



U. S. CHEMICAL SAFETY AND HAZARD INVESTIGATION BOARD

INVESTIGATION REPORT

PROPANE TANK EXPLOSION (2 DEATHS, 7 INJURIES)



Herrig Brothers Feather Creek Farm
Albert City, Iowa
APRIL 9, 1998

KEY ISSUES:

- DESIGN & INSTALLATION DEFICIENCIES
- REGULATORY OVERSIGHT
- BLEVE HAZARD & EMERGENCY RESPONSE

Report No. 98-007-I-IA

Abstract: This report explains the explosion/BLEVE that took place on April 9, 1998, at the Herrig Brothers Feather Creek Farm, located in Albert City, Iowa. Two volunteer fire fighters were killed and seven other emergency response personnel were injured. Safety issues covered in the report include protection of propane storage tanks and piping, state regulatory oversight of such installations, and fire fighter response to propane storage tank fires. Recommendations concerning these issues were made to the Herrig Brothers Feather Creek Farm, the Iowa State Fire Marshal, the Fire Service Institute of Iowa State University, and the National Propane Gas Association.

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EXECUTIVE SUMMARY

ES.1 INTRODUCTION

On April 9, 1998, at approximately 11:28 pm, an 18,000-gallon propane tank exploded at the Herrig Brothers Feather Creek Farm (the farm) in Albert City, Buena Vista County, Iowa. The explosion killed two volunteer fire fighters and injured seven other emergency response personnel. Several buildings were also damaged by the blast.

ES.2 INITIATING EVENT

The farm raised turkeys, which were housed in seven barns. Space heaters and furnaces provided heat for these turkey barns. Fuel for these space heaters and furnaces was supplied by a propane storage and handling system that included the propane tank that exploded.

On the evening of the incident, eight high-school-aged teens gathered at the farm for a party. According to one of the co-owners of the farm, the youths had attended similar social gatherings at the farm on other dates, but with neither the knowledge nor the consent of the owners. Neither owner lived at the farm.

At approximately 11:00 pm, one of the youths began driving an all-terrain vehicle (ATV) around the farm. Then the driver of the ATV picked up a passenger and continued his ride. The ATV was heading east between the propane tank and a turkey barn when it struck two aboveground propane pipes (liquid and vapor lines) that ran parallel to one another from the propane tank to direct-fired vaporizers approximately 37 feet to the north of the tank. (The direct-fired vaporizers were components of the system that used heat to transform liquid from the tank into a

gas that was piped to space heaters and furnaces on the farm.) The ATV damaged both the liquid and vapor lines.

The liquid line (which measured approximately $\frac{3}{4}$ -inch inside diameter) was completely severed from the tank at the location where it was connected to a manual shut-off valve directly beneath the tank. An excess flow valve protecting the liquid line failed to function, and propane leaked out of the tank at the point of the break. As the liquid propane sprayed out of the tank, it rapidly changed to vapor. Propane vapor may have also leaked from the damaged vapor line. Within a few minutes, propane from the damaged lines ignited, most likely when it reached one of the direct-fired vaporizers approximately 37 feet away. A fire, fed by the broken liquid line, began burning vigorously under the tank. Two of the teenagers drove to the home of a neighbor, approximately $\frac{1}{2}$ mile from the farm, to report what had happened. At 11:10 pm, the neighbor called the 911 operator to report the fire.

Twenty members of the Albert City Volunteer Fire Department and two Buena Vista County Sheriff Deputies were the first responders to reach the farm. Upon arrival at about 11:21 pm, the fire fighters observed flames originating from two primary locations: from under the west end of the tank and from the pressure relief valve pipes located on the top of the tank. One fire fighter reported that the “west end of the tank [near the broken liquid line] was *engulfed* in flames” (emphasis added). Another stated that “the propane tank was fully engulfed and flames were 70-100 yards in the air.” Fire fighters stated that the noise from the pressure relief valves was “like standing next to a jet plane with its engines at full throttle.”

At approximately 11:28 pm, as fire-fighting equipment was being moved into position, the tank exploded, scattering metal tank fragments in all directions. One large piece of the tank traveled in a northwesterly direction, striking and killing two volunteer firemen. Seven other emergency personnel sustained injuries as a result of the explosion.

ES.3 KEY FINDINGS

- The explosion that occurred at the farm is known as a Boiling Liquid Expanding Vapor Explosion or BLEVE. A BLEVE can occur when a pressure vessel containing a flammable liquid, like a propane tank, is exposed to fire. The book, *Loss Prevention in the Process Industries*, provides the following description of a BLEVE:

When a vessel containing a liquid under pressure is exposed to fire, the liquid heats up and the vapour pressure rises, increasing the pressure in the vessel. When this pressure reaches the set pressure of the pressure relief valve, the valve operates. The liquid level in the vessel falls as the vapour is released to the atmosphere. The liquid is effective in cooling that part of the vessel wall which is in contact with it, but the vapour is not. The proportion of the vessel wall which has the benefit of liquid cooling falls as the liquid vaporizes. After a time, metal which is not cooled by liquid becomes exposed to the fire; the metal becomes hot and then may rupture.

- In this incident, the tank was engulfed in flames due to a leak of propane under the tank. These flames created the conditions that produced the BLEVE.
- Neither the propane tank nor its aboveground piping were protected by a fence or any other physical barrier designed to prevent damage from vehicles.
- The propane tank was equipped with an excess flow valve to protect the tank's liquid line leading to the vaporizers. In the event of a complete break in the liquid line downstream from the valve, it was designed to close and greatly reduce the flow of propane from the broken pipe. (Even when an excess flow valve is activated, a small amount of fluid bleeds through a tiny hole in the valve. Consequently, installation of a shut-off valve immediately downstream from the excess flow valve is required to stop all flow.) When the ATV severed the liquid line at this installation, however, the excess flow valve failed to close because the flow capacity of the outlet piping system downstream of the valve was less than the closing rating of the excess flow valve installed in the tank.
- Fire fighters were positioned too close to the burning propane storage tank when it exploded. They believed that they would be protected from an explosion if they avoided the ends of the tank.

- The propane storage and handling system was installed at the farm in 1988. When the tank system was installed, Iowa law provided that the 1979 edition of the National Fire Protection Association's *Standard for the Storage and Handling of Liquefied Petroleum Gases* (NFPA 58) governed the installation. Under NFPA 58 and other relevant Iowa law, the State Fire Marshal should have received a plan of the farm's propane tank storage and handling system before it was installed. Iowa law, however, did not specifically designate which party -- the owner or the installer of a large propane storage facility -- was required to notify the State Fire Marshal. The CSB's investigation revealed that the State Fire Marshal had no record of the system and that it was not installed in compliance with all NFPA 58 requirements adopted as Iowa law.

Root Causes

1. Protection for aboveground piping was inadequate.

Two aboveground pipes (liquid and vapor lines) that ran from the propane storage tank to its vaporizers were not protected from potential physical damage from vehicles. Lack of piping protection allowed a vehicle to crash into these pipes, breaking them and releasing the propane that ignited.

2. The diameter of the pipe downstream from an excess flow valve was too narrow, which prevented the valve from functioning properly.

An excess flow valve that was designed to stop the flow of all but an extremely small amount of liquid propane in the event of a severed line did not function because the diameter of the pipe downstream from the valve was too narrow to allow the valve to activate. Post-incident tests of the valve showed that it would have operated as designed if the pipe downstream had been the proper size. A functioning excess flow valve on the liquid line would have greatly reduced the severity of the fire that engulfed the tank. This likely would have prevented the BLEVE.

3. Fire fighter training for responding to BLEVEs was inadequate.

Some training materials provided to the fire fighters led them to believe that they would be protected from a propane tank explosion by positioning themselves to the sides of the tank and by avoiding the areas extending from the two ends of the tank. As a consequence, fire fighters were positioned too close to the sides of the burning propane storage tank when it exploded. Fire fighters did not adequately recognize the potential for a BLEVE and that a BLEVE can scatter tank fragments in all directions. In this incident, flying tank fragments from the explosion killed two fire fighters located approximately 100 feet from the side of the tank.

Contributing Cause

The State Fire Marshal did not detect deficiencies in the design and installation of the propane storage facility.

Under Iowa law, the State Fire Marshal should have received a plan of the farm's propane system prior to its installation in 1988. The State Fire Marshal had no record of the farm's system, however. Iowa law did not specifically designate which party -- the owner or the installer of a large propane tank facility -- was required to notify the State Fire Marshal. In addition, the State Fire Marshal did not have a program in place to adequately monitor or inspect large propane storage facilities.

ES.4 RECOMMENDATIONS

Herrig Brothers Farm

1. Install protection (i.e., fencing or barricades) to protect aboveground propane pipes from possible damage from vehicles.

2. Install properly sized propane outlet piping from excess flow valves.

Iowa State Fire Marshal

Develop a program to ensure implementation of the requirements of the National Fire Protection Association's *NFPA 58 Standard for the Storage and Handling of Liquefied Petroleum Gases*, as adopted by Iowa law. Ensure that this program includes, at a minimum, the following elements:

- Designation by regulation of the party (such as a facility owner or installer) who is responsible for submitting planned construction or modification documents to the State Fire Marshal;
- Procedures for approving the plans for new or modified installations;
- Procedures governing the issuance and posting of permits authorizing the use of equipment; and
- On-site inspections of new, modified, and existing propane and other Liquefied Petroleum Gas storage facilities that are covered by Iowa state law.

Fire Service Institute of Iowa State University

Ensure that fire fighter training materials address proper response procedures for BLEVEs.

National Propane Gas Association (NPGA)

1. Ensure that fire fighter training materials address proper response procedures for BLEVEs.
2. Distribute the CSB findings and recommendations in this report to NPGA members.

1.0 INTRODUCTION

1.1 BACKGROUND

On April 9, 1998, at approximately 11:28 pm, an 18,000-gallon propane tank exploded at the Herrig Brothers Feather Creek Farm (the farm) in Albert City, Iowa. The blast occurred less than half an hour after an all-terrain vehicle (ATV), driven by a minor without the owner's permission, damaged two aboveground propane pipes and a fire resulting from that accident engulfed the tank. The explosion that occurred at the farm is known as a Boiling Liquid Expanding Vapor Explosion or BLEVE.¹ Tank fragments produced by the BLEVE killed two volunteer fire fighters.² In addition, seven other emergency response personnel were injured, and several buildings were damaged by the blast. The arrow in Figure 1 points to the location of the tank prior to the blast.



Figure 1. Aerial View of the Farm on April 10, 1998

¹ A BLEVE can occur when “a pressure vessel containing a flammable liquid like a propane tank is exposed to fire so that the metal loses strength and ruptures.” Lees, Frank P. *Loss Prevention in the Process Industries: Hazard Identification, Assessment and Control*, 2nd ed.; Butterworth-Heinemann: Oxford, England; 1996, Vol. 2, 17/177. For further discussion of BLEVEs, see section 3.3.

² In recent years, six other fire fighters have been killed in BLEVE incidents on farms. Duval, Robert. *Fire Fighter Fatalities Albert City Iowa April 9, 1998*; National Fire Protection Association: Quincy, MA, 1999; 27.

1.2 INVESTIGATION PROCESS

The scope of the investigation was to determine the root and contributing causes of the deaths and injuries to emergency response personnel. The investigation focused on the design and installation of the propane storage and handling system at the farm, state regulatory oversight of that and similar installations, and the fire fighter response to this incident. The ultimate objective of this investigation was to develop recommendations to help prevent similar incidents.

The investigation team conducted material and structural analyses to estimate what the pressure was when the tank ruptured, as well as failure mode and effects analysis to confirm that a BLEVE caused the tank's failure. Investigators identified deficiencies in the design of the propane storage and handling system. A NASA laboratory, the Kennedy Space Center Materials Science Division, performed an incident reconstruction analysis to determine why an excess flow valve³ protecting an aboveground liquid propane pipe failed to activate. A certified fire investigator from the Department of the Treasury's Bureau of Alcohol, Tobacco and Firearms examined tank fragments for evidence of significant flame patterns. Further discussion of the methodologies and test results used to determine the causes of the BLEVE is contained in Appendix A.

The U. S. Chemical Safety and Hazard Investigation Board (CSB) greatly appreciates the contribution of the following organizations which provided information or other assistance with respect to this investigation: Kennedy Space Center Materials Science Division; Department of the Treasury's Bureau of Alcohol, Tobacco and Firearms; Oak Ridge National Laboratory; the Iowa Labor Services Division⁴; Iowa State Fire Marshal's Office; Buena Vista County Sheriff's Department; National Fire Protection Association; and J.L. Hall Engineering Services, P.C.

³ An excess flow valve is designed to greatly reduce the flow of liquid from a pipe that is damaged in such a fashion that flow through the line exceeds a predetermined flow rate. For a detailed discussion of excess flow valves, see section 4.1.2.

⁴ Since the incident, the Iowa Labor Services Division has conducted a series of workshops for emergency responders which have included a discussion of lessons learned from this incident.

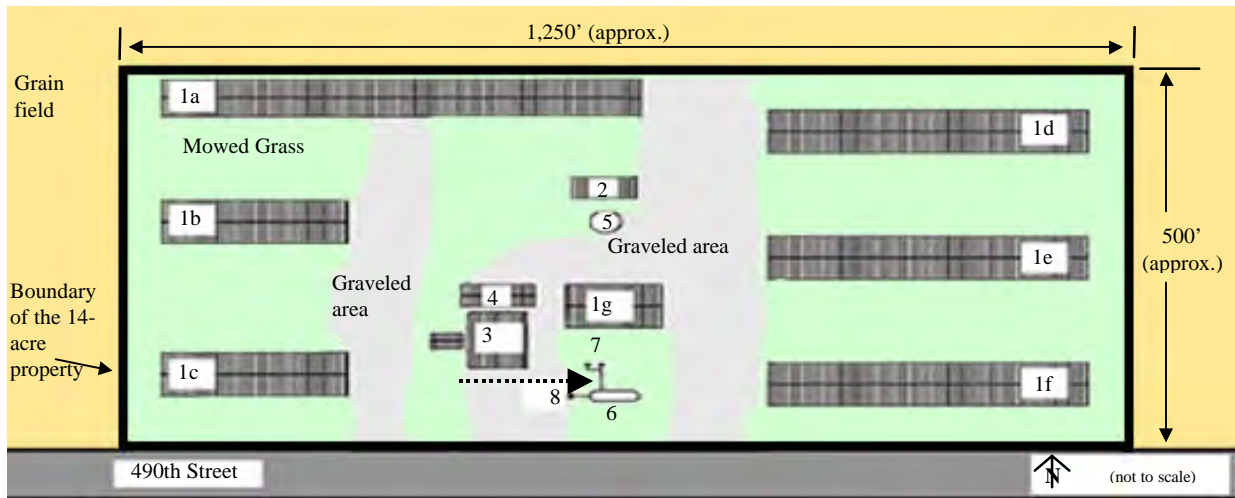
2.0 FARM OPERATION AND PROPANE SYSTEM

The farm, located on 14 acres in rural Iowa, housed approximately 50,000 turkeys in seven barns. In addition to its two co-owners, one full-time employee and two part-time employees were involved in operating the farm. The ATV was used solely for business purposes prior to the incident -- primarily the daily pickup of dead turkeys from the various building on the farm. The ATV towed a trailer, which was filled with turkey carcasses that were then deposited at a central collection point for pickup and disposal by a rendering company.

The Albert City area where the farm is located can be extremely cold during the winter months. For example, the mean daily temperature in January is 13.9°F. Even in April, the daily mean is approximately 46.7°F. Space heaters and furnaces provided heat for the farm's turkey barns. Fuel for these space heaters and furnaces was supplied by a propane storage and handling system that included a non-fireproofed⁵, 18,000-gallon propane tank located on the south side of the farm. (Propane is widely used on farms for heating and as a fuel for trucks, generators, and other farm equipment. According to the Iowa State Fire Marshal, the number of aboveground propane tanks in Iowa has increased significantly in recent years.)

This tank, which was originally fabricated in 1964, was installed on the farm in 1988. When the tank system was installed, Iowa law provided that the 1979 edition of the National Fire Protection Association's *NFPA 58 Standard for the Storage and Handling of Liquefied Petroleum Gases* governed the installation. At the time of the incident, the tank contained approximately 10,000 gallons of propane. The plot plan in Figure 2 on the following page shows the major buildings and structures on the farm. The dotted line represents the approximate path of the ATV that struck the propane piping near the tank.

⁵ Some propane storage tanks have an insulation-type fireproof coating applied to the outside of the tank to provide protection in a fire.



Major Buildings and Structures

- 1. Turkey barns (1a - 1g)
- 2. Machine shed
- 3. Office
- 4. Workshop
- 5. Feed storage bin
- 6. 18,000-gallon propane tank
- 7. Direct-fired vaporizers
- 8. Fueling truck point-of-transfer

Note:

- 1. Direct-fired vaporizers (Item 7) are located approximately 37 ft north of the 18,000-gallon propane tank (Item 6).
- 2. Fueling truck point-of-transfer (Item 8) is located approximately 40 ft west of the 18,000-gallon propane tank (Item 6).
- 3. South side of turkey barn 1g is approximately 87 ft north of the 18,000-gallon propane tank (Item 6).
- 4. Centerline of 490th Street is approximately 78 ft south of the 18,000-gallon propane tank (Item 6).

Figure 2. Plot Plan of Farm, 2243 490th Street, Albert City, Iowa

2.1 SYSTEM LAYOUT AND COMPONENTS

The propane tank, which was made of carbon steel, was approximately 42 feet long and 9 feet in diameter. It was located approximately 78 feet north of the 490th Street centerline (see Figure 2, item 6). The tank rested on two concrete saddles with the bottom of the tank located approximately 4 feet above ground level. Figure 3 is a view of the tank looking north from 490th Street.



Figure 3. The 18,000-gallon Propane Tank That Exploded

Aboveground piping from the tank ran in two directions:

- 1) Parallel liquid and vapor lines used for propane supply ran to the west for approximately 40 feet. These lines terminated at the fueling truck point-of-transfer located at the edge of a gravel parking area (see Figure 2, item 8 and Figure 7). These lines were not involved in this incident.
- 2) Parallel liquid and vapor lines also ran north from the tank for approximately 37 feet to two direct-fired vaporizers⁶ (vaporizers) (see Figure 2, item 7 and Figure 7). The liquid line was located to the east of the vapor line. The ATV struck these two lines.

Neither the tank nor the aboveground piping was protected by a fence or any other barrier designed to prevent damage from vehicles. According to one of the co-owners of the farm, the closest that vehicles came to the tank was when propane supply trucks parked at the fueling truck point-of-transfer to the west of the tank. There were no posted warnings for vehicles to stay out of the area immediately adjacent to the tank.

⁶ The direct-fired vaporizers were components of the system that used heat to transform liquid propane from the tank into a gas that was piped to space heaters and furnaces on the farm.

The first component in the liquid line leading to the vaporizer was a 3-inch excess flow valve. This metal valve was threaded into a 3-inch pipe coupling that was welded to the bottom shell of the tank. This excess flow valve was connected to a manual shut-off valve by a 2-inch diameter pipe (nipple) that was 2 inches in length. This metal 90°-angle valve changed the orientation of the liquid line from a downward direction to a horizontal and eastward direction. Two bushings (adapters designed to permit the joining of pipes with different diameters) connected the shut-off valve to a ¾-inch schedule 80 carbon steel pipe (outlet pipe). This outlet pipe ran to the east for approximately 30 inches toward the concrete saddle supporting the tank, and then turned downward for approximately 7 inches. This segment of pipe was subsequently labeled “A1” for evidentiary purposes (See Figure 4 below and Figure 29 in Appendix B). The outlet pipe then turned again to the north and ran to the vaporizers on a series of steel supports spaced at regular intervals. These supports placed the outlet pipe approximately 3 feet above the ground for its entire 37-foot course from the tank to the vaporizers. The arrows in Figure 4 point to liquid line components and to the approximate location of the break that occurred under the tank.

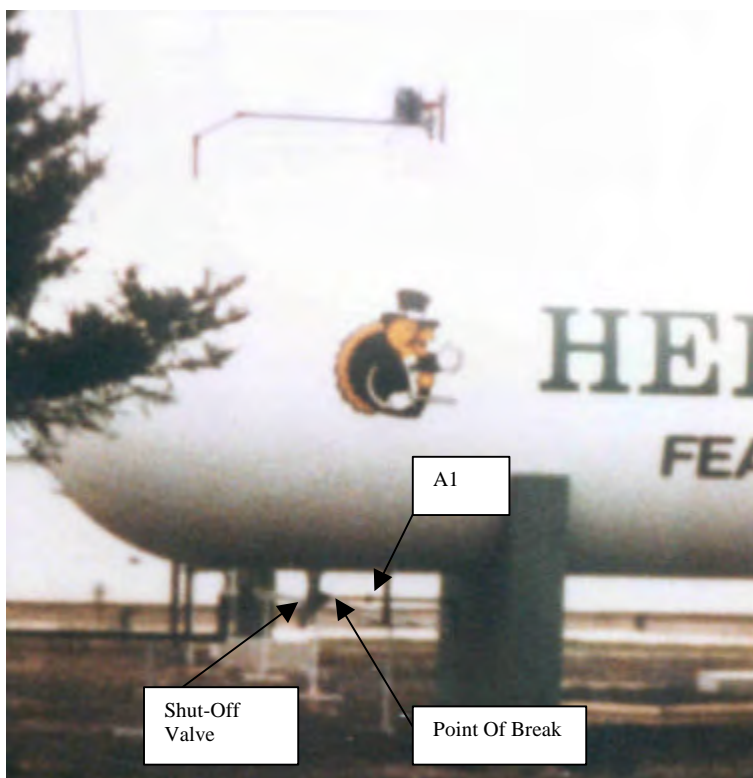


Figure 4. Liquid Line Shut-Off Valve and Point of Break

The vapor line involved in this incident exited the tank vertically from a 2-inch excess flow valve screwed into the manway⁷ on top of the tank. A small segment of pipe connected this excess flow valve to a shut-off valve. This 90°-angle valve changed the course of the vapor line to a horizontal direction. The vapor line then ran northward until it extended beyond the side of the tank and then ran downward to the same elevation as the liquid line. From this point, the vapor line ran parallel to the liquid line on the same series of steel supports until both lines reached the vaporizers. Figures 5a and 5b are photographs of the west end of the tank that illustrate the vapor lines exiting the manway. The arrows point to the vapor line that ran to the vaporizers.



Figure 5a. Southern Exposure



Figure 5b. Northern Exposure

Piping from the vaporizers to the various buildings was buried underground. Figure 6 on the following page is a piping diagram for the propane storage and handling system.

⁷ The manway was a lid on the top of the tank that housed the following components: two vapor excess flow valves and three pressure relief valves. See Appendix B, Figure 6.

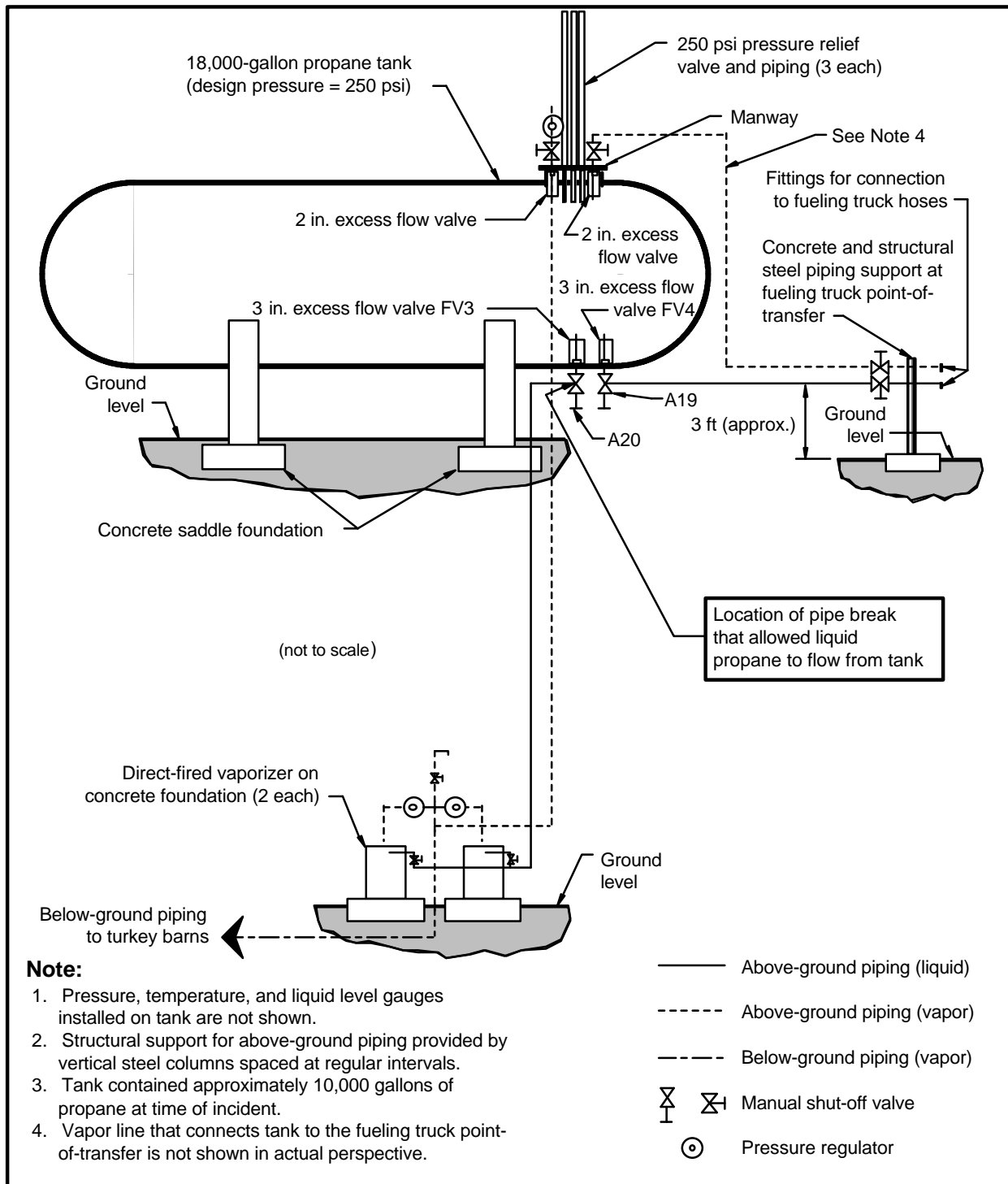


Figure 6. Piping Diagram for the Propane Storage and Handling System

2.2 SYSTEM OPERATION

During normal operations, liquid propane was withdrawn from the tank through the 3-inch excess flow valve (FV3 in Figure 6), past the open shut-off valve (A20 in Figure 6), and then into the ¾-inch outlet pipe to the vaporizers shown in Figure 7. These vaporizers used heat to convert the liquid propane into a gas. After passing through a pressure regulator, the propane gas was piped underground to the various space heaters and furnaces located in the buildings on the farm.

On cold winter days, as much as 1,000 gallons of propane were required to heat the buildings and structures on the farm. Based on this usage, fueling truck deliveries occurred as often as every week during severe winter months. When a fueling truck arrived at the farm, it parked in the gravel area located west of the propane tank (see Figure 2, item 8). The dotted arrow in Figure 7 below represents the approximate course of the ATV prior to striking the propane lines.



Figure 7. Aerial View of Tank Area

3.0 DESCRIPTION OF THE INCIDENT

3.1 PRE-INCIDENT EVENTS

On the evening of the incident, eight high-school-aged teens (including the son of one of the co-owners) gathered at the farm for a party. According to one of the co-owners of the farm, the youths had attended similar social gatherings at the farm on other dates, but with neither the knowledge nor the consent of the owners. Neither owner lived at the farm.

At approximately 11:00 pm, one of the youths began driving an all-terrain vehicle (ATV) around the farm. Then the driver of the ATV picked up a passenger and continued his ride. The ATV was heading east between the propane tank and a turkey barn when it struck the two aboveground propane pipes (liquid and vapor lines) that ran from the propane tank to direct-fired vaporizers approximately 37 feet to the north of the tank (See Figure 2). The ATV damaged both the liquid and vapor lines.

The liquid line (which measured approximately $\frac{3}{4}$ -inch inside diameter) was completely severed from the tank at the location where it was connected to a manual shut-off valve directly beneath the tank (see Figure 6, item A20). An excess flow valve protecting the liquid line (see Figure 6, item FV3) failed to function, and propane leaked out of the tank at the point of the break. As the liquid propane sprayed out of the tank, it rapidly changed to vapor. Propane vapor may have also leaked from the damaged vapor line.⁸ Propane from the damaged pipes formed a cloud, and within a few minutes this propane vapor ignited. Although the source of ignition was not conclusively established, the likely source was the direct-fired vaporizers.⁹ A fire, fed by the broken liquid line, began burning vigorously under the tank.

Two of the teenagers drove to the home of a neighbor, approximately $\frac{1}{2}$ mile from the farm, to report what had happened. At 11:10 pm, the neighbor called the 911 operator to report the fire.

⁸ Although the vapor line was also damaged by the ATV and may have leaked some propane, CSB investigators found no conclusive evidence that damage to the vapor line otherwise contributed to the explosion. For further discussion of this issue, see section 4.6.

⁹ Possible ignition sources from the direct-fired vaporizers include the pilot light, the burner flame, or a hot surface.

3.2 EMERGENCY RESPONSE

Twenty members of the Albert City Volunteer Fire Department and two Buena Vista County Sheriff Deputies were the first responders to reach the farm.¹⁰ Upon arrival at about 11:21 pm, the fire fighters observed flames originating from two primary locations: from under the west end of the tank and from the pressure relief valve pipes located on the top of the tank. One fire fighter reported that the “west end of the tank [near the broken liquid line] was *engulfed* in flames” (emphasis added).¹¹ Another stated that “the propane tank was fully engulfed and flames were 70-100 yards in the air.”¹² Because of the fire, the fire fighters did not attempt to reach the manual shut-off valve on the broken pipe (see Figure 6, item A20). Thus, the fire fighters could not stop the propane release, and the fire continued to burn out of control. Fire fighters stated that the noise from the relief valves was “like standing next to a jet plane with its engine at full throttle.”¹³

The Chief of the Albert City Fire Department told one of Buena Vista County Deputies that the plan was to let the fire burn itself out and at the same time to water down the buildings adjacent to the tank.¹⁴ Two fire fighter hose teams positioned themselves at different locations near a building located about 90 feet north from the side of the burning tank (see Figure 2, Building 1-G, and Figure 8, fire fighters 1, 2, 5, and 6). Fire fighters did not attempt to spray the tank with water. Instead, they set up to spray water from a fire truck onto the surrounding buildings, hoping to prevent the buildings from catching on fire. Because there was no source of fire-fighting water at the farm, one of the fire trucks was sent away to obtain more water.

At approximately 11:28 pm, the tank exploded. One of the responding Buena Vista County Deputies stated that he saw the tank swell before the blast. Immediately after observing the swelling of the tank, he heard a loud explosion. The tank and its associated piping were blown into at least 36 pieces. One of the large pieces traveled in a northwesterly direction, striking and

¹⁰ For a detailed description of the emergency response, see Duval, Robert. *Fire Fighter Fatalities Albert City Iowa April 9, 1998*; National Fire Protection Association: Quincy, MA, 1999.

¹¹ Buena Vista County Sheriff. *Buena Vista County Sheriff's Incident Report* (Incident Number 98-002070-I): Storm Lake, Iowa, 1998.

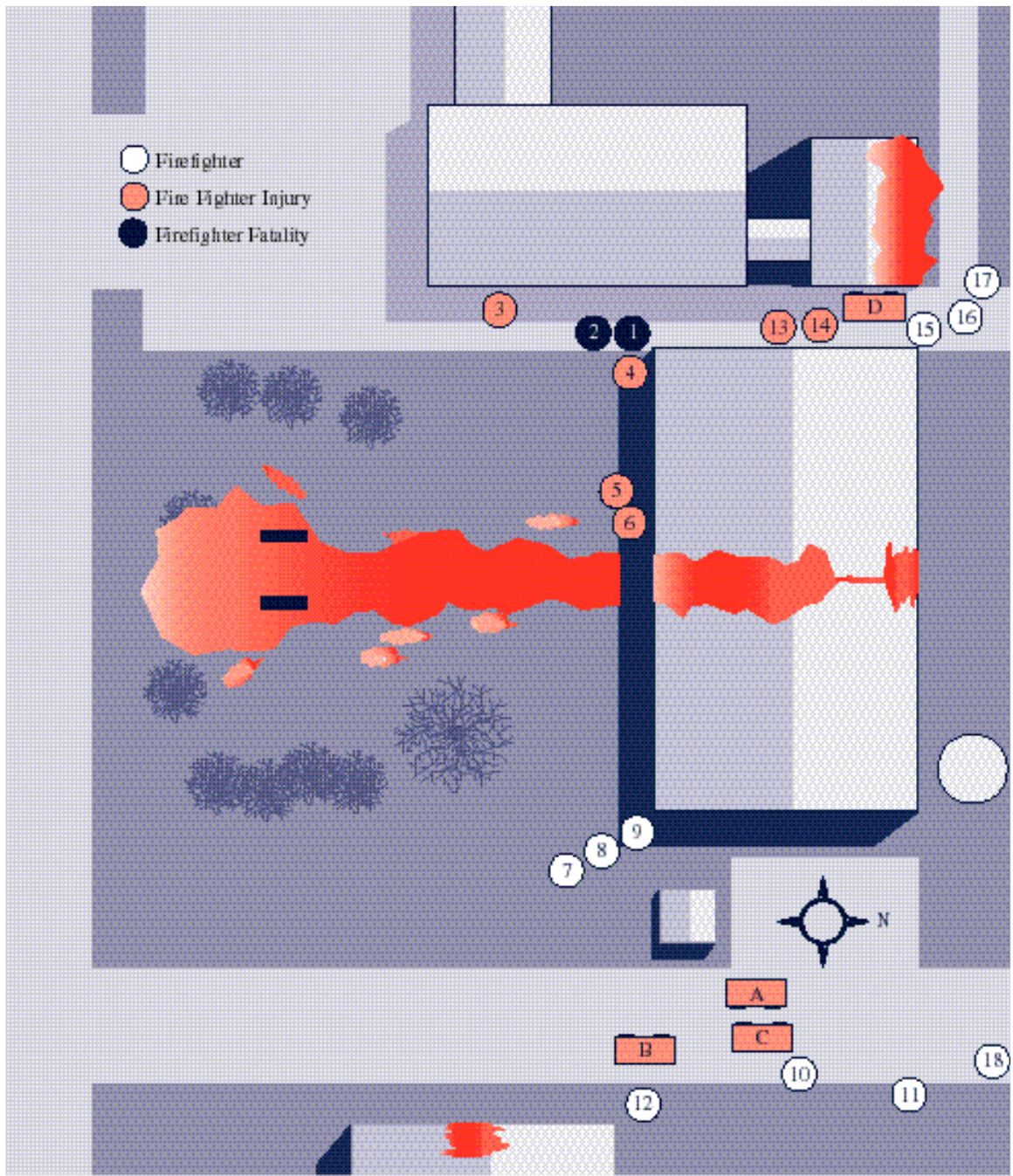
¹² *Ibid.*

¹³ *Ibid.*

¹⁴ *Ibid.*

killing two volunteer firemen. The Iowa State Medical Examiner listed the cause of death in each instance as massive trauma to all body systems. The fire fighters who died were located about 100 feet from the northwest side of the tank, as depicted in Figure 8 (numbers 1 and 2). The tank piece that struck two of the fire fighters narrowly missed the Fire Chief (see Figure 8, number 4). Another large piece of the tank was propelled directly north, just missing two other fire fighters (see Figure 8, numbers 5 and 6). Seven emergency response personnel sustained injuries as a result of the explosion. These injuries ranged from scrapes and bruises to severe burns.¹⁵ This explosion easily could have caused numerous additional fire fighter fatalities.

¹⁵ For additional information on the injuries sustained by emergency response personnel, see Duval, Robert. *Fire Fighter Fatalities Albert City Iowa April 9, 1998*; National Fire Protection Association: Quincy, MA, 1999, 12-14 and Buena Vista County Sheriff. *Buena Vista County Sheriff's Incident Report (Incident Number 98-002070-I): Storm Lake, Iowa, 1998.*



© 1999 National Fire Protection Association, Quincy, MA. Illustration provided courtesy of the NFPA Fire Investigations Department.

Figure 8. Fire fighters (numbers) and Response Vehicles (letters) at the Time of the Blast (not to scale)

3.3 BLEVE

3.3.1 Nature of a BLEVE

The explosion that occurred at the farm is known as a Boiling Liquid Expanding Vapor Explosion or BLEVE. A BLEVE can occur when a flammable liquid inside a container is exposed to fire. The book, *Loss Prevention in the Process Industries*, provides the following description of a BLEVE:

When a vessel containing a liquid under pressure is exposed to fire, the liquid heats up and the vapour pressure rises, increasing the pressure in the vessel. When this pressure reaches the set pressure of the pressure relief valve, the valve operates. The liquid level in the vessel falls as the vapour is released to the atmosphere. The liquid is effective in cooling that part of the vessel wall which is in contact with it, but the vapour is not. The proportion of the vessel wall which has the benefit of liquid cooling falls as the liquid vaporizes. After a time, metal which is not cooled by liquid becomes exposed to the fire; the metal becomes hot and then may rupture.¹⁶

*

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*

The essential features of a BLEVE are (1) the vessel fails, (2) the failure results in a flash-off of vapour from the superheated liquid and, if the liquid is flammable, (3) the vapour ignites and forms a fireball.¹⁷

3.3.2 Events Leading to the BLEVE at the Farm

Once the leaking propane ignited, fire, fed by the broken liquid line, engulfed the tank. As the fire burned, the flames heated the walls of the tank above the liquid level, causing changes in the properties of the tank material. At the same time, heat from tank surfaces located below the liquid level was transferred rapidly to the propane, causing it to boil. As the propane boiled, the pressure inside the tank increased because of the expanding vapors. Approximately 10 minutes after the fire started, the pressure increase caused the relief valves to open to vent excess pressure

¹⁶ Lees, Frank P. *Loss Prevention in the Process Industries: Hazard Identification, Assessment and Control*, 2nd ed.; Butterworth-Heinemann: Oxford, England; 1996, Vol. 2, 17/177.

¹⁷ *Ibid.* at 17/178.

from the tank. After about 18 minutes, when the overheated tank wall lost sufficient strength and could no longer resist the pressure-induced forces, fracture initiated. Because there was no liquid propane near the top of the tank to absorb the heat, fracture probably initiated at a point above the liquid level, where the tank wall was the hottest.

Immediately after the initial fracture in the tank wall, the following events occurred within moments. The remaining propane inside the tank began escaping into the surrounding atmosphere, where it vaporized almost instantaneously. As the liquid and vapors escaped, the tank wall continued tearing, allowing even more propane to escape. The propane ignited, and the explosion occurred. Tank fragments were propelled in all directions. Figure 9 shows the conditions that produced the BLEVE.¹⁸

¹⁸ Kletz, Trevor. *What Went Wrong? Case Histories of Process Plant Disasters*, 2nd ed.; Gulf Publishing Company: Houston, Texas; October 1988, 112-120.

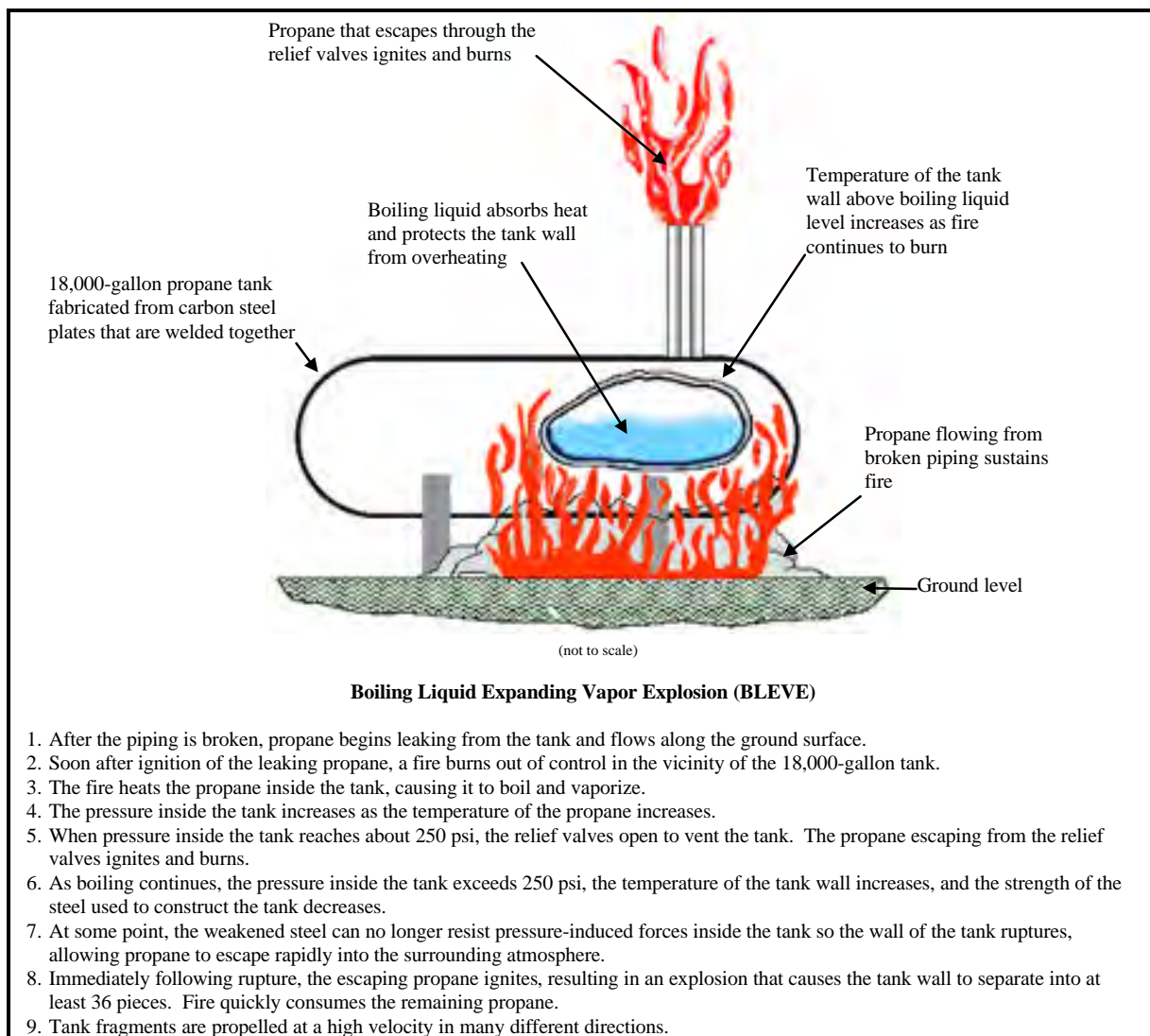


Figure 9. BLEVE

3.4 DISPERSAL OF TANK FRAGMENTS AND DAMAGE TO PROPERTY

3.4.1 Dispersal of Tank Fragments

The explosion dispersed tank fragments in all directions. Four large pieces caused most of the destruction. One of the largest pieces of the tank (approximately 23 feet long and 9 feet in

diameter) was propelled to the east, through the end of a turkey barn wall (see Figure 2, item 1f) and came to rest inside the barn (see Figure 10). This piece, which represented about one-half of the tank, caused the damage to the west end of turkey barn 1f, shown in Figure 11. A second large fragment traveled north, causing the damage to another turkey barn shown in Figure 12. (See also Figure 2, item 1g for location of the barn). Two other large pieces traveled in a northwesterly direction and landed between a workshop and a feed storage bin. One of these pieces likely caused the damage to the two-story workshop shown in Figure 13. Smaller tank pieces traveled in various directions. Some of these pieces were discovered in the grain fields that surround the property. A map that depicts the location of tank debris following the explosion is provided in Appendix C.

3.4.2 Damage to Property

The explosion caused approximately \$240,000 damage to buildings located on the farm.



Figure 10. Piece of 18,000-gallon Tank Inside Turkey Barn (1f)



Figure 11. Damage to West End of Turkey Barn (1f)



Figure 12. Damage to Turkey Barn (1g) Caused by Impact of Large Tank Fragment



Figure 13. Southeastern View of Damage to Workshop Caused by Impact of Large Tank Fragment

3.5 METEOROLOGICAL INFORMATION

The temperature at the time of the incident was approximately 38°F. The relative humidity was 86%. The wind was 10 mph and blowing to the northwest. This weather information was recorded at 10:53 pm at the Spencer, Iowa, municipal airport. Spencer is located fewer than 30 miles northwest of the farm.

4.0 ANALYSIS OF THE INCIDENT

4.1 DESIGN AND INSTALLATION DEFICIENCIES

The propane storage and handling system was installed at the farm in 1988. When the tank system was installed, Iowa law provided that the 1979 edition of the National Fire Protection Association's *Standard for the Storage and Handling of Liquefied Petroleum Gases* (NFPA 58) governed the installation.¹⁹ As discussed below, the propane system at the farm did not comply with NFPA 58 in two significant respects that contributed to the incident: Aboveground piping was not protected from potential damage from vehicles, and the liquid propane outlet pipe downstream from an excess flow valve was too narrow in diameter.

4.1.1 Lack of Protection from Vehicular Damage

Section 3120(c) of NFPA 58 provided as follows: "Where physical damage to LP-Gas containers, or systems of which they are a part, from vehicles is a possibility, precautions against such damage shall be taken."²⁰ In addition, section 3165 of NFPA 58 stated that "[a]boveground piping shall be well supported and protected against physical damage."²¹

The area where the tank and its aboveground pipes²² were located was bordered on the south by a public road and on the east and west by gravel driveways (see Figure 1). Fueling truck deliveries occurred as often as every week during severe winter months. In addition, there was

¹⁹ Section 680-5.250(101) of the Iowa Administrative Code in effect on the date of the installation provided that "[t]he standards of 'Storage and Handling of Liquefied Petroleum Gas,' No. 58, 1979 edition of the National Fire Protection Association . . . shall be the rules governing liquefied petroleum gases in the state of Iowa."

²⁰ Under current Iowa law, the 1992 edition of NFPA 58 governs the storage and handling of propane and other LP-Gases in the state. Section 3-2.4.1(c) of the 1992 edition of NFPA 58 states: "Where physical damage to LP-Gas containers, or systems of which they are a part, from vehicles is a possibility, precautions shall be taken against such damage."

²¹ Section 3-2.8.6 of the 1992 edition of NFPA 58 states, in part that, "[a]boveground piping shall be well supported and protected against physical damage."

an all-terrain vehicle (ATV) stored at the farm. Despite the regular exposure of the tank and its aboveground piping to potential damage from vehicles, neither the propane tank nor its piping were protected by a fence or any other physical barrier designed to prevent such damage. The lack of piping protection for the propane system at the farm allowed the ATV to crash into the pipes that ran from the tank to its vaporizers, breaking them and releasing the propane that ignited.²³

4.1.2 Improper Size of Outlet Pipe from Excess Flow Valve FV3

The liquid line that ran from the tank to the vaporizers was equipped with an excess flow valve, which was designed to automatically close when the flow through the valve exceeded a predetermined rate -- the closing rating. This particular valve had a closing rating of approximately 200 gallons per minute. In the event of a complete break in the outlet pipe downstream from the excess flow valve, the valve should have closed and greatly reduced²⁴ the flow of propane from the broken pipe. When the ATV severed the liquid line, however, the excess flow valve failed to close because the flow capacity of the outlet piping system was less than the closing rating of the excess flow valve.

At this installation, the outlet piping downstream from the valve was too narrow for the valve installed in the tank.²⁵ If the pipe downstream from an excess flow valve is too narrow in

²² Two aboveground pipes (liquid and vapor lines) ran from the propane tank to its vaporizers. Aboveground piping also ran from the tank to the fueling truck point-of-transfer to the tank. See Figure 2, item 8.

²³ The National Fire Protection Association (NFPA) investigated and reported on this incident. NFPA determined, in part, that “[h]ad this installation been protected against vehicular traffic, the liquid lines would not have been damaged by the ATV, which began the tragic chain of events that led up to the death of the two fire fighters.” Duval, Robert. *Fire Fighter Fatalities Albert City Iowa April 9, 1998*; National Fire Protection Association: Quincy, MA, 1999, 22.

²⁴ Even when an excess flow valve is activated, a small amount of fluid bleeds through a tiny hole in the valve. Consequently, installation of a shut-off valve immediately downstream from the excess-flow valve is required to stop all flow.

²⁵ The CSB has focused in this report on a specific flaw in the design of the liquid line to the vaporizers: that the diameter of the outlet pipe was too narrow for the excess flow valve installed in the tank. Alternative valve and pipe combinations (i.e., a smaller excess flow valve matched with the outlet pipe that was used) may have also prevented this incident or been more appropriate for this system. Thus, the CSB does not intend to imply that a larger outlet pipe to the vaporizers was the *only* possible alternative design for this particular installation. A complete discussion of possible alternative designs, however, is beyond the scope of this report.

diameter, flow through a severed line can be restricted so that it will not exceed the closing rating required for the valve to activate. Thus, an excess flow valve will generally not close if the pipe downstream is smaller in diameter than the valve, even if a complete break of the line occurs. For this reason, section 3135(a)(3) of NFPA 58 provided that “[t]he connections, or line, leading to or from any individual opening shall have greater capacity than the rated flow of the excess flow valve protecting the opening.”²⁶

At this installation, however, the piping downstream of the excess flow valve did not conform to this NFPA requirement. Specifically, shut-off valve A20, which was downstream from excess flow valve FV3, was fitted with two bushings that reduced the flow of propane by decreasing the diameter of piping in the line to approximately $\frac{3}{4}$ of an inch. In this incident, the break in the line occurred at the point where the second bushing connected to the $\frac{3}{4}$ -inch outlet pipe to the vaporizers (see Figure 6). Following the break, the excess flow valve did not close because the flow of propane through the line was restricted by the reducer bushings to a rate below the closing rating of the valve.

A NASA laboratory, the Kennedy Space Center Materials Science Division, conducted tests on the excess flow valve which demonstrated that the valve closed properly when it was installed in accordance with the manufacturer’s recommendations and that it did not close when attached to a $\frac{3}{4}$ -inch inside-diameter pipe. Details and results of this reconstruction analysis are provided in Appendix B.

²⁶ Under current Iowa law, the 1992 edition of NFPA 58 governs the storage and handling of propane and other LP-Gases in the state. Section 2-3.7 of the 1992 edition contains language identical to section 3135(a)(3).

4.2 REGULATORY OVERSIGHT

4.2.1 Overview

The Iowa State Fire Marshal was (and remains) responsible for enforcing state regulations concerned with the “storage, transportation, handling and use of liquid petroleum gas.”²⁷ Under Iowa law, the State Fire Marshal should have received a plan of the farm’s propane tank storage and handling system before it was installed. The CSB’s investigation revealed that the State Fire Marshal had no record of the propane system at the farm and that it was not installed in compliance with all NFPA 58 requirements adopted as Iowa law. Even if a plan had been submitted prior to the installation, however, the State Fire Marshal’s Office probably would not have uncovered both deficiencies in the installation that contributed to the incident; that office did not have a program in place to adequately monitor or inspect large propane tank storage facilities.

4.2.2 State Regulatory Oversight

Under NFPA 58 and other relevant Iowa law, the State Fire Marshal should have received a plan of the farm’s propane tank storage and handling system before it was installed. Section 1400 of the 1979 edition of NFPA 58 stated that “[p]lans for fixed (stationary) installations utilizing storage containers of over 2000 gallons individual water capacity . . . shall be submitted to the authority having jurisdiction before the installation is started.” Iowa law, however, did not specifically designate which party -- the owner or the installer of a large propane tank facility -- was required to submit a plan to the “authority having jurisdiction,” the State Fire Marshal. In this instance, one of the owners of the farm had no knowledge of the requirement to submit a plan. He believed that this was the obligation of the company that connected the tank to the

²⁷ See 5 Iowa Code Ann. §100.1(4)(c) (1998).

vaporizers. That company, in turn, maintained that it had no responsibility to submit a plan to the State Fire Marshal and that it was the tank owner's responsibility to do so. Clarification of Iowa law in this regard and communication of this information to interested parties would help eliminate such confusion. In the meantime, the State Fire Marshal estimated that "a great many tanks are installed without plans being sent in."²⁸

As discussed above, the propane system at the farm did not comply with NFPA 58 as adopted by Iowa in two significant respects. First, aboveground piping that ran from the storage tank to the vaporizers was not protected from potential damage from vehicles. Second, the diameter of the outlet pipe downstream from an excess flow valve was too narrow, which prevented that valve from functioning properly.

If a plan of the propane system at the farm had been submitted to the State Fire Marshal as required in 1988, it is likely that the State Fire Marshal's Office would have noticed the lack of physical protection from vehicle damage. Since at least 1988, the State Fire Marshal has reviewed plans of propane systems for compliance with certain NFPA 58 requirements. According to the State Fire Marshal's Office, this "plan review" checks for "fencing, vehicle protection, and other items that can be determined from a site plan."²⁹ The State Fire Marshal stated that a plan for the farm's installation would have been checked for "aboveground piping protection and items visible on the drawings."³⁰

Even if a plan had been submitted in 1988, however, the State Fire Marshal's plan review would not have uncovered the improper sizing of the piping from the excess flow valve. The State Fire Marshal acknowledged that a review of the plan for the propane system at the farm would probably not have detected the improper "sizing of excess flow valves and connecting piping."³¹ Moreover, the State Fire Marshal explained that he lacked (and still lacks) the resources needed to conduct an inspection of each regulated propane system in the state for full compliance with Iowa law (NFPA 58). He employs one inspector on a part-time basis to handle LP-Gas *and* all other flammable liquids regulated by his office. He estimates that three full-time inspectors

²⁸ Marshal, Roy. Iowa State Fire Marshal. Correspondence to CSB, December 18, 1998.

²⁹ *Ibid.*

³⁰ *Ibid.* The State Fire Marshal explained that the Fire Prevention inspector assigned to review the plans receives training "in the area of LP gas and Flammable Liquids."

solely dedicated to LP-Gas matters would be required to effectively enforce NFPA 58 requirements.

4.3 DAMAGE TO LIQUID LINE

CSB investigators based the conclusion that the impact of the ATV broke off the liquid pipe at its connection to the shut-off valve on a number of factors. The piece of ¾-inch liquid pipe broken off was labeled A1 following the incident (see Figures 29 and 36 in Appendix B). As these figures illustrate, a bend was discovered in the A1 segment between the threads and the union (a coupling used to connect two segments of pipe). This bend indicates that this segment of A1 was subjected to a significant horizontally applied load before fracture occurred.

Horizontal stress patterns identified on the edge of the A1 pipe segment that connected to the A20 valve also revealed that the pipe failed in a horizontal plane (see Figure 37, Appendix B). Had the A1 piece been completely connected to the A20 valve at the time of the explosion, these stress patterns would almost certainly have been twisted with a vertical orientation, not a horizontal one. Thus, the force required to produce these stress patterns most likely occurred when the ATV hit the liquid line. The direction of thread deformation on the A1 edge (Appendix B, Figures 36-39) also indicates that the pipe was subjected to a horizontally applied load such as that likely caused by the impact of the ATV.

In addition, the debris map in Appendix C illustrates that the A1 piece was discovered in the immediate area of the original tank location following the blast. The discovery of A1 at this location suggests that it was severed from the shut-off valve prior to the explosion. The shut-off valve, which had been connected to A1, was thrown a significant distance from its original location by the explosion (see Appendix C, item A20).

If the A1 piece were still connected to the shut-off valve at the time of the explosion, there would most likely be dents or other types of damage visible on the pipe surface similar to the damage

³¹ *Ibid.*

observed on other pieces of debris. For example, the shut-off valve (A20) exhibited a number of abrasions that likely occurred as a result of the explosion. As Figure 29 in Appendix B shows, the A1 piece was not dented or damaged. Finally, eyewitness reports of fire under the north and west end of the tank following the impact of the ATV were consistent with a propane leak in the vicinity of the A20/A1 connection under the tank.

4.4 ALBERT CITY VOLUNTEER FIRE DEPARTMENT TRAINING

The Albert City Fire Department (department) is an all-volunteer force that covers a response area of 100 square miles and serves a population of 850.³² Members of the department received some initial training, which varied depending upon each member's availability to attend specific training courses. Training topics included "personal safety, forcible entry, ventilation, fire apparatus, ladders, self-contained breathing apparatus, hose loads, streams and special hazards."³³ In addition, as discussed in sections 4.4.1-4.4.3 below, certain members of the department received some additional training on responding to LP-Gas leaks and fires. Fire fighters in this incident, however, had inadequate training on recognizing the potential for a BLEVE and appropriate response procedures.

4.4.1 National Propane Gas Association Training Materials

According to the Chief of the department, he and about 90 percent of the department's fire fighters had watched a videotape entitled *Handling LP-Gas Leaks and Fires*. Certain members of the department viewed the tape during a three-hour training session in September, 1997.

³² Duval, Robert. *Fire Fighter Fatalities Albert City Iowa April 9, 1998*; National Fire Protection Association: Quincy, MA, 1999, 8.

³³ *Propane Tank Explosion Results in the Death of Two Volunteer Fire Fighters, Hospitalization of Six Other Volunteer Fire Fighters and a Deputy Sheriff – Iowa*; Fire Fighter Fatality Investigation Report 98F-14; National Institute of Occupational Safety and Health, Fire Fighter Fatality and Investigation Program, <http://www.cdc.gov/niosh/face9814.html> (accessed April 1999).

The National Propane Gas Association (NPGA) produced the videotape. One of the recommendations in the videotape for responding to propane tank fires is that fire fighters should “approach the container from the sides and from upwind.”³⁴ The videotape, however, does not warn fire fighters that fragments may be thrown in all directions when a BLEVE occurs, causing death and injury to responders approaching from the sides of the container.

The NPGA training guide accompanying its videotape, entitled *LP-Gas Fire Control and Hazmat Training Guide*, states: “should the container rupture, it can and will, most likely, travel in the direction it is pointed.”³⁵ Although the NPGA mentions BLEVEs in another section of its guide, it does not explain that in a BLEVE, fragments can travel in all directions.

The NPGA recommendations could be interpreted by fire fighters to mean that staying away from the ends of a burning propane tank will protect them in the event of an explosion. In this incident, the Fire Chief reported that he relied on NPGA and other similar training guidelines and believed that avoiding the ends of the burning tank would protect fire fighters. Avoiding the ends of a tank does not provide protection when a BLEVE occurs.

4.4.2 Training By The Fire Service Institute, Iowa State University

In order to respond to a hazardous material release such as the one at the farm, the Albert City volunteer fire fighters should have received the training required by the Hazardous Waste Operations and Emergency Response law known as HAZWOPER.³⁶ The Fire Service Institute of Iowa State University provided HAZWOPER operations-level training for some members of the Albert City Volunteer Fire Department. The two deceased fire fighters and the Assistant Fire Chief successfully completed the twelve-hour, operations-level training course in March or April of 1996. According to the Institute, the Fire Chief did not complete operations-level training. Even if all of the members of the department had received the training offered by the Institute, however, this training would have been insufficient to prepare members of the department to

³⁴ National Propane Gas Association. *Handling LP-Gas Leaks & Fires*. Video #0994. Lisle, Illinois, 1992.

³⁵ National Propane Gas Association. *LP-Gas Fire Control and Hazmat Training Guide*, Lisle, IL, 1991, 4.

³⁶ Iowa has adopted the federal HAZWOPER standard. For further information on the federal HAZWOPER training requirements, see 29 CFR § 1910.120 (q)(6).

properly respond to a potential BLEVE. The Fire Service Institute's student manual entitled *Iowa Hazardous Materials Operations*,³⁷ contained only basic information about BLEVEs.

In addition, first responders trained at the operations level are individuals who should respond in a defensive fashion. "Their function is to contain the release from a safe distance, keep it from spreading, and prevent exposures."³⁸ If members of the department had responded in a defensive fashion (see section 4.5 of this report), it is likely that the fatalities could have been prevented.

4.4.3 Guidance on Propane Tank Fires in *1996 North American Emergency Response Guidebook*

The *1996 North American Emergency Response Guidebook* is widely used by emergency responders and was carried by fire fighter response vehicles at this incident. The Chief of the department said that he did not consult the guidebook on the night of the incident, but that he was generally familiar with the propane fire response guidelines it contained. Had it been consulted, some of the recommendations in the guidebook could have prevented the fire fighter fatalities. For example, Guide Number 115, which addresses propane tank fires, recommends, in part, that responders to a massive fire "use unmanned hose holders or monitor nozzles" or, if this is not possible, to "withdraw from the area and let fire burn."³⁹

On the other hand, one of the recommendations in the guidebook might have been misleading. Guide Number 115 recommends that responders "ALWAYS stay away from the ends of tanks."⁴⁰ As with the NPGA response guidelines discussed above, fire fighters could interpret this Department of Transportation (DOT) recommendation to mean that by avoiding the ends of the tank they would be safe. In a BLEVE such as the one in this incident, however, fragments from the explosion can travel in all directions from the tank. Avoiding the ends of the tank does not provide protection for responders when a BLEVE occurs. Because the guidebook was not

³⁷ Ballard, David. *Iowa Hazardous Materials Operations: Student Manual*, Fire Service Institute, Iowa State University Extension: Ames, IO, 1996.

³⁸ 29 CFR 1910.120(q)(6)(ii).

³⁹ United States Dept. of Transportation. *1996 North American Emergency Response Guidebook*, J. J. Keller & Associates, Inc.: Neehah, Wisconsin, 1996, 178-179.

consulted in responding to the fire at the farm, the CSB did not find that the potentially misleading DOT guideline contributed to causing the casualties in this incident.

4.5 ANALYSIS OF EMERGENCY RESPONSE

Fire fighter training material published by the International Fire Service Training Association (IFSTA)⁴¹ include the following guidelines for responding to propane tank fires:

- Do not assume that the venting of propane from relief valves will prevent overpressurization and rupture of the tank;
- Apply large quantities of water to the tank. For large propane tanks, at least 500 gallons per minute is needed;
- If a flame is impinging on the tank, water must be applied directly to the impinged area in order to prevent a BLEVE;
- Water should be sprayed by use of an unmanned fire hose system; and
- If a continuous supply of water is not available, withdraw and isolate the area for ½ mile in all directions.

Fire fighters responding to this incident did not follow response guidelines such as those published by the IFSTA. Not following response guidelines such as these had the following consequences:

- Fire fighters did not spray water on the burning tank to try to prevent a BLEVE;⁴² and
- Fire fighters were deployed too close to the tank. They did not withdraw and isolate for ½ mile as recommended by IFSTA. This allowed fragments from the exploding tank to strike and kill two fire fighters.

⁴⁰ *Ibid.*

⁴¹ International Fire Service Training Association. *Hazardous Materials for First Responders*, 1st ed.; Fire Protection Publications, Oklahoma State University: Stillwater, OK, 1990, 276-80.

⁴² Fire fighters may not have recognized that even if they started to spray water on the tank, the inadequate water supply likely would have prevented them from effectively cooling the tank.

4.5.1 The Time Factor in Responding to the Scene of a Potential BLEVE

BLEVEs can take place rapidly when a fire is impinging on the surface of a non-fireproofed⁴³ propane tank above the liquid level of the tank. According to the American Petroleum Institute (API), this type of storage tank usually ruptures violently after 10-30 minutes of direct exposure to flame if water is not applied to cool the tank.⁴⁴ The API also notes that some tanks have ruptured after only 10 minutes of exposure to flame.⁴⁵ The quickness with which a BLEVE can occur is very important for fire fighters to consider when deciding how they will respond to a propane tank fire. If too much time has elapsed, the best action fire fighters can take may be to retreat to a safe distance. In this incident, only 18 minutes elapsed from the time of the 911 call until the BLEVE occurred, as shown in the table below:

Event	Time	Elapsed time
ATV strikes propane piping	11:00 pm ⁴⁶	
Leaking propane ignites	11:05 pm ⁴⁷	5 minutes
Notification to 911 operator	11:10 pm	5 minutes
Albert City Volunteer Fire Department Dispatched to Scene	11:11 pm	1 minute
Fire fighters arrive at the scene	11:21 pm	10 minutes
BLEVE occurs	11:28 pm	<u>7 minutes</u> 28 minutes

4.5.2 Deployment of Personnel When Fighting a Propane Tank Fire

Some propane storage tanks, such as the one involved in this incident, are horizontal in shape and therefore have distinct ends and sides (see Figure 3). The Albert City Fire Chief believed

⁴³ Use of fireproofing materials on storage tanks does not eliminate the possibility of a BLEVE, but it can increase the time that elapses prior to a BLEVE taking place. For additional information, see Duval, Robert. *Fire Fighter Fatalities Albert City Iowa April 9, 1998*; National Fire Protection Association: Quincy, MA, 1999, 21-22.

⁴⁴ American Petroleum Institute. *Fire-Protection Considerations for the Design and Operation of Liquefied Petroleum Gas (LPG) Storage Facilities*; API Publication 2510A, 1st ed.; Washington, DC, 1989, 31.

⁴⁵ *Ibid.*

⁴⁶ This is an estimate based on witness accounts.

⁴⁷ This is an estimate based on witness accounts.

that fire fighters would be safe if they avoided the areas extending from the ends of the tank. Based on the training that he had received, the Fire Chief also thought that, in the event of an explosion, the tank would rupture and throw fragments from the ends. He did not think that fragments would be thrown from the sides of the tank. A BLEVE, however, can disperse tank fragments in all directions.⁴⁸ Thus, even if circumstances (i.e., water supply and time factors) allow for the application of water to a tank in an effort to prevent a BLEVE, water should be sprayed by use of an unmanned fire hose system as recommended by the IFSTA and the *1996 North American Emergency Response Guidebook*.

4.6 ALTERNATIVE SCENARIO

The CSB received a comment theorizing that the impact of the ATV caused a partial break⁴⁹ in the vapor line to the vaporizers, at a location near the manway on the top of the tank. This damage, the comment asserted, in turn caused a leak of propane that ignited and directed flame downward onto the top of the tank. CSB investigators found no evidence to support the theory that flame from this vapor line source contributed to causing the BLEVE.

NASA investigators found no conclusive evidence that the vapor line piping in the vicinity of the manway was partially broken or severed by the impact of the ATV. In addition, none of the eyewitnesses observed flame being directed downward onto the top of the tank. Finally, a certified fire investigator with the Department of the Treasury's Bureau of Alcohol, Tobacco and Firearms examined the tank shell. He did not find any flame pattern markings on the top of the tank which indicated that a flame had been directed downward onto the top portion of the tank.

⁴⁸ For a discussion of recent research on the BLEVE hazards of small containers, see Hildebrand, M.S.; Noll, G.G. *Propane Emergencies*; Red Hat Publishing Company, Inc.: Chester, MD, 1999, 136-137.

⁴⁹ An excess flow valve protected the vapor line that was damaged by the ATV. If that line was completely severed by the impact of the ATV, that excess flow valve would have been activated, thus virtually shutting off the flow of propane in that line. The comment assumed that the impact of the ATV did not cause a complete break anywhere in the line and that the valve was not activated. It is possible that the ATV did completely sever the vapor line, thus activating the excess flow valve on that line. The CSB, however, did not conclusively determine whether the vapor line was severed completely prior to the explosion.

4.7 ROOT AND CONTRIBUTING CAUSES

Root Causes

1. Protection for aboveground piping was inadequate.

Two aboveground pipes (liquid and vapor lines) that ran from the propane storage tank to its vaporizers were not protected from potential physical damage from vehicles. Lack of piping protection allowed a vehicle to crash into these pipes, breaking them and releasing the propane that ignited.

2. The diameter of the pipe downstream from an excess flow valve was too narrow, which prevented the valve from functioning properly.

An excess flow valve that was designed to stop the flow of all but an extremely small amount of liquid propane in the event of a severed line did not function because the diameter of the pipe downstream from the valve was too narrow to allow the valve to activate. Post-incident tests of the valve showed that it would have operated as designed if the pipe downstream had been the proper size. A functioning excess flow valve on the liquid line would have greatly reduced the severity of the fire that engulfed the tank. This likely would have prevented the BLEVE.

3. Fire fighter training for responding to BLEVEs was inadequate.

Some training materials provided to the fire fighters led them to believe that they would be protected from a propane tank explosion by positioning themselves to the sides of the tank and by avoiding the areas extending from the two ends of the tank. As a consequence, fire fighters were positioned too close to the sides of the burning propane storage tank when it exploded. Fire fighters did not adequately recognize the potential for a BLEVE and that a BLEVE can scatter tank fragments in all directions. In this incident, flying fragments from the explosion killed two fire fighters located approximately 100 feet from the side of the tank.

Contributing Cause

The State Fire Marshal did not detect deficiencies in the design and installation of the propane storage facility.

Under Iowa law, the State Fire Marshal should have received a plan of the farm's propane system prior to its installation in 1988. The State Fire Marshal had no record of the farm's system, however. Iowa law did not specifically designate which party -- the owner or the installer of a large propane tank facility -- was required to notify the State Fire Marshal. In addition, the State Fire Marshal did not have a program in place to adequately monitor or inspect large propane storage facilities.

5.0 RECOMMENDATIONS

Herrig Brothers Farm

1. Install protection (i.e., fencing or barricades) to protect aboveground propane pipes from possible damage from vehicles. (98-007-I-IA-R1)
2. Install properly sized propane outlet piping from excess flow valves. (98-007-I-IA-R2)

Iowa State Fire Marshal

Develop a program to ensure implementation of the requirements of the National Fire Protection Association's *NFPA-58 Standard for the Storage and Handling of Liquefied Petroleum Gases*, as adopted by Iowa law. Ensure that this program includes, at a minimum, the following elements:

- Designation by regulation of the party (such as a facility owner or installer) who is responsible for submitting planned construction or modification documents to the State Fire Marshal; (98-007-I-IA-R3)
- Procedures for approving the plans for new or modified installations; (98-007-I-IA-R4)
- Procedures governing the issuance and posting of permits authorizing the use of equipment; (98-007-I-IA-R5) and
- On-site inspections of new, modified, and existing propane and other Liquefied Petroleum Gas storage facilities that are covered by Iowa state law. (98-007-I-IA-R6)

Fire Service Institute of Iowa State University

Ensure that fire fighter training materials address proper response procedures for BLEVEs. (98-007-I-IA-R7)

National Propane Gas Association (NPGA)

1. Ensure that fire fighter-training materials address proper response procedures for BLEVEs. (98-007-I-IA-R8)
2. Distribute the CSB findings and recommendations in this report to NPGA members. (98-007-I-IA-R9)

BY THE CHEMICAL SAFETY AND HAZARD INVESTIGATION BOARD

Paul L. Hill, Jr.
Chairman

Gerald V. Poje
Member

Andrea Kidd Taylor
Member

Isadore Rosenthal
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June 23, 1999

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APPENDIX A: Methodologies Used to Determine Causes

Material and Structural Analysis

Fracture of the 18,000-gallon propane tank likely initiated at an internal pressure in excess of 250 psi. This conclusion is based on observations by eyewitnesses that the relief valves, which were set to open at 250 psi, were discharging before the tank failed, and that the tank had been subjected to a hydrostatic test pressure of 375 psi after fabrication. Although the failure pressure was probably greater than 250 psi, it is impossible to establish an exact failure pressure without knowing the complete pressure-temperature history for the tank. It is possible, however, to identify an upper bound failure pressure and estimate the actual failure pressure using fundamentals of science and engineering.

Design rules in the American Society of Mechanical Engineers Boiler and Pressure Vessel Code provide a substantial margin of safety against overpressurization. Under certain operating temperatures and conditions, the factor of safety can be as high as four. Based on this value, the pressure corresponding to failure could have been as high as 1,000 psi, provided the temperature of the shell and heads remained relatively low (less than about 650 F). However, because of the fire and the deleterious effect heat has on the properties of carbon steel, it is likely that the tank failed at a pressure below 1,000 psi.

At about 650 F, the tensile strength of carbon steel begins to decrease as the temperature increases. When carbon steel begins to glow red at about 1,000 to 1,100 F, its tensile strength is only about 60 percent of its room-temperature strength. Any reduction in tensile strength resulting from high-temperature exposure produces a corresponding reduction in the failure pressure. With the maximum flame temperature of propane in air approximately 3,595 F and the presence of fire underneath the tank, it is likely that the properties of the steel in the vicinity of the flames were affected by the intense heat of the fire.

As propane leaked from the tank and fueled the fire, the flames heated the tank wall above the liquid level inside the tank, causing changes in the properties of the steel. At some point when the overheated steel lost sufficient strength and could no longer resist the pressure-induced forces, fracture initiated. Because there was no liquid propane near the top of the tank to absorb the heat, fracture probably initiated at a point above the liquid level where the metal was the hottest. However, fracture initiation at a point below the liquid level is also possible because of film boiling and the formation of a vapor blanket at the steel-liquid interface inside the tank resulting from direct flame impingement.

Results of metallurgical studies conducted by NASA on selected pieces of steel cut from the tank are provided in Appendix B. These results provide evidence that the tank failed by overpressurization in a ductile, not brittle, manner. Steel that exhibits ductile failure experiences significant stretching before separation occurs. In addition, there was no evidence of pre-existing cracks or defects in the steel that could have caused the tank to fracture prematurely or

that the strength of the steel was less than specified. Based on NASA findings, the tank performed its intended function as a physical barrier to the pressurized propane that it contained.

Failure Modes and Effects Analysis

Rupture of the tank as a result of overpressurization is consistent with a BLEVE. Fragments produced by the explosion produced significant property damage and was the cause of the deaths to emergency response personnel.

Based on visual examination of the shapes of the piping and metal debris discovered at the scene following the incident, it is unlikely that the carbon steel pipes and fittings used to construct the piping system failed by overpressurization. Observed piping fractures probably occurred for one or more of the following reasons:

- the all-terrain vehicle struck the ¾-inch nominal size liquid propane piping, causing the pipe connection at the bushings in shut-off valve A20 to fail;
- pieces of the tank impacted the piping following the explosion; or
- the piping separated from the tank and broke as a result of the explosion.

Shut-off valves A19 and A20, used on the liquid propane piping lines (see Figure 6), were rated for 400-psi service at temperatures up to 150°F. However, pressure required to cause failure is usually at least twice the rated operating pressure. Shut-off valves A19 and A20 did not fail by overpressurization. Observed damage was probably caused by impact following the explosion.

Damage to the concrete saddles that served as foundations for the tank was probably caused by forces produced by the explosion, heat generated by the fire, or impact by pieces of the tank. It is unlikely that the concrete had any measurable effect on the failure mode of the tank, but the saddles may have influenced the trajectory of some of the pieces.

Incident Reconstruction Analysis

Testing of piping components retrieved from the Herrig Brothers Farm following the incident was conducted by NASA at the Kennedy Space Center in Florida to reconstruct the incident scenario. This testing was conducted to establish the flow performance and behavioral characteristics of excess flow valve FV3 (see Figure 6), which was part of the 18,000-gallon propane storage and handling system piping impacted by the ATV.

Flow testing was performed using two configurations. One configuration was intended to simulate installation in accordance with manufacturer's recommendations. In this test, excess flow valve FV3 closed as soon as simulated fracture of the attached piping occurred, thus demonstrating that the valve was capable of performing its intended function. In the second configuration, excess flow valve FV3 was provided with downstream piping of the same size as the actual installation. In this test, the valve did not close as soon as the simulated fracture of the attached piping occurred. This result demonstrated that the actual piping arrangement produced

flow conditions sufficient to keep excess flow valve FV3 from closing. Details of the NASA flow testing program are provided in Appendix B.

APPENDIX B: NASA Analysis*

*[**Editor's note:** Because of space considerations, certain photographs and the test procedure (appendix A to the NASA report) are not included here. Interested parties may request a full copy of the report, including these omitted materials, by contacting the CSB at the address indicated in the Abstract. References to the "one inch pipe" in this appendix correspond to references to the ¾-inch schedule 80 outlet pipe to the vaporizers in the body of the CSB report. References to excess flow valves A14 and A33 in the NASA report do not correspond precisely to items A14 and A33 listed in Appendix C.]

NASA
DIRECTOR OF LOGISTICS OPERATIONS
MATERIALS SCIENCE DIVISION
ANALYSIS BRANCH
LO-G4-MA
KENNEDY SPACE CENTER, FLORIDA 32899

AUGUST 18, 1998

KSC-MSL-0741-1998

SUBJECT: Analysis of the Excess Flow Control Valves and Metallurgical Studies of a Propane Storage Tank Involved in the Boiling Liquid Expanding Vapor Explosion (BLEVE) near Albert City, Iowa.

RELATED DOCUMENTATION: KSC-MSL-0741-1998-03
KSC-MSL-0741-1998-01
REGO Catalog L-500, ECII, Section F
Manufacturer's Data Report For Unfired Pressure Vessels,
Form U-1-A, National Board Number 5446

1.0 ABSTRACT

The four excess flow control valves from the subject propane tank were tested using water at various pressures and flow rates and found to behave as they were designed to function. The material composition of the propane tank sheet metal was determined to be AISI 1525 (UNS G15250) carbon steel. Examination of the fracture surface of the pipe that connected to the propane vaporizing system indicated that the pipe failed due to an overload (overstress) condition. Metallurgical analyses indicated that the propane storage tank failed via overload (overstress), with no evidence of a pre-existing crack discernible. A portion of the tank appeared to have been heated and deformed, indicating a fire was existing immediately before the event.

2.0 FOREWORD

- 2.1 The Kennedy Space Center (KSC) Materials Science Division (MSD) was contacted by personnel at Oak Ridge National Laboratory, Tennessee, to enlist support in the subject investigation for the U.S. Chemical Safety and Hazard Investigation Board, Washington, D. C. The scope of support was to determine the metallurgical properties of the subject propane tank; the pipe that carried liquid propane to a vaporizer system; and to develop information relevant to the fluid flow components involved in the fire and explosion of the subject propane storage tank.
- 2.2 The explosion occurred on a farm that raised turkeys for market. The propane storage tank contained liquid and gaseous propane used as an energy source to heat the turkey barns in colder weather conditions. It was reported that the pipe beneath the propane storage tank was hit by an all-terrain vehicle and broken open. A fire ensued, and when the storage tank ruptured, two volunteer firemen were victims of the flying debris.
- 2.3 The tank components were collected by Hall Engineering Services, P. C., Ames, Iowa, at the site after the explosion near Albert City, Iowa, and moved to Des Moines, Iowa, for storage and preservation. MSD personnel visited the storage site to determine which items would be sent to KSC for testing; the Albert City site was also visited in an effort to understand events relating to the incident. While in the Albert City area, another farm site was visited that had a similar propane heating system and components.
- 2.4 Two liquid excess flow control valves from the base of the ruptured propane tank were sent to KSC for testing and examination. The two valves are shown installed in the tank section in Figures 1 and 2. Figure 3 shows the excess flow control valve designated FV4 (that previously connected to the liquid tank fill stub) after the valve had been removed from the tank section. Valve FV4 is shown as-received in the laboratory in Figure 4. Figure 5 shows the second excess flow control valve, FV3, as-received in the laboratory. Valve FV3 fed the pipeline connected to the vaporizer system.
- 2.5 The man-way cover containing the two smaller excess control valves is shown in Figure 6. These two excess control valves were used in the vapor side of the propane system. Valve A14, used in the vapor return line for the tank filling system, is shown in Figure 7 as it was received in the laboratory. The excess flow control valve that connected to the vaporizer system, A33, is shown in Figure 8 as it was received in the laboratory. It can be noted in Figure 6 that the three pressure relief valves on the small castle on the man-way have disintegrated and the internal parts have blown out.

- 2.6 The hand valve connected to excess flow control valve FV4 is shown in Figure 9 as it was received in the laboratory. This hand valve was labeled A19. The hand valve that was connected to the flow control valve FV3 is shown in Figure 10, both at the storage warehouse in Des Moines, Iowa, and as-received in the laboratory. The hand valve A20 connected the excess flow control valve to the smaller pipeline that fed the vaporizing unit. (This is the pipe that was reported to have been broken open and been a possible contributor to the incident.) Figure 11 shows this pipe, labeled A1, as-received in the laboratory.
- 2.7 The four flow control valves FV3, FV4, A14 and A33 were manufactured by Engineered Controls International, Inc., 100 Rego Drive, Elon College, North Carolina, 27244. Flow control valves FV3 and FV4, having a three inch inlet connection, are thought to be Part Number A7539T6. Identifying marks were partially obscured or destroyed. Flow control valves A14 and A33 used in the vapor portion of the propane system had a two inch connection, and are thought to be Part Number A7537L4 for similar reasons. Hand valves A19 and A20 were manufactured by Fisher, with “400WOG” and “Ductile” cast into the valve body. It is thought that the hand valves may have been manufactured by Fisher Controls, Marshalltown, Iowa, 50158. Hand valve A19 was not used in the testing at KSC.
- 2.8 The three pressure relief valves remaining in the man-way cover were only valve bodies. The internal components are thought to have been expelled prior to the propane tank explosion, probably due to excessive pressures inside the tank. These valves were not removed or tested, as they are not functional in their current condition. It was reported that the pressure relief valves were set to open at 250 psi pressure.
- 2.9 The U-1-A form indicated that the tank was constructed in 1964 in Memphis, Tennessee.

3.0 INVESTIGATIVE PROCEDURES AND RESULTS

- 3.1 MSD personnel performed an on-site examination of the remnants at the storage warehouse in Des Moines, Iowa. Four major remnants of the tank (Figures 12-15) and the pipe (Figure 16 [subject A1]) that connected the vaporizer unit to the valve FV3 were examined visually and with low-power magnification. The fracture surfaces of the head and shell sections of the propane tank were oriented at 45°. One section of the tank shell (Figure 13) appeared to have been exposed to heat and internal pressure, causing necking of the tank material (Figure 17). The exterior of the tank appeared to have been scorched by fire, although the most severe heat damage was concentrated in the necked region of the shell. A section of the tank from the necked region (Figure 17), as well as a section of the tank shell that did not appear to have been affected by the heat (Figure 18), were permitted to be removed. The thinning that occurred on one of the tank sections is shown in

Figure 20. Three sections of steel, approximately one foot square, were cut from the remainder of the tank for metallurgical studies. The cutting operation is shown in Figure 21. Figures 22-24 show the three steel tank specimens. One section of the tank head, adjacent to the welded region near the man-way access port, displayed a lamellar fracture; a section was removed from that region (Figure 25). Destructive testing was authorized on all of the sections removed from the tank. Destructive testing was not permitted on the vaporizer pipe (A1) or other flow components.

- 3.2 The section of the tank shell that exhibited necking (Figure 26), the section that appeared unaffected by the heat (Figure 27), the tank head section (Figure 28), and the vaporizer pipe (Figure 29) underwent stereo- and macroscopic examination at KSC. The fracture surface in the necked-down region appeared corroded and smeared (Figure 30). Likewise, the section that was unaffected by the heat appeared corroded (Figure 31) and severely smeared (Figure 32). A comparison of the necked region with the unaffected region revealed the substantial ductility of the area that had been affected by the heat, i.e., the necked region (Figure 33). The lamellar region (Figures 34 and 35) appeared slightly corroded with minimal post-fracture damage. The end of the vaporizer pipe (Figure 36) that mated with the hand valve (A20) appeared rough and slightly corroded (Figure 37). The end of the pipe was bent approximately 25° with respect to the longitudinal axis. The threads of the pipe displayed mechanical damage (Figure 38), with the threads on the concave side of the bend appearing compressed (Figure 39).
- 3.3 The fracture surfaces of the various sections from the shell and head of the tank were cleaned in a dilute citric acid solution and analyzed via scanning electron microscope (SEM). The fracture surfaces from the necked region of the tank shell (Figure 40) displayed microvoid coalescence (MVC), typical of ductile overload. Likewise, the fracture surface from the tank head displayed MVC (Figure 41). A laboratory-induced overload exemplar of the shell displayed MVC (Figure 42).
- 3.4 Inductively coupled argon plasma and combustion spectrometric methods revealed that the specimens from the head and shell of the tank had compositions similar to a high-strength manganese-bearing carbon steel, similar to UNS G15250.
- 3.5 Sections of the head and shell were prepared for metallographic examination. The necked section (Figure 43) of the tank shell displayed extensive deformation of the pearlitic grains (Figures 44 and 45). The microstructure of the shell that appeared unaffected by the heat consisted of pearlite in a ferritic matrix (Figures 46 and 47). The microstructure of the tank head section that displayed lamellar features consisted of a banded pearlitic microstructure (Figure 48). Converted microhardness measurements of the necked shell section averaged 90 Rockwell B (HRB) scale, corresponding to an approximate

tensile strength of 89 ksi. Converted microhardness measurements of the unaffected area averaged 87 HRB scale, corresponding to an approximate tensile strength of 84 ksi. Converted microhardness measurements of the head section from the tank averaged 24 Rockwell C scale away from the lamellar region, corresponding to an approximate tensile strength of 118 ksi. Measurements adjacent to the lamellar region averaged 90 HRB, corresponding to an approximate tensile strength of 89 ksi.

- 3.6 The components described above in Figures 1-11 were transported from the storage site warehouse in Des Moines, Iowa, to Hall Engineering Services, P.C., Ames, Iowa, for packaging and then transported to KSC. After testing was completed, the components along with the tank material were returned to Hall Engineering Services, Ames, Iowa.
- 3.7 The test setup is shown in Figure 49. Figure 50 shows the hardware setup and Figure 51 shows a close-up of the tank base housing the excess flow control valve and the horizontal discharge pipe. Figure 52 shows a typical test run. Water was discharged from the pressurized holding tank, through the test items onto a paved area and into a storm drain at the Launch Equipment Test Facility (LETF) at KSC. A three inch ball valve was used in the pipe setup to facilitate rapidly opening the flow path.
- 3.8 The test procedure and recorded results are contained in Appendix A. Twenty-eight (28) different test runs were conducted to generate data that simulated various physical conditions and combinations of equipment. The tests verified that the excess flow control valves operated at certain conditions and did not operate at other flow conditions.

4.0 DISCUSSION

- 4.1 The failure of the tank likely originated at the necked region of the shell where it had been heated. The pressure in the tank increased until the weakened section burst. The remainder of the tank displayed typical overload features, both optically and fractographically. No evidence of a pre-existing crack was observed. The corrosion on the various fracture surfaces was post-fracture and not considered a contributing factor.
- 4.2 The vaporizer pipe appeared to have been broken mechanically from the reducer bushing in hand valve A20. Due to the constraint of not being able to dissect the pipe in the laboratory, further analysis was not possible. The corrosion on the fracture of the pipe was post-fracture and not a contributing factor.
- 4.3 The head and shell sections of the tank had compositions corresponding to a high strength carbon steel. Converted microhardness measurements corresponded to tensile strengths above the minimum 70 - 75 ksi typically used

for similar components. The lamellar and banded structure observed on the propane tank head section sample corresponded to the heat affected zone of a weld adjacent to the man-way access.

- 4.4 The excess flow control valves were individually tested using water and various pressures. The water flow rates were also measured and recorded. The valves closed when the ball valve in the experimental set-up was opened and water allowed to flow through the three inch discharge pipe.
- 4.5 When flow control valve FV3 and hand valve A20 were tested in series, the liquid flow was restricted due to the reducer bushings installed in the hand valve outlet to accommodate the one inch pipe leading to the vaporizer units. The reduced flow was insufficient to cause the excess flow control valve to close, resulting in the continuous flow seen in Figure 20. This test condition comes closest to simulating the flow conditions that likely existed at the time the propane storage tank exploded.

5.0 CONCLUSIONS

- 5.1 The one inch pipe that fed the vaporizer units failed from mechanical overload.
- 5.2 The excess flow control valve in the flow path feeding liquid propane to the vaporizer units did not close during the tests simulating conditions thought to exist at the time of the explosion because the flow of water was restricted by the reducer bushings installed in the outlet of the hand valve downstream of the flow control valve.
- 5.3 The shell of the propane storage tank necked down prior to fracture. The necking was facilitated by heat from the fire and high pressure inside the tank. The fracture in the steel of the tank shell was due to overload. The material was AISI 1525 (UNS G15250) carbon steel that failed in maximum shear stress. No evidence of any pre-existing crack in the tank shell material was observed.

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FIGURE 1

The two liquid excess flow control valves in the tank section prior to removal for testing purposes.

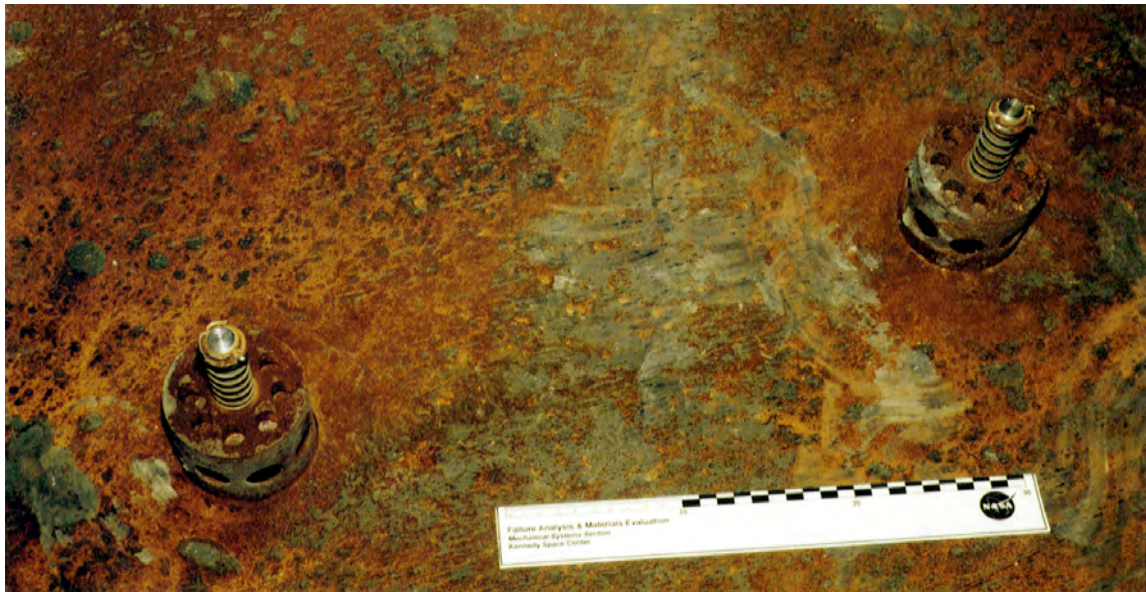


FIGURE 2

The two liquid excess flow control valves as seen from the interior side of the tank section.



FIGURE 5

Liquid flow control valve FV3 as-received in the laboratory.



FIGURE 6

Propane tank man-way cover as seen in the Des Moines, Iowa storage warehouse. Vapor excess flow control valves are labeled A14 and A33. Three pressure relief body shells can be seen on the elevated connection plate.



FIGURE 10

The lower view is the hand valve A20 as-received in the laboratory.



FIGURE 11

Fracture surface of the one inch pipe that previously connected to hand valve A20.



FIGURE 29

View of the pipe that fed liquid propane to the vaporizer units.



FIGURE 36

View of the end of the liquid propane pipe which fed the vaporizer and mated with the outlet of the hand valve. Note the tube bend and deformation of the threads (arrow).



Figure 37
View of the fracture surface of the one inch pipe (A1) which carried liquid propane to the vaporizer unit

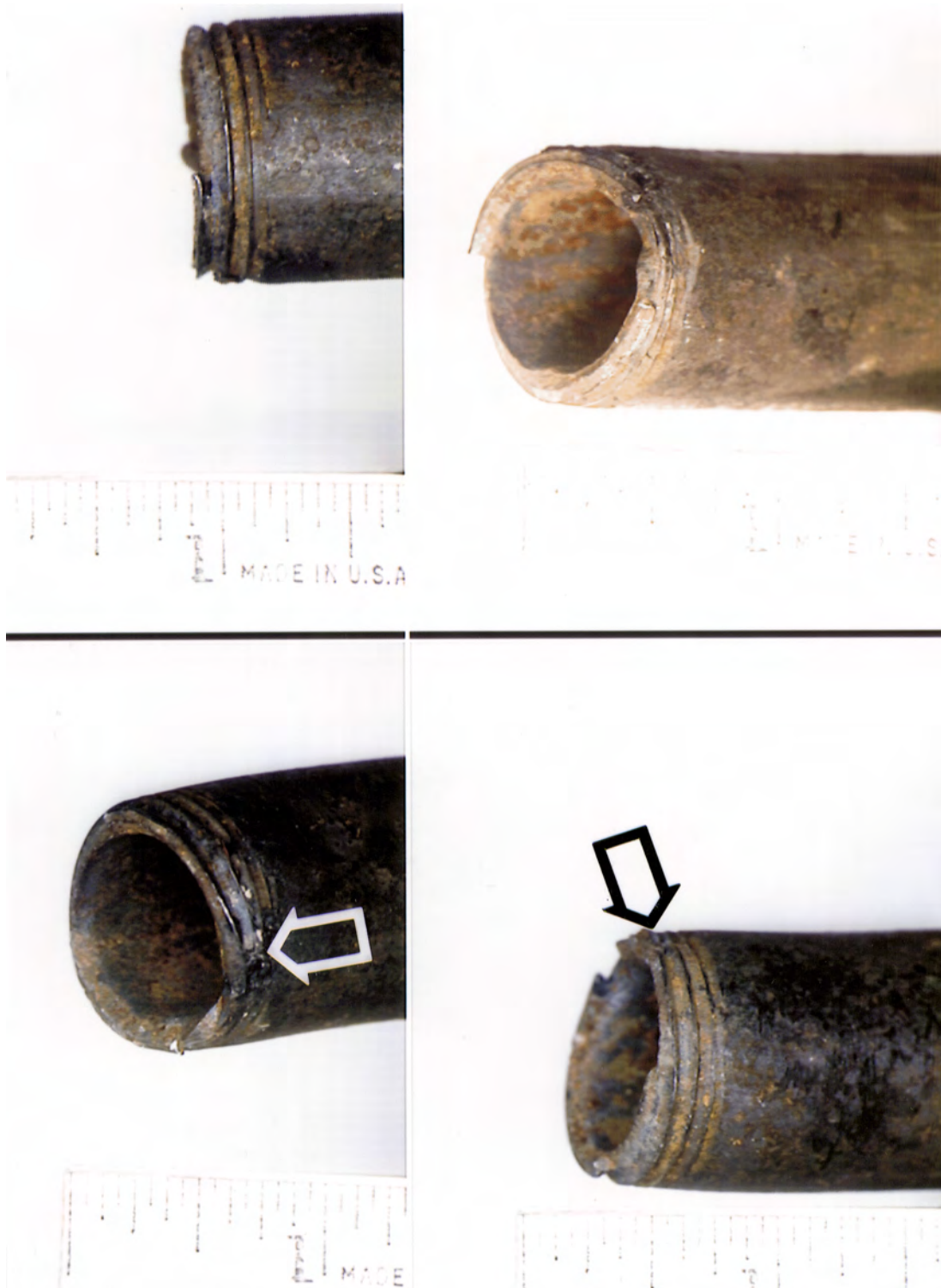


Figure 38

90° rotational view of the threaded end of the one inch pipe (A1). Arrow indicate deformed threads.



Figure 39
90° rotational view of the condition of the pipe threads on the one inch pipe (A1).
MAGNIFICATION: 5X

APPENDIX C: Debris Map

[Editor's note: Debris map and evidence description provided courtesy of J.L.Hall Engineering Services, Inc., Ames Iowa.]

EVIDENCE	DESCRIPTION
A1	3/4" pipe with union and elbow
A2	section of fill piping
A3	section of fill piping 12' 3" long
A4	section of fill piping 5' long
A5	13' 6" piping northwest of explosion
A6	15' piping with elbow near tank location
A7	piece of flat steel
A8	bulkhead Southwest of explosion in field
A9	steel piping in field SW of explosion
A10	spring in field SW of explosion
A11	west end of tank in field SW of explosion
A12	small section of flat steel from tank
A13	section of relief valve riser piping
A14	section of piping with valve west of explosion
A15	manual valve
A16	spring west of explosion
A17	portion of LP tank west of explosion
A18	LP tank section north of explosion
A19	Fisher valve NW of explosion
A20	Fisher valve NW of explosion
A21	large LP tank section east of explosion
A22	steel piping in field west of explosion
A23	steel piping in field west of explosion
A24	section of relief valve riser piping
A25	ladder from tank NW of explosion
A26	fill station and piping
A27	vaporizers and associated piping
A28	section of steel piping north of explosion
A29	float arm from inside LP tank
A30	section of relief valve riser piping
A31	spring located SW of explosion
A32	artifact in field SW of explosion
A33	steel piping in field SW of explosion
A34	cap in field SW of explosion
A35	cap in field SW of explosion
A36	actuator arm for gauge inside LP tank
A	face plate for liquid volume gauge
B	piece of flat steel
C	small LP regulator
D	small piece of tank metal

N →
Not to Scale

