B-end) was propelled approximately 400 feet southeast of the track and the head of the car (A-end) ended up approximately 450 feet northeast of the track. The 1/3 portion of the A-end of the car was split wide open and laid flat about 50 feet north of the track.

Between 4:45 and 6:30 PM, three tank cars (UTLX 203411, UTLX 211777, and NATX 303405) experienced heat induced tears resulting in fiery explosions. Between 6:30 and 7:00 PM, two more tank cars (ACFX 200416 and UTLX 204772) experienced heat induced tears and also exploded. The fire firefighters on hand reported hearing some of the pressure relief devices "whistle" for 5-10 minutes before seeing the fireballs of the explosion.

Figure 9: Plevna, MT derailment UTLX204722

Figure 10: Plevna, MT derailment UTLX203411

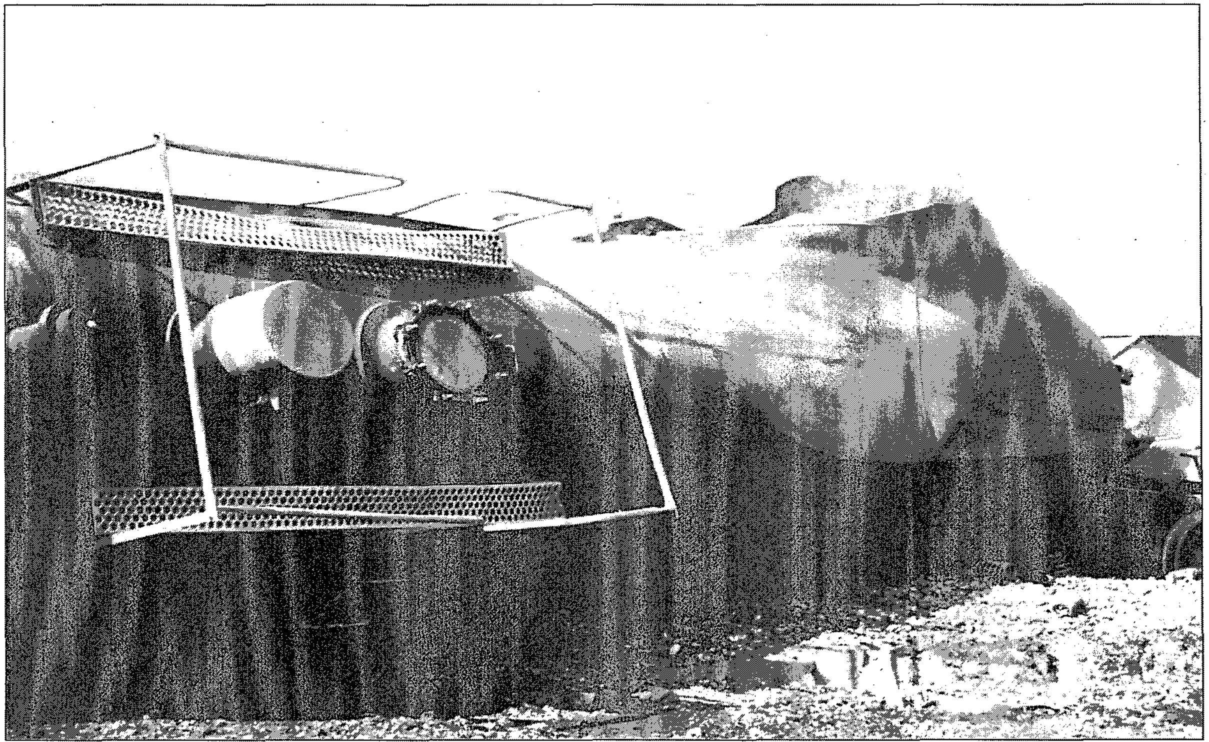

Figure 11: Plevna, MT derailment UTLX211777

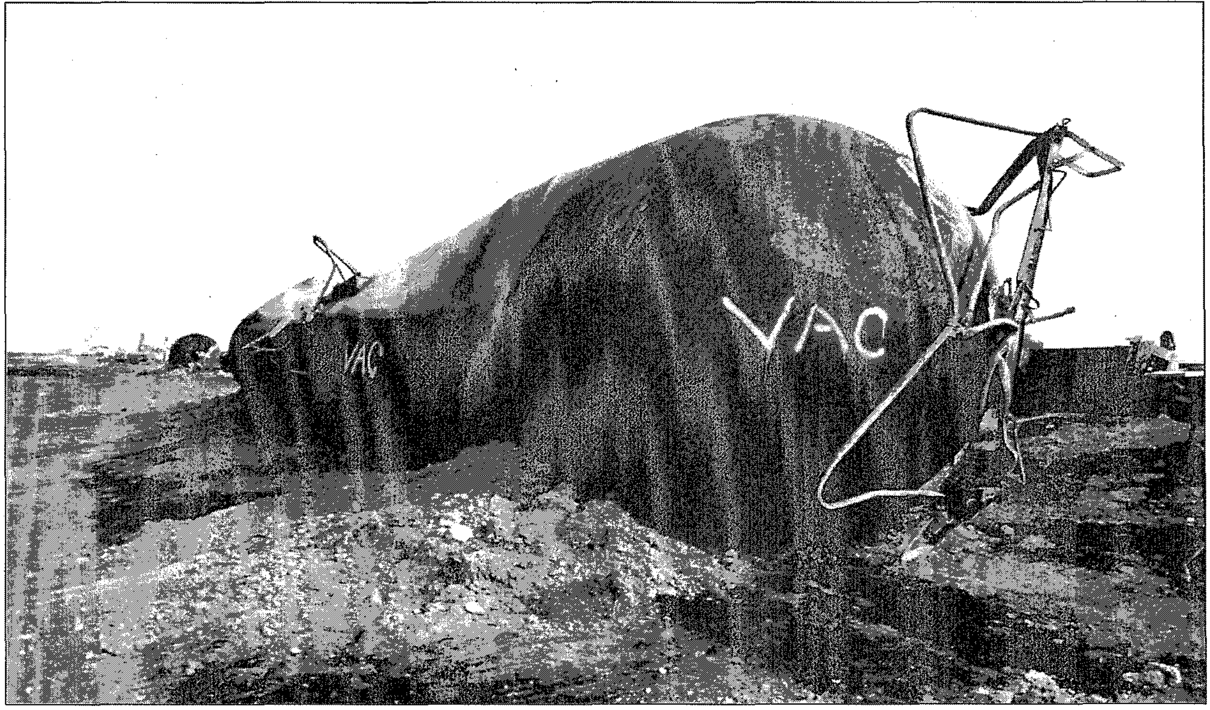

Figure 12: Plevna, MT derailment NATX303405

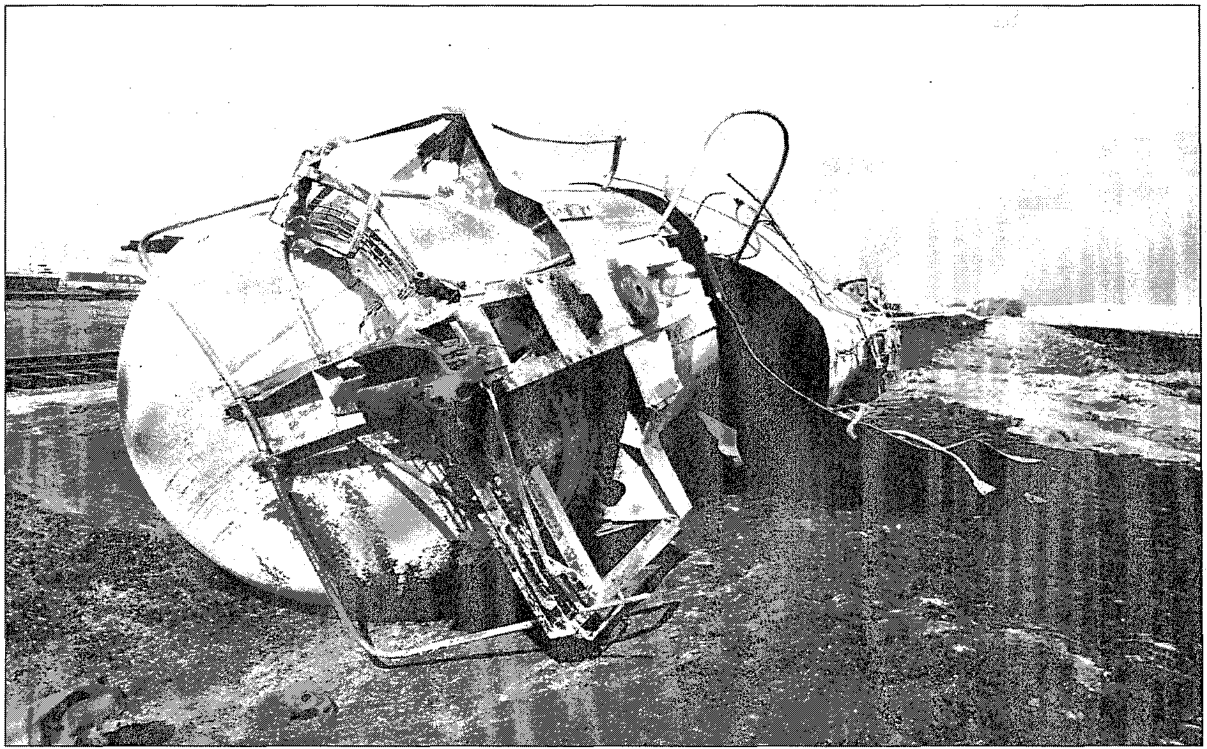

Figure 13: Plevna, MT derailment ACFX200416

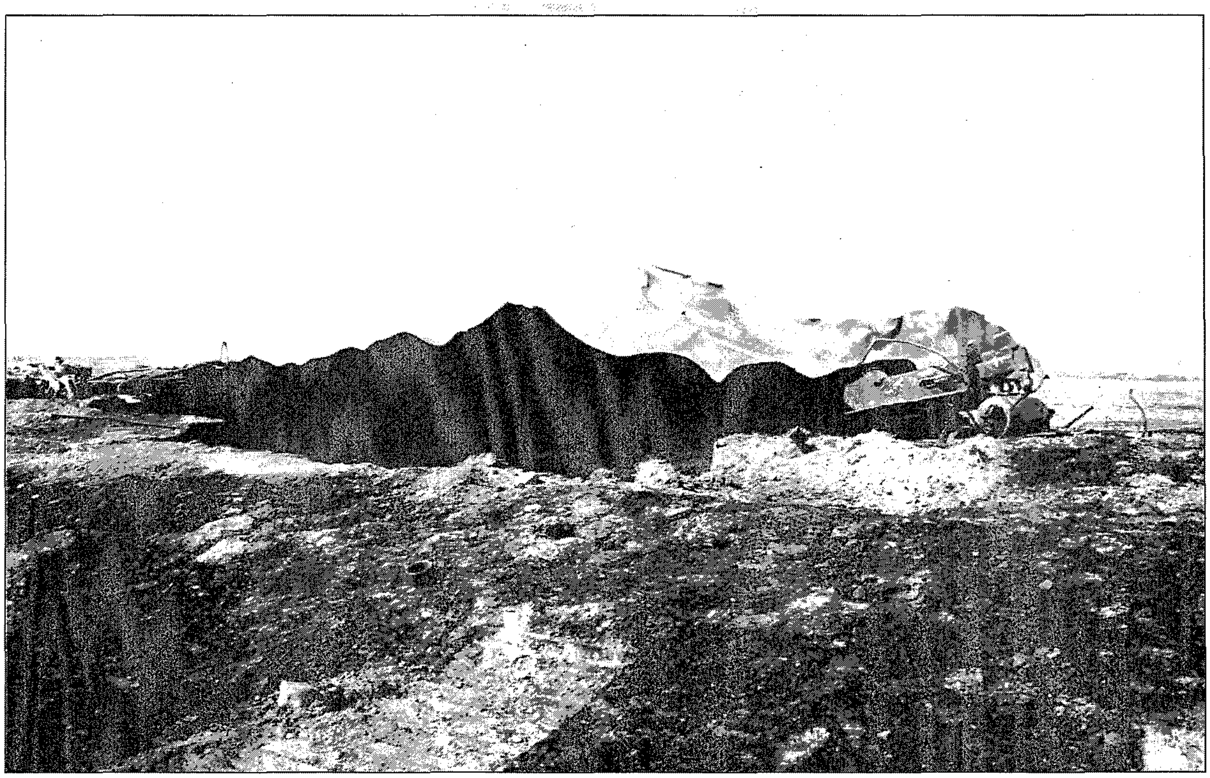

Figure 14: Plevna, MT derailment GATX200855

Columbus

Car number	Location in derailment	Location in consist	Shell material	thickness	normalized	Build date	PRV number	Flow	Req'd flow	STDP
NATX364017	10	12	TC-128	7/16"	Yes	5/1/07	1	21602	20,520	75

NATX364118	12	14	TC-128	7/16"	Yes	7/1/07	1	21602	20.520	75

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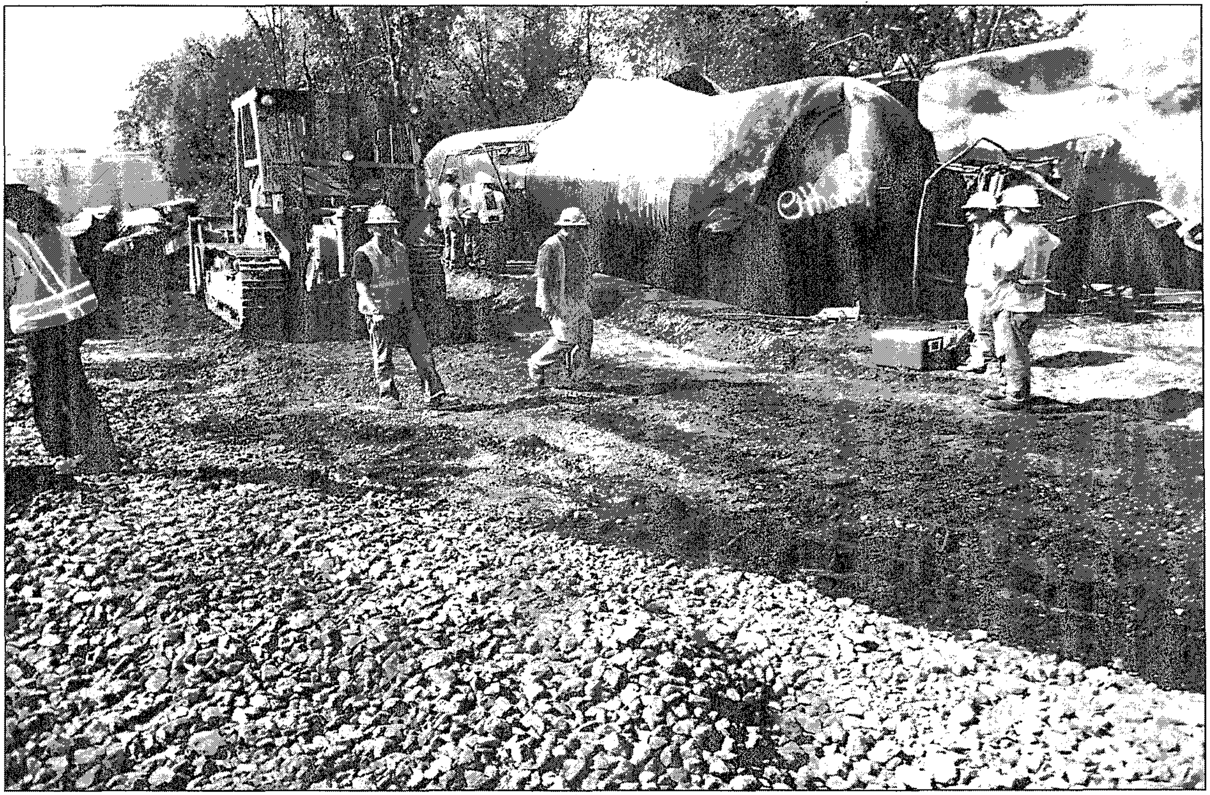

Figure 15: Columbus, OH derailment NATX364017

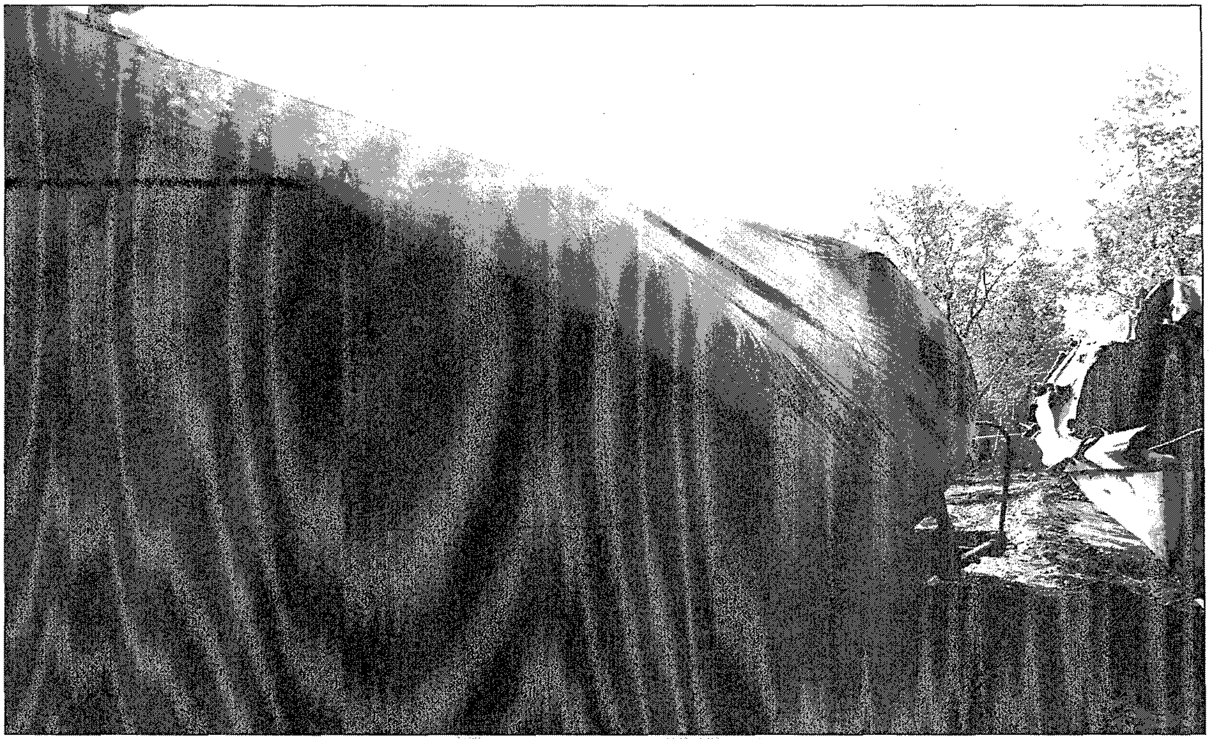

Figure 16: Columbus, OH derailment NATX364118

Tiskilwa

Car number	Location in derailment	Location in consist	Shell material	thickness	normalized	Build date	PRV number	Flow	Req'd flow	STDP
UTLX204101	4	22	TC-128B	7/16"	No	3/5/04	1	38,902	26,292	165
TILX290381	5	23	TC-128B	7/16"	No	1/17/03	1	21,602	10,846	75
GATX203706	6	24	TC-128B	7/16"	No	2/25/05	1	21,602	10,846	75

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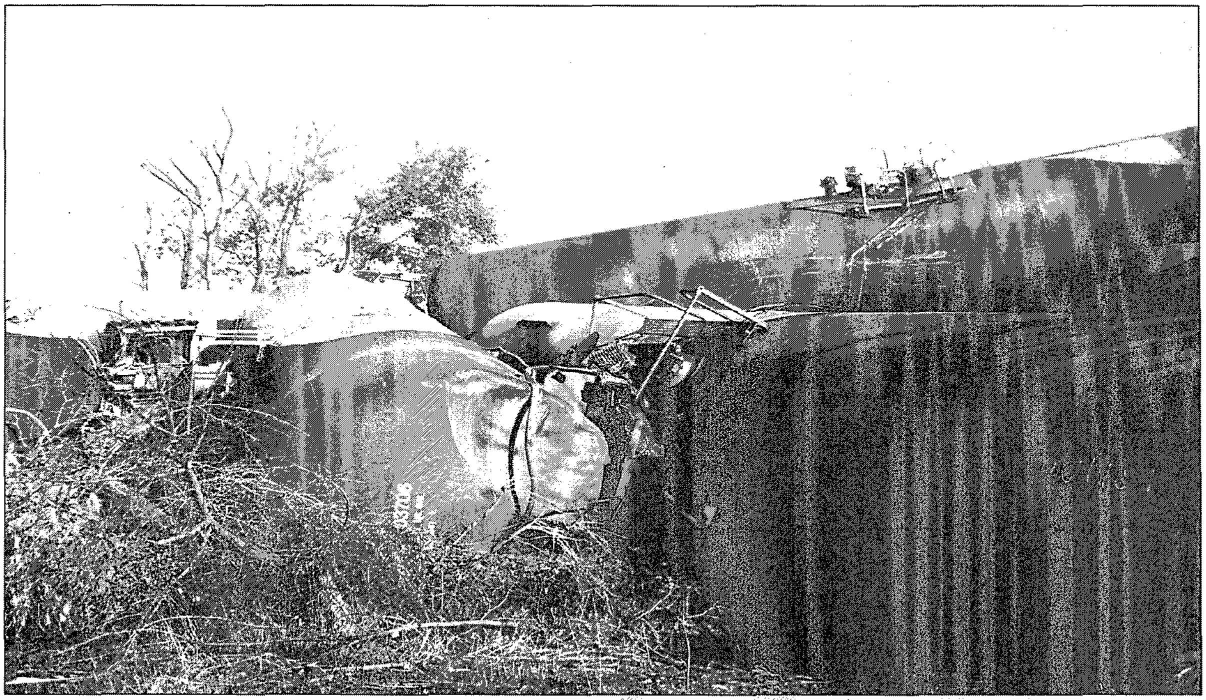

Figure 17: Tiskilwa, Il derailment UTLX204101

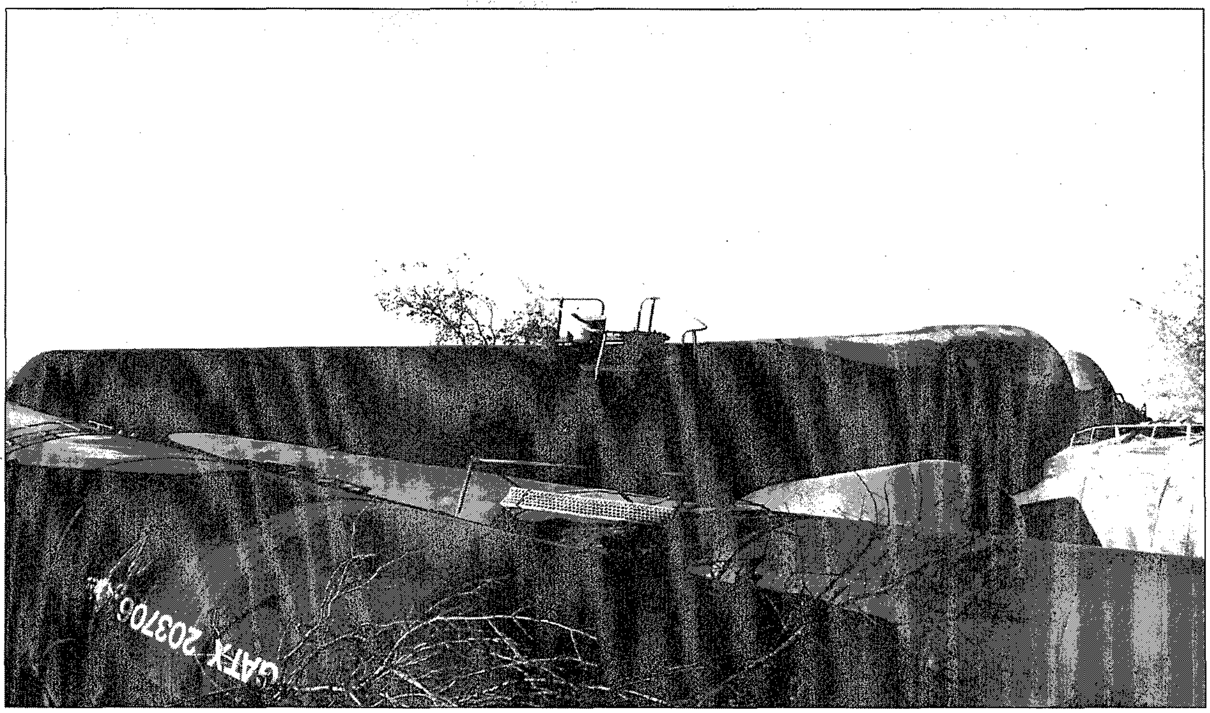

Figure 18: Tiskilwa, Il derailment TILX290381

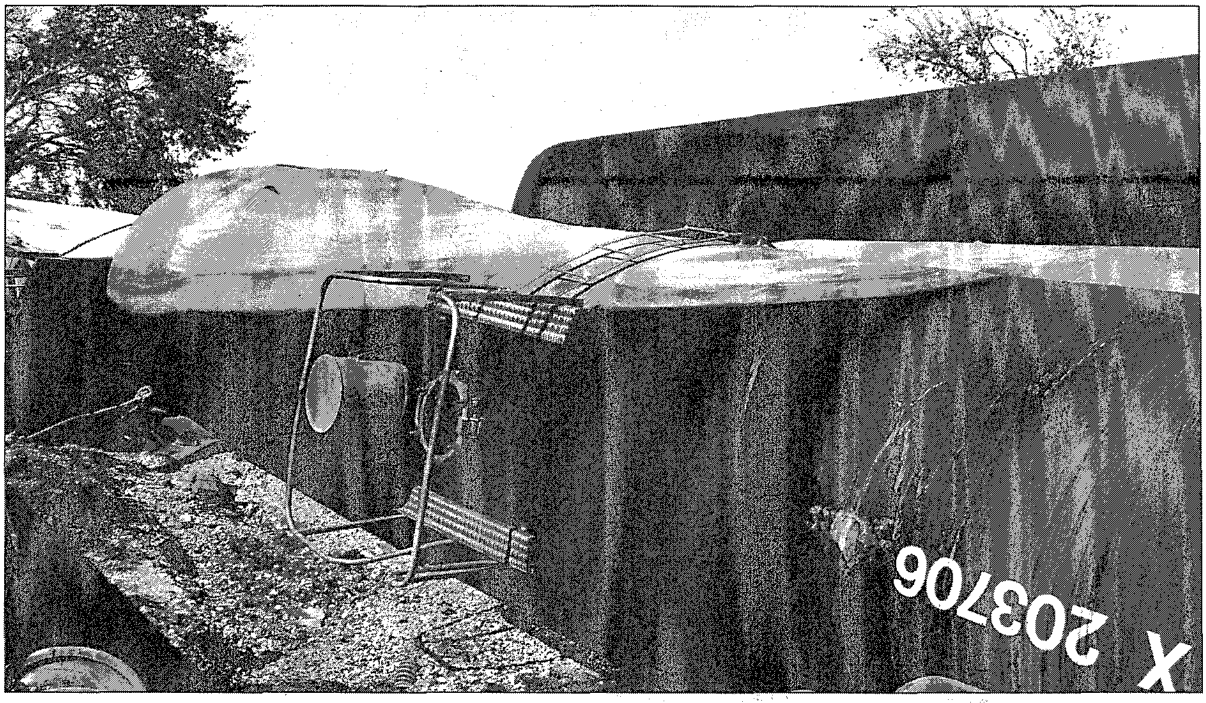

Figure 19: Tiskilwa, Il derailment GATX203706

Aliceville

Car number	Location in derailment	Location in consist	Shell material	thickness	normalized	Build date	PRV number	Flow	Req'd flow	STDP
UTLX210592	2	3	TC-128	7/16"	no	4/23/07	1	38,902	26,292	165
UTLX207353	5	6	TC-128	7/16"	no	9/1/07	1	38,902	26,292	165
SHPX208867	21	22	TC-128	7/16"	no	2/15/08	1	20,605	20,515	75
SHPX205274	22	23	TC-128	7/16"	no	4/12/02	1	20,605	20,520	75
UTLX210577	24	25	TC-128	7/16"	no	4/23/07	1	38,902	26,292	165

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Figure 20: Aliceville, AL derailment UTLX210592

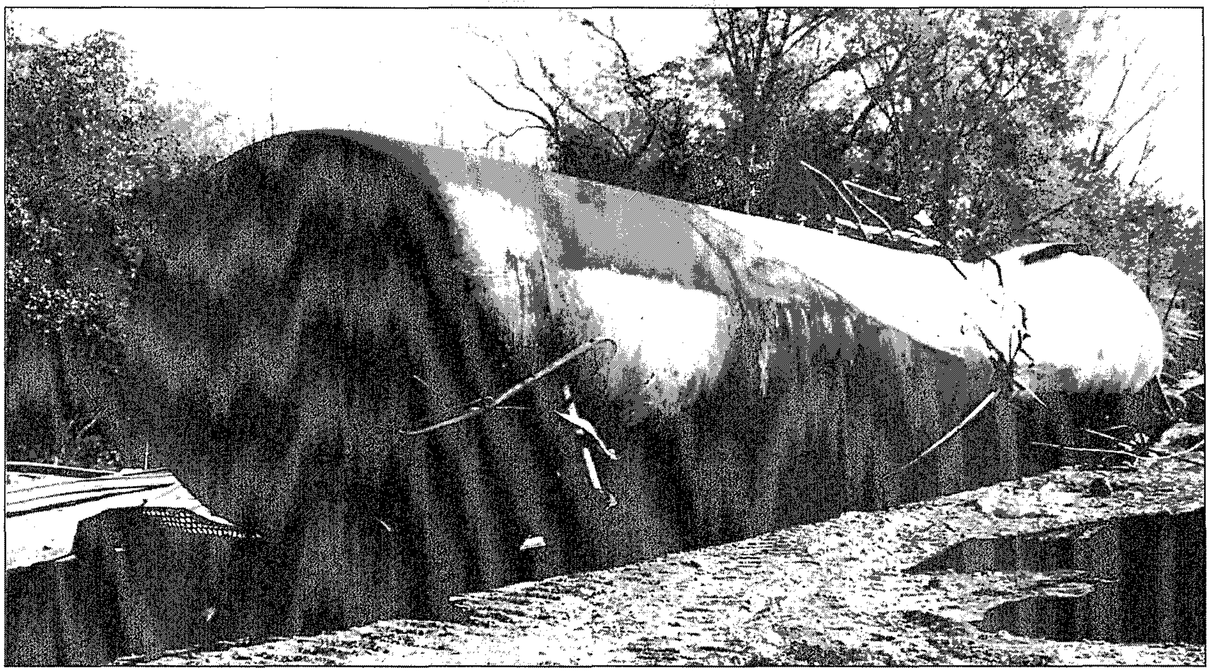

Figure 21: Aliceville, AL derailment UTLX207353

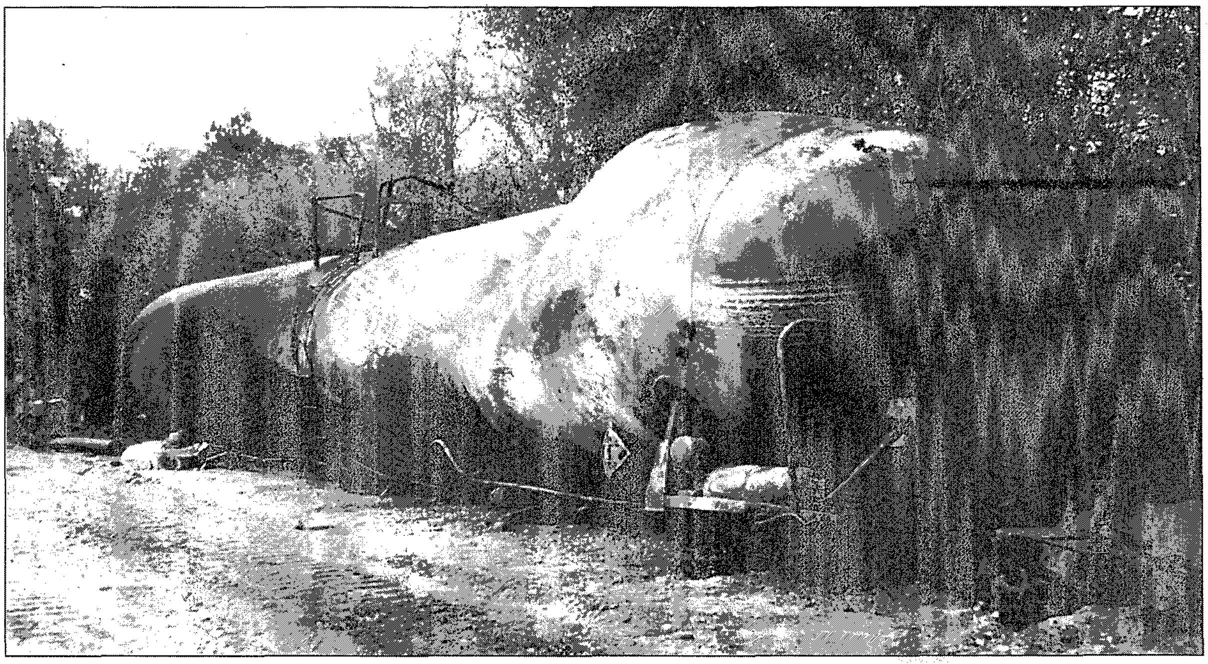

Figure 22: Aliceville, AL derailment SHPX208867

Figure 23: Aliceville, AL derailment SHPX205274

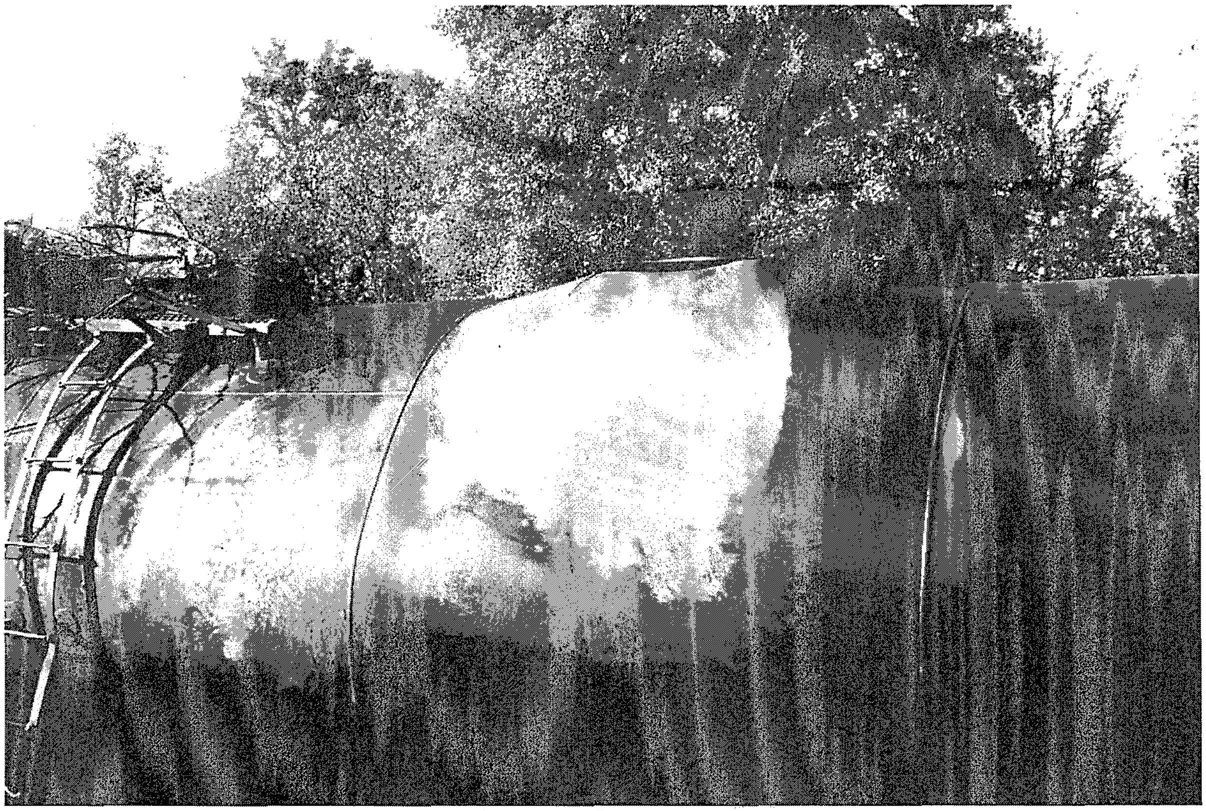

Figure 24: Aliceville, AL derailment UTLX210577

Casselton, ND

Car number	Location in derailment	Location in consist	Shell material	thickness	normalized	Build date	PRV number	Flow	Req'd flow	STDP
GATX33125	17	17	TC-128B	7/16"	No	6/1/05	1	21,602	10,846	75
SHPX208638	10	10	TC-128B	7/16"	No	3/1/08	1	20,605	20,520	75
GATX33119	2	2	TC-128B	7/16"	No	6/1/05	1	21,602	10,846	75

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Figure 25: Casselton, ND derailment GATX33125

Figure 26: Casselton, ND derailment SHPX208638

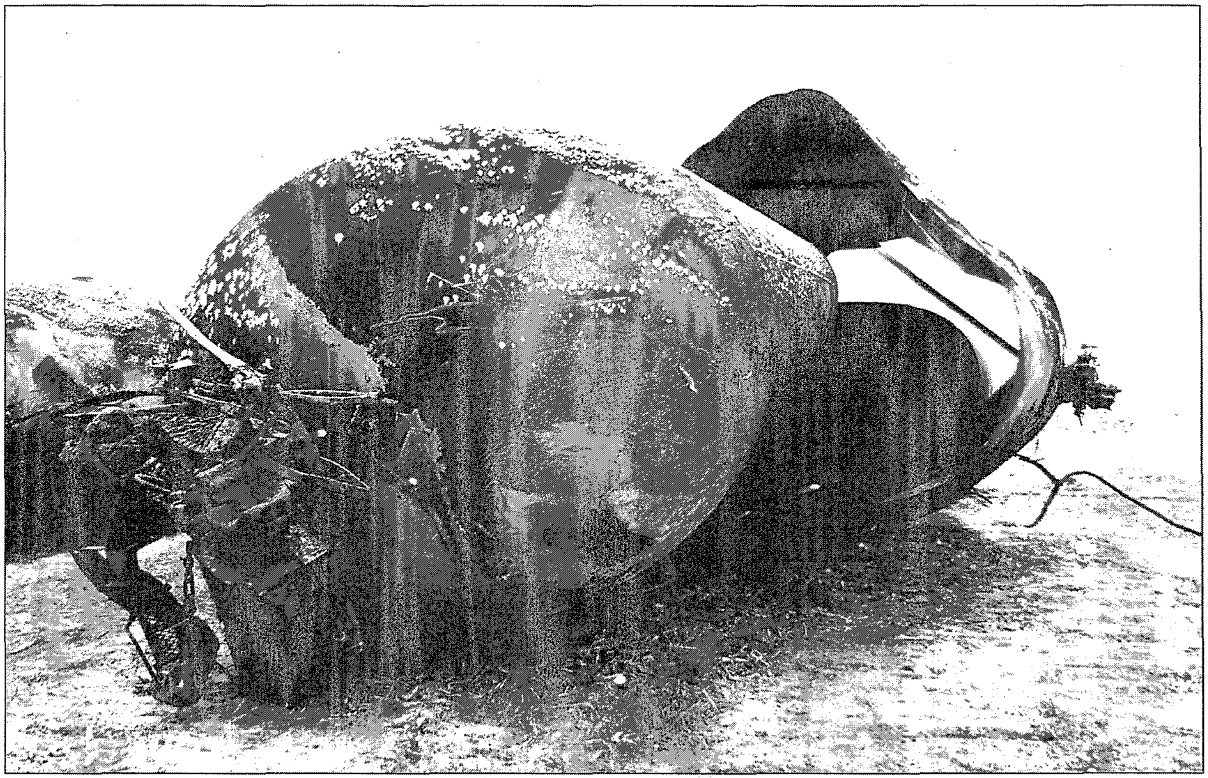

Figure 27: Casselton, ND derailment GATX33119

Lac-Megantic

Car number	Location in derailment	Position in consist	Shell material	thickness	normalized	Build date	PRV number	Flow	Req'd flow	STDP
WFIX130608	4	2	TC128B	7/16"	No	4/29/11	1	20,464	19,841	75
TILX316333	18	16	TC128B	7/16"	No	4/29/11	1	20,464	19,841	75
PROX24293	26	24	TC128B	7/16"	No	12/1/06	1	38,902	26,929	165
NATX310515	63	61	TC128B	7/16"	Yes	5/5/11	1	38,902	28,253	165

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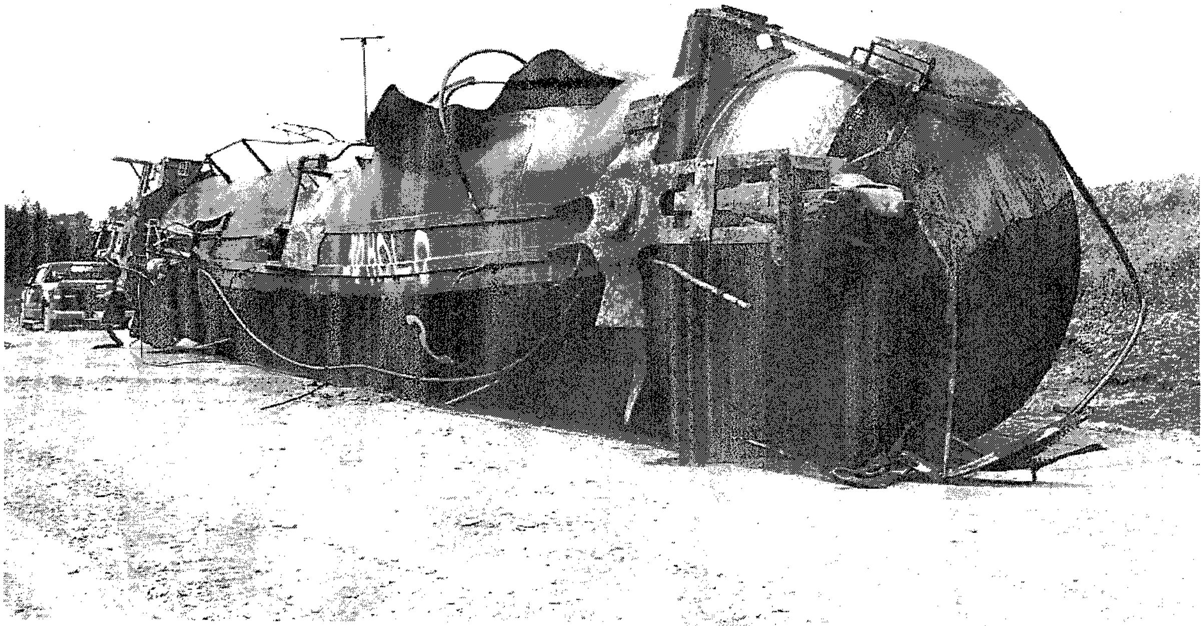
Figure 28: Lac-Megantic derailment WFIX130608

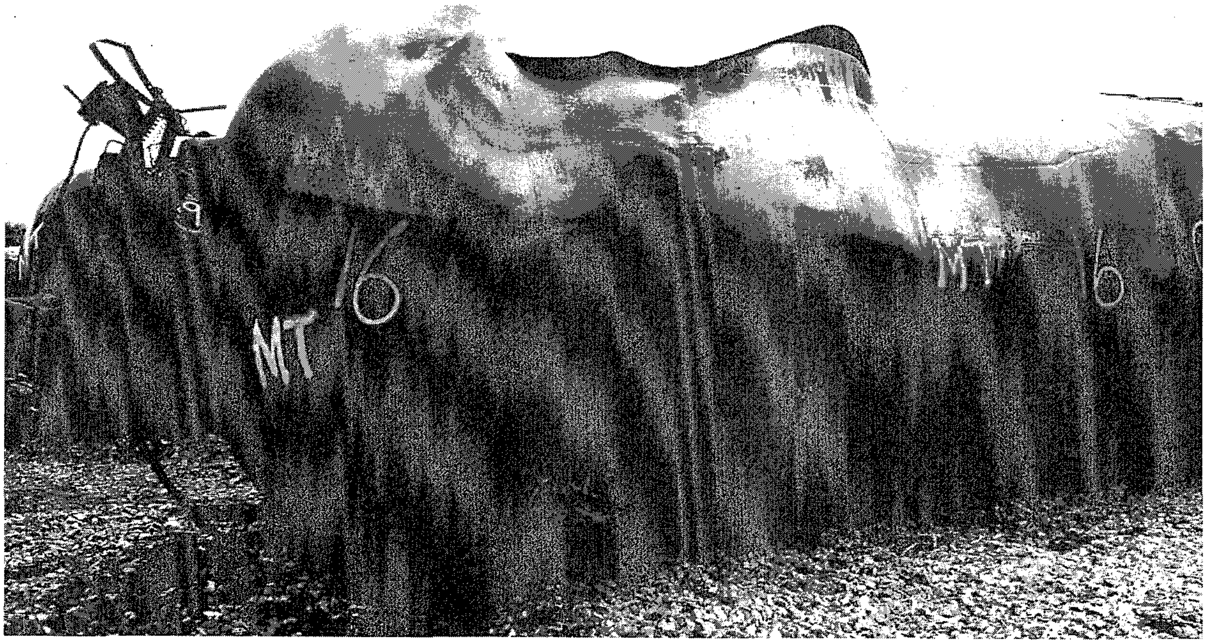

Figure 29: Lac Megantic derailment TILX316333

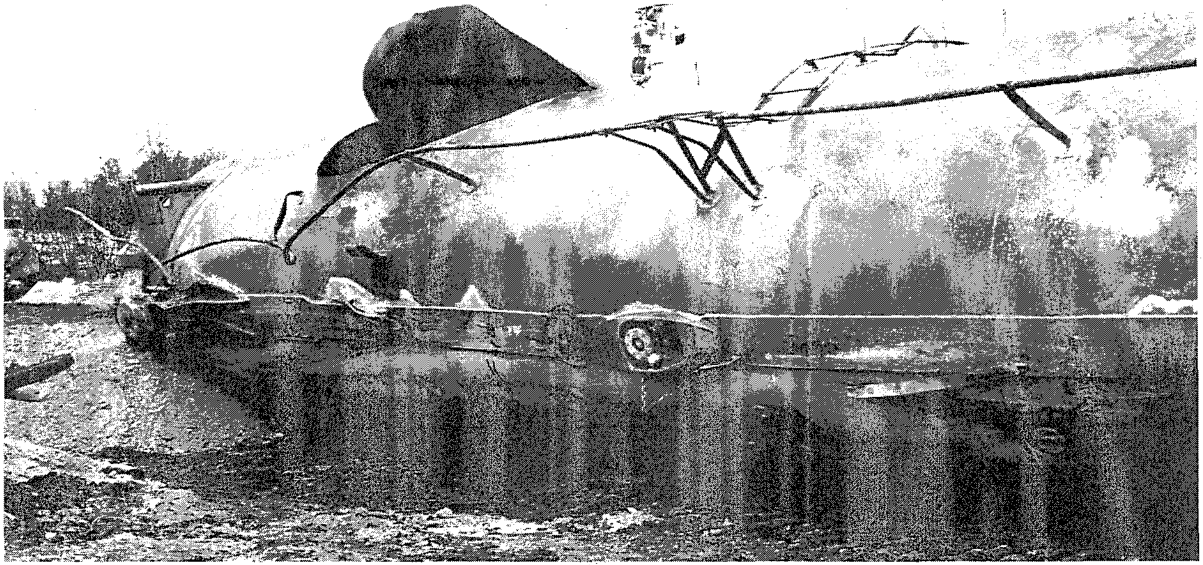

Figure 30: Lac-Megantic derailment PROX44293

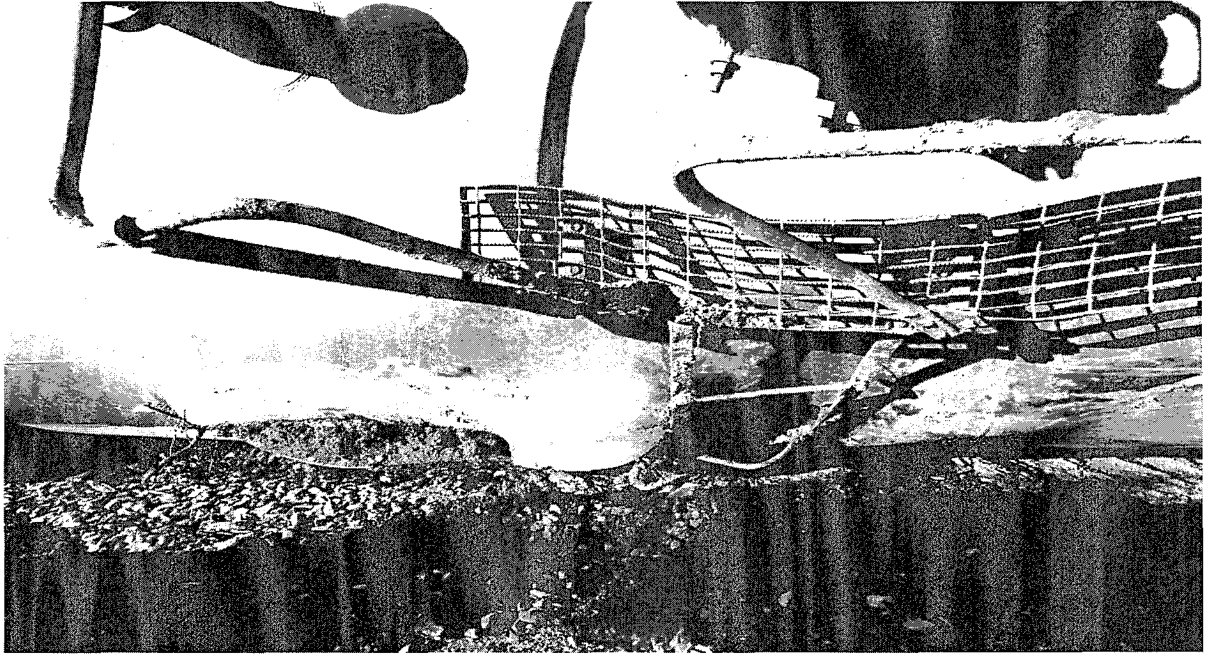

Figure 31: Lac-Megantic Derailment NATX310515

Appendix B – Summary of damage to tank cars involved in the derailments in Luther, OK[1]

Car number	Location in derailment	Position in consist	Shell material	thickness	normalized	Build date	PRV number	Flow	Req'd flow	STDP
UTLX201925	-	-	516-70	7/16"	No	3/01/89	1			
TILX194831	-	-	TC128	7/16"	No	4/1/2007	1	-	-	-
TILX193325	-	-	TC128	7/16"	No	2/1/2006	1	-	-	-

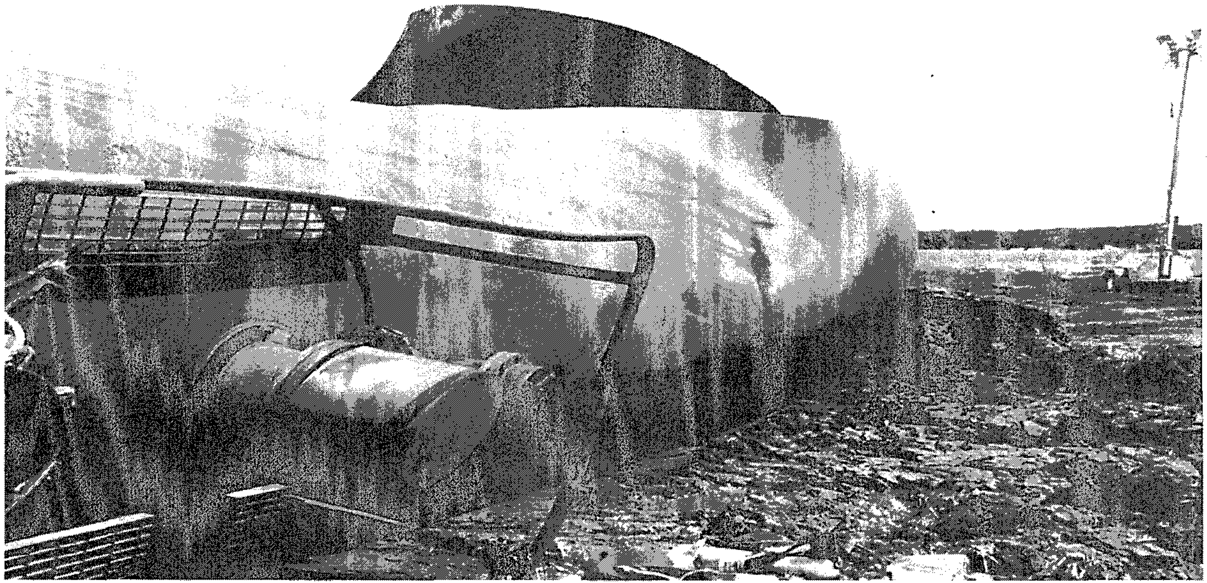

Figure 1: Luther, OK derailment UTLX 201925

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[1] The material was classified as Class 3, Packing group III.

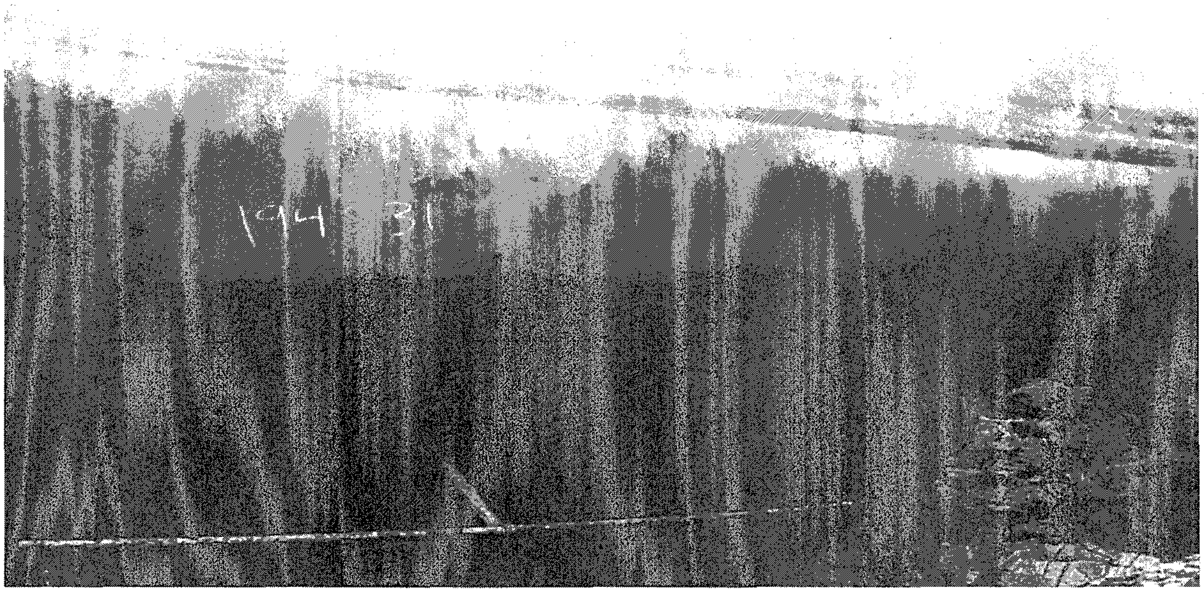

Figure 2: Luther, OK derailments TILX194831

Figure 3: Luther, OK TILX193325

Appendix C - Summary of observations at derailments of trains transporting crude oil and denatured alcohol

- Timing of explosions – In two derailments occurrence of explosions was recorded.
    - Arcadia
        - Alarm received at 2:16 a.m.
        - Arrived on site at 2:24 a.m.
        - Three distinct explosions were recorded in the Fire Department report.
    - Columbus
        - At 2:04 a.m. the Columbus Fire Department received a 911 call reporting a train derailment and fire. The train conductor reported an explosion occurred at 2:32 a.m. The first responder (Battalion Chief 3) reported a large blast/ explosion occurred at 2:39 a.m.
- Liquid line/vapor space (relative to pressure relief valve) – in all cases the car rotated around the longitudinal axis and in 26 of the 29 tank cars under consideration the pressure relief device was below the liquid line in the tank.
- Thinning of steel
    - Measurements - The original thickness of the steel is 0.4375" (nominal)
        - Arcadia (ADMX30917) – Thickness measurements were taken circumferentially (perpendicular from the longitudinal fracture surface.

Measurement Number	Edge	1"	1'	2'	3'	2'	1'	5"	Edge
thickness	.282	.307	.406	.428	.431	.427	.429	.359	.267

- Luther, OK (TILX201925) - Sampling of thickness measurements taken along edge of fracture surface.

Measurement Number	1	2	3	4	5	6	7	8	9
thickness	.285	.285	.312	.322	.356	.300	275	.220	.220

- Tiskilwa, IL (UTLX201401) – Thickness measurements taken along the fracture surface.

Distance from termination of crack	6"	12"	18"	24"	30"	36"
thickness	.213	.226	.223	.322	.239	.218

- Photographs – Below is a photo of the "knife edge" of the fracture surface of tank car UTLX211623 involved in the Arcadia, OH derailments. A pencil with a width of 5/16" is used as a reference. The measured thickness was less than 1/8".

Figure 1: Thinning of shell of UTLX211623

- Bubble around thermal tear is a result of plastic deformation to the shell wall as a result of weakening of the shell materials and the increasing principal stress.
- The length of the thermal tears ranged from 2 – 16 feet prior to crack arrest. These events are not BLEVES. All BLEVEs lead to a shock waves and rocketing fragments of ruptured vessels. It has been suggested that for a BLEVE to occur the tank must first be weakened where an initial pinhole is formed. This may occur due to plastic thinning of the heated wall or it may form at a flaw in the tank wall. The initial rupture normally grows in a direction perpendicular to the principal stress (hoop stress). In some cases the crack may arrest at stronger materials or because of a decrease in the pressure in the tank. The reduction in pressure occurs following a transient jet release. The jet release will have significant impact on the geometry of the fireball and its rapid rise[1].
- Twenty-four thermal tears
- Tank cars with thermal tears retain the lading (the materials is not released to prolong the fire)
- Based on a paper prepared by Queen's University[2], there is a direct relationship between the amount of material remaining in the tank at the time of breach and the violence of the overall failure.
- If the length of the thermal tear is similar to the diameter of the tank the size of the explosion will be similar to those seen in classic BLEVEs. The magnitude of the explosion (detonation or shockwave strength) generated by the BLEVE depends on the degree of superheat of the liquid, its thermodynamic properties, and the rapidity of depressurization. A relatively slow tear of the tank shell will result in a continuous depressurization followed by the release of vapor that may burn as a fireball but without explosion. However, if the tear is very rapid (opening of the tank

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1 Abassi, T., Abassi, S.A., "The boiling liquid expanding vapor explosion (BLEVE): Mechanism, consequence assessment, management", Journal of Hazardous Materials, 141(2007) 489-519.

2 "Fire Tests of Propane Tanks to Study BLEVEs and Other Thermal Ruptures: Detailed Analysis of Medium Scale Test Results", Department of Mechanical Engineering, Queen's University, Kingston, Ontario, Nov 1997.

wall is seconds) it will result in an extremely rapid boiling of the liquid inside of the tank and the release of a very large mass of vapor in a very short time resulting in the formation of a true explosion and a very large subsequent fireball.

- Three near complete separations
- Two complete separations