U.S. CHEMICAL SAFETY AND HAZARD INVESTIGATION BOARD

INVESTIGATION REPORT

CONFINED VAPOR CLOUD EXPLOSION

(10 Injured, and 24 Houses and Six Businesses Destroyed)

CAI, INC. AND ARNEL COMPANY, INC.

DANVERS, MASSACHUSETTS

NOVEMBER 22, 2006

KEY ISSUES:

- SAFE HANDLING OF FLAMMABLE LIQUIDS
- FIRE CODE COMPLIANCE AND ENFORCEMENT
- STATE AND LOCAL GOVERNMENT HAZARDOUS FACILITY LICENSING

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Acronyms and Abbreviations

ATF	U.S. Bureau of Alcohol, Tobacco, Firearms, and Explosives
CFR	Code of Federal Regulations
CMR	Code of Massachusetts Regulations
CMU	Concrete masonry unit
CSB	U.S. Chemical Safety and Hazard Investigation Board
DoD	U.S. Department of Defense
EPA	U.S. Environmental Protection Agency
EPCRA	Emergency Planning and Community Right to Know Act
ERP	Emergency response plan
HMIS	Hazardous Materials Inventory Statement
HMMP	Hazardous Materials Management Plan
IC	Incident Commander
ICC	International Code Council
IFC	International Fire Code
lb_m	Pounds mass
IPPIC	International Paint and Printing Ink Council
LEPC	Local Emergency Planning Committee
LFL	Lower flammability limit
MSDS	Material safety data sheet
NAPIM	National Association of Printing Ink Manufacturers
NFPA	National Fire Protection Association
NPCA	The National Paint and Coatings Association
OSHA	Occupational Safety and Health Administration
psig	Pounds per square inch gauge (psi)
psia	Pounds per square inch absolute
PSM	Process Safety Management (29 CFR 1910.119)
SARA	Superfund Amendments and Reauthorization Act
SERC	State Emergency Response Commission
UFL	Upper flammability limit
UST	Underground storage tank

Executive Summary

On November 22, 2006, at about 2:45 am, a violent explosion at the CAI/Arnel manufacturing facility rocked the town of Danvers, MA. The explosion and subsequent fire destroyed the facility, heavily damaged dozens of nearby homes and businesses, and shattered windows as far away as two miles. At least 10 residents required hospital treatment for cuts and bruises. Twenty-four homes and six businesses were damaged beyond repair. Dozens of boats at the nearby marina were heavily damaged by blast overpressure and debris strikes.

The fire department ordered the evacuation of more than 300 residents within a half-mile radius of the facility. Numerous residents could not return for many months while they waited for their houses to be rebuilt or repaired. Seventeen months after the explosion, six homes had yet to be reoccupied as repairs were not complete.

The U.S. Chemical Safety and Hazard Investigation Board (CSB) determined that the explosion was fueled by vapor released from a 2000-gallon tank of highly flammable liquid. An open steam valve on the tank heater most likely caused the flammable liquid to overheat and accumulate in the building production area to what is calculated to have been a near-ideal vapor-air concentration. An unknown ignition source ignited the flammable atmosphere, causing the explosion.

The rapidly expanding ignited vapor inside the building created a pressure wave that shattered the rigid, brittle brick walls—disintegrating the structure—and ignited thousands of gallons of flammable liquids stored inside the building and some 51,000 pounds of industrial-grade nitrocellulose material stored nearby. The resultant fire burned for more than 17 hours.

The CSB identified the following incident causes:

1. CAI management did not conduct a process hazards analysis or similar systematic review to ensure that the flammable liquids processes were safely designed and operated.
   - CAI heated Class I flammable liquids in unsealed tanks inside a closed building.
   - CAI did not install or use automated process controls, alarms, or safeguards when heating flammable liquids in process equipment inside a closed building.
   - CAI did not maintain adequate building ventilation during all flammable liquids process operations.
2. CAI management did not use written procedures or checklists to ensure that flammable liquids manufacturing processes were operated safely.

The CSB also found that Commonwealth of Massachusetts statutes requiring the head of the local fire department to periodically inspect facilities that handle flammable liquids and solids do not define the inspection frequency or provide inspection criteria. The Danvers fire department had not inspected the CAI/Arnel facility in more than four years, and a 2002 inspection did not identify a number of fire code compliance deficiencies involving flammable liquids storage. Furthermore, the 2002 inspection did not identify that the permits required by the state fire code had either expired or were never issued to the companies by the fire department.

The CSB makes recommendations to the General Court of the Commonwealth of Massachusetts and the Massachusetts Office of Public Safety, the town of Danvers, CAI, Inc., the National Fire Protection Association, and the International Code Council.

1.0 Introduction

1.1 Background

On Wednesday morning, November 22, 2006, at 2:46 am, a violent explosion shook the Danversport community in Danvers, Massachusetts, 20 miles north of Boston. The explosion and subsequent fire destroyed a 12,000 square foot ink and paint manufacturing facility jointly operated by CAI, Inc. and Arnel Company, Inc. (Figure 1).

Figure 1. Danversport peninsula. CAI/Arnel facility explosion site circled (ATF photo).

The explosion heavily damaged dozens of nearby homes and businesses and shattered windows as far away as two miles. At least 10 residents required hospital treatment for cuts and bruises. Twenty-four homes and six businesses were damaged beyond repair, and dozens of boats at a nearby marina were heavily damaged by the blast wave and debris strikes.

The Danvers fire department ordered the evacuation of more than 300 residents within a half-mile radius of the facility. Search-and-rescue teams helped evacuate the injured and trapped residents and the workers trapped inside a partially collapsed bakery. Neighbors also helped each other evacuate. Firefighters declared the fire extinguished on Wednesday afternoon, more than 17 hours after the building exploded.

A few months after the incident, community residents created Safe Area for Everyone (SAFE), a community group formed to oppose any new operation on the CAI/Arnel property involving the use or handling of hazardous materials. SAFE is working with the Danvers town government to improve town bylaws addressing land use planning and regulations.

In the fall of 2007, the town of Danvers reestablished a Local Emergency Planning Committee (LEPC) to coordinate emergency planning among the local businesses that handle hazardous chemicals, local and state emergency response agencies, and the local residents (Section 4.4).[1] A member of the Danvers fire department serves as the LEPC chair.

Some residents were still in temporary housing more than seventeen months after the explosion. Rebuilding efforts on six heavily damaged or destroyed homes had not been finished. Six property owners had not settled claims with their insurance companies.

This report makes recommendations to the General Court of the Commonwealth of Massachusetts and the town of Danvers designed to improve land use planning and hazardous materials licensing regulations. It also makes recommendations to CAI, Inc., the National Fire Protection Association, and the International Code Council. Management of businesses that heat flammable liquids in

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[1] The 1986 Emergency Planning and Community Right to Know Act (SARA Title III) provides the requirements and responsibilities of the Local Emergency Planning Committee. The LEPC in Danvers had been disbanded many years before the November 2006 incident.

unsealed tanks located where flammable vapor can accumulate should closely examine the lessons learned from this incident and ensure similar unsafe conditions or operating practices at their facilities are promptly corrected to prevent future incidents.

1.2 Investigative Process

The CSB investigators arrived on scene the morning of November 24, 2006. The team comprehensively reviewed the damage in the community and collected information from residents and businesses near the CAI/Arnel facility. Explosion analysts contracted to assist the CSB team catalogued and photographed the damage throughout the surrounding community. These data were used to estimate the pressures and energy released by the explosion (Section 3.2).

The Environmental Protection Agency (EPA) Region 1 Regional Response Team was responsible for site cleanup, including classifying hazards for disposal, monitoring air quality during cleanup, and controlling worker exposure to contaminants. Working with the EPA, the CSB team collected physical evidence from the scene, including samples of the solvents used by the two companies, residue from the mix tanks, process hardware, and other equipment. The CSB investigators also extensively photographed the explosion site.

The CSB investigators interviewed CAI and Arnel employees, including personnel who were working at the facility the day before the explosion, CAI management personnel located in their Georgetown, MA, corporate headquarters and production facility, and the electrical and plumbing contractors who routinely worked at the facility. Over subsequent weeks, they interviewed the Danvers fire department Incident Commander and representatives from the town of Danvers including the town manager, public safety officials, and building department personnel. The town also provided building permit records, fire department inspection records, and underground utility documents.

As the investigation progressed, the CSB team interviewed management personnel working for KeySpan, which operates the natural gas utility distribution system in Danvers, and management personnel working for Maritimes and Northeast Pipeline, which operates the interstate natural gas transmission line located near the CAI/Arnel property. The CSB investigators also interviewed personnel from nearby businesses, residents who lived near the facility, and the contractor who performed boiler maintenance at the CAI/Arnel facility.

The CSB team identified, photographed, and documented the post-explosion location of production area fire doors, equipment, and building components, and identified items for recovery from the debris. In addition, the CAI ink recipe[2] that operators prepared the day before the explosion was duplicated in a laboratory and analyzed to determine pertinent physical parameters.

On May 9, 2007, the CSB investigation team presented preliminary incident findings to the Board and the community at a public meeting held in Danvers, MA. The Board received comments from impacted individuals regarding their experiences during the emergency. Meeting attendees expressed concern about the history of natural gas leaks in the community and the possibility that natural gas caused or contributed to the incident. The former Massachusetts state fire marshal urged the CSB to recommend that the state laws addressing flammable materials licensing be changed to require that specific information be provided to local fire departments.

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[2] A recipe is a detailed instruction used to make a specific product. It typically includes equipment preparation prerequisites, raw material quantities, addition sequence, and critical process parameters such as temperature, pressure, and flow. Recipes sometimes include warnings, cautions, and special personal protective equipment needed to manufacture the material.

1.3 Companies Involved

Prior to 1985, a single company manufactured printing inks and specialty paints in the Danversport facility. In 1985, the company divided into two separately owned entities: CAI, Inc. and Arnel Company, Inc. The two companies continued to manufacture their respective products in the facility.

1.3.1 CAI, Inc.

Headquartered in Georgetown, MA, 14 miles north of Danvers, CAI employs about 20 personnel and manufactures water- and solvent-based printing inks. The Georgetown facility houses the finance, accounting, sales, and warehouse operations for all products, as well as the water-based manufacturing process equipment.

The CAI production manager and five employees manufactured solvent-based inks in the Danvers facility. At the end of each day, they loaded the day's production of ink products onto a truck and delivered it to the Georgetown warehouse. CAI stored alcohols, heptane, other solvents, and pigments and resins in the building and in three 3000-gallon underground storage tanks (USTs).

Some of CAI's ink products also contained industrial grade nitrocellulose. At the time of the incident, CAI had about 160 300-pound fiber drums of nitrocellulose pellets[3] stored in a 40-foot trailer located adjacent to the east side of the building.

1.3.2 Arnel Company, Inc.

Nine Arnel employees worked in the Danvers facility, which was the company's only business location. Arnel manufactured solvent- and water-based stains, lacquers, coatings, and paints, as well as polyurethane coatings and adhesives. They stored alcohols and other solvents, pigments, paint

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[3] The Massachusetts fire code and OSHA classify the nitrocellulose used by CAI and Arnel as a flammable solid.

resins, and industrial grade nitrocellulose at the facility. At the time of the incident, about 15 300-pound fiber drums of nitrocellulose were stored in a trailer adjacent to the CAI trailer at the east end of the facility.

1.4 Facility Description

1.4.1 Building Configuration

The CAI/Arnel property is located at the west end of the Danversport peninsula. A large marina sits on the south shore of the peninsula. The CAI/Arnel and marina properties are separated by a marina access road. A few small businesses abut the west side of the CAI/Arnel property. A bulk propane distribution facility and a large warehouse are located 400 feet to the west, across Route 35-Water Street, a busy two-lane thoroughfare (see Figure 1).

Since the early 1900s, the peninsula has transitioned from a minimally populated area to one with many single-family and duplex homes, some located only 150 feet to the north of the facility (Figure 2). During the same period, the facility transitioned from a leather tanning business that used a few hundred gallons of flammable liquids to ink and paint manufacturing businesses using thousands of gallons of flammable liquids and thousands of pounds of flammable nitrocellulose pellets in their manufacturing processes.

Figure 3 shows the general layout of the CAI/Arnel building prior to the explosion. The exterior and interior walls were constructed with unreinforced concrete masonry unit blocks (CMUs). Steel trusses supported a steel sheet roof above area C. The roof above area E was 2- to 3-inch-thick reinforced concrete supported by steel beams, and the other roof structures were constructed of wood.

Figure 2. West end of the Danversport peninsula before the explosion.
CAI/Arnel facility circled.

Photo: Office of Geographic and Environmental Information (MassGIS), Commonwealth of Massachusetts, Executive Office of Energy and Environmental Affairs.

The south side of the CAI/Arnel building structure contained office and laboratory areas for the two companies (areas A and B). Two small steam boilers were located in a room adjacent to the west end of area J. The boilers were accessed through a door in the northeast corner of area B. The fuel oil tanks were located in the west end of area J. A wall-mounted fan in the boiler room provided air for combustion and room cooling. The air exhausted into area J, and into area B when the boiler access door was open.

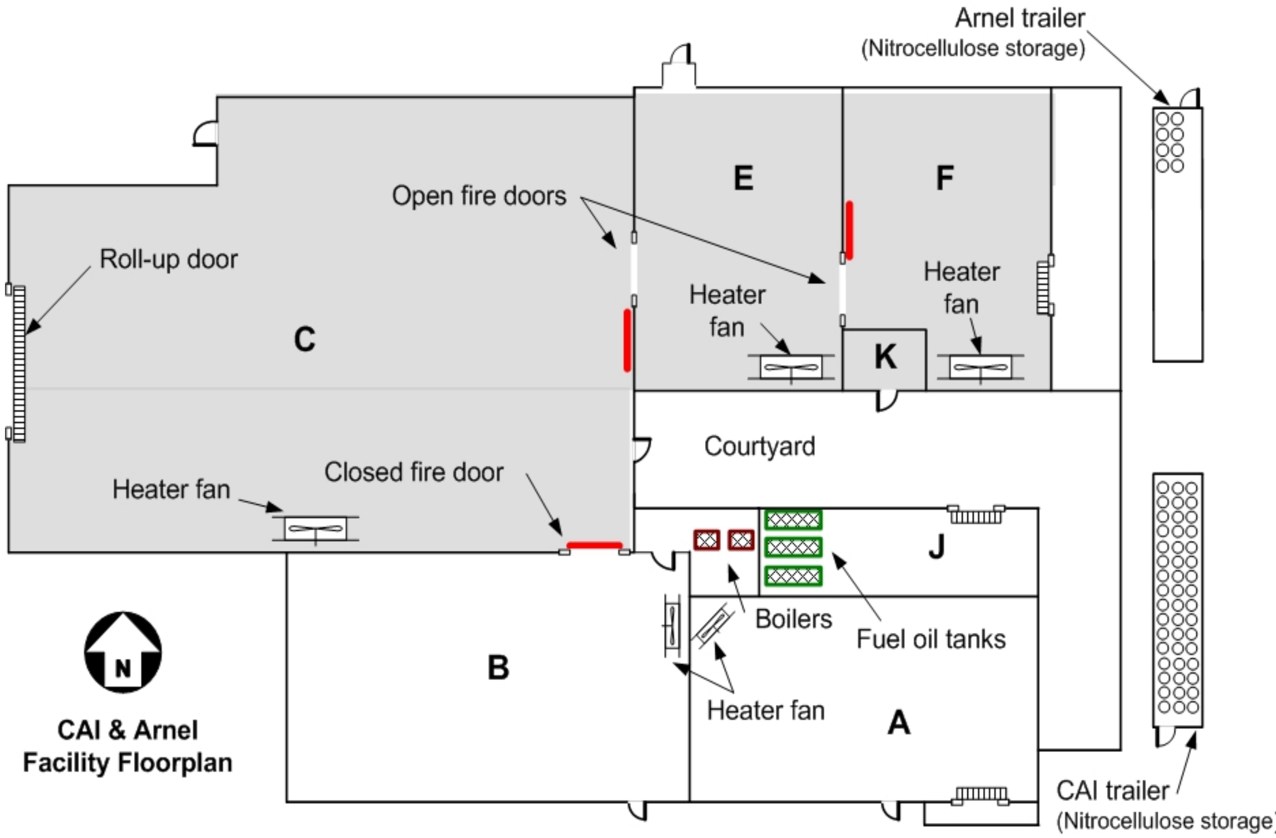

Figure 3. CAI/Arnel building layout. Production areas are highlighted.

Areas C, E, and F housed the production equipment, raw materials, and product storage for both companies. The electrical equipment in the production areas was required to be rated for use in a flammable environment because of the potential for a flammable atmosphere to be present.[4, 5] The CSB investigation team noted that the permanent lighting fixtures, mixer motors, electrical conduit, and other electrical equipment in the production area debris after the explosion appeared to be appropriately rated.[6] The CSB team also recovered a few non-rated electrical devices from the debris,

[4] National building and fire standards provide the requirements for electrically classifying work areas.

[5] 29 CFR 1910 Subpart S, Electrical 1910.307. *Hazardous (classified) Locations*

[6] Many equipment nameplates and labels were destroyed by the fire; thus, manufacturers' ratings could not be confirmed.

but could not determine if any had been located in a hazardous area or connected or energized the night of the explosion.

Three USTs were outside, about 15 feet north of area E. Each 3000-gallon UST had two chambers that CAI and Arnel used to store various flammable liquid solvents. Underground piping connected each chamber to piping manifolds located on the north wall inside area E. Each company had its own transfer pump and piping manifold to withdraw solvents from their respective UST chambers. Distribution piping manifolds directed the solvent from each pump to the appropriate process tank or mixer within the production areas.

Employee interviews and hardware found in the debris indicate that the employees in both companies were careful to avoid accumulating dangerous static charges when transferring flammable liquids from one container to another. The process equipment was grounded to minimize static charge accumulation, and the portable containers were bonded.[7] Solvent discharge pipes directed the liquid flow against the side of the mix tanks to minimize static charge generation. Employees were also required to bond portable containers to the process equipment when transferring flammable liquids and to wear personal grounding devices when handling nitrocellulose.

1.4.2 Heating and Ventilation Systems

1.4.2.1 Cold Weather Comfort Heating System

Steam-coil fan units (Figure 4) mounted near the ceiling heated the building. Wall-mounted thermostats controlled the heater fans in the office and laboratory areas. Production area heaters were located in the southeast corner of area C, on the south wall of area E, and on the south wall of area F (see Figure 3). The fan motors would likely not be required to be rated for use in a flammable

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[7] Grounding electrically connects equipment to an earth ground. Bonding electrically connects two pieces of equipment.

atmosphere because they were located high on the wall and far from the process equipment where flammable vapors could be present. Employees reported that the heater fans in the production area were controlled by wall-mounted on/off switches and remained on during cold weather even when the building was unoccupied, which was the case on the night of the explosion.

Figure 4. Steam coil air heater recovered from the debris.
Fan motor is at the lower center of the photo.

1.4.2.2 Dust Handling System

The facility was equipped with two independent dust collection systems to capture dust when employees added resin or coloring pigments to the ink and paint mixing equipment. One dust collector was outside the building near the northwest corner of area C; the other was in the courtyard between areas E and J. When adding resin, pigment, or other dusty components to a tank or mixer, the operator opened a slide valve on the dust duct attached to the process equipment to draw airborne dust into the collector, closing the slide valve when complete. CAI and Arnel personnel reported that they turned the dust collector fans off each night, including the night of the explosion.

1.4.3 Building Ventilation System

CAI and Arnel used and stored large quantities of flammable liquids inside the building. The Massachusetts fire code[8] and the Occupational Safety and Health Administration (OSHA) Flammable and Combustible Liquids standard[9] require adequate building ventilation to prevent flammable vapor from accumulating to dangerous concentrations during handling or processing operations.[10]

The building ventilation system consisted of a fresh air distribution system and production area exhaust fans to remove flammable vapor from around the unsealed ink and paint mixers (Figure 5 and Figure 6). A perforated air duct attached to a 6000 cubic feet per minute (cfm) fresh air supply fan in area E distributed fresh air along the ceilings of areas C and E. Three 6000-cfm exhaust fans were installed in the production area: one near the floor on the south wall of area E, one near the floor on the east wall of area C, and one in the northeast corner of area C about four feet above the floor. The CSB investigators recovered one of these wall fans from the debris. Although the motor was heavily damaged by the intense fire, it appeared to be rated for use in a flammable atmosphere.[11] Employees told the CSB investigators that all three wall-mounted fans were identical.

A 960-cfm blower fan located outside on the north wall of area E drew air out of area E near the floor through an eight-inch duct. This fan assembly was recovered at the property fence, about 50 feet north of its installed location. Although flammable vapor might have been present in the exhausted air, the fan and motor were not rated for use in a flammable atmosphere.

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[8] 527 Code of Massachusetts Regulations

[9] 29 CFR 1910.106

[10] Building ventilation requirements specify maximum flammable vapor concentration limits at specific distances from flammable vapor sources.

[11] The fan motor and nameplate were destroyed by the fire, preventing investigators from determining if the assembly was rated for use in a flammable vapor environment.

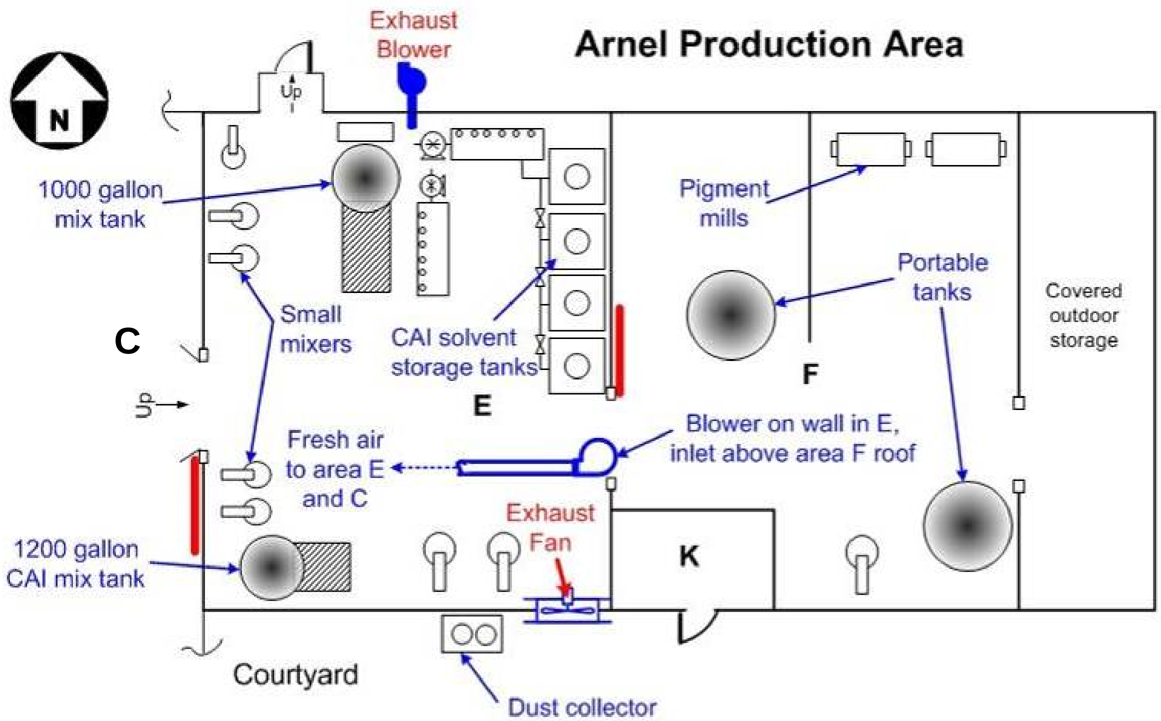

Figure 5. Arnel production area equipment and ventilation systems, areas E and F. CAI solvent storage and one mix tank also located in area E.

CAI management reported that CAI employees turned off the ventilation system at night to allay nearby residents' complaints about excessive noise and to reduce heat loss from the building.

Flammable liquids were stored in containers permanently connected to a distribution manifold using elastomeric hoses and compression clamps. In addition, open-top mix tanks routinely contained flammable liquids, sometimes with agitators energized, even during the unoccupied overnight hours when the ventilation system was not operating. Four mix tanks had heaters connected to the continuously operating steam system. If a leak occurred from a storage container, pipe manifold, or mix tank, or if a tank heater malfunctioned, flammable vapor could accumulate to dangerous concentrations within the building. However, CAI management did not recognize the increased risk of fire or explosion due to flammable vapor accumulation in the unventilated and unoccupied building.

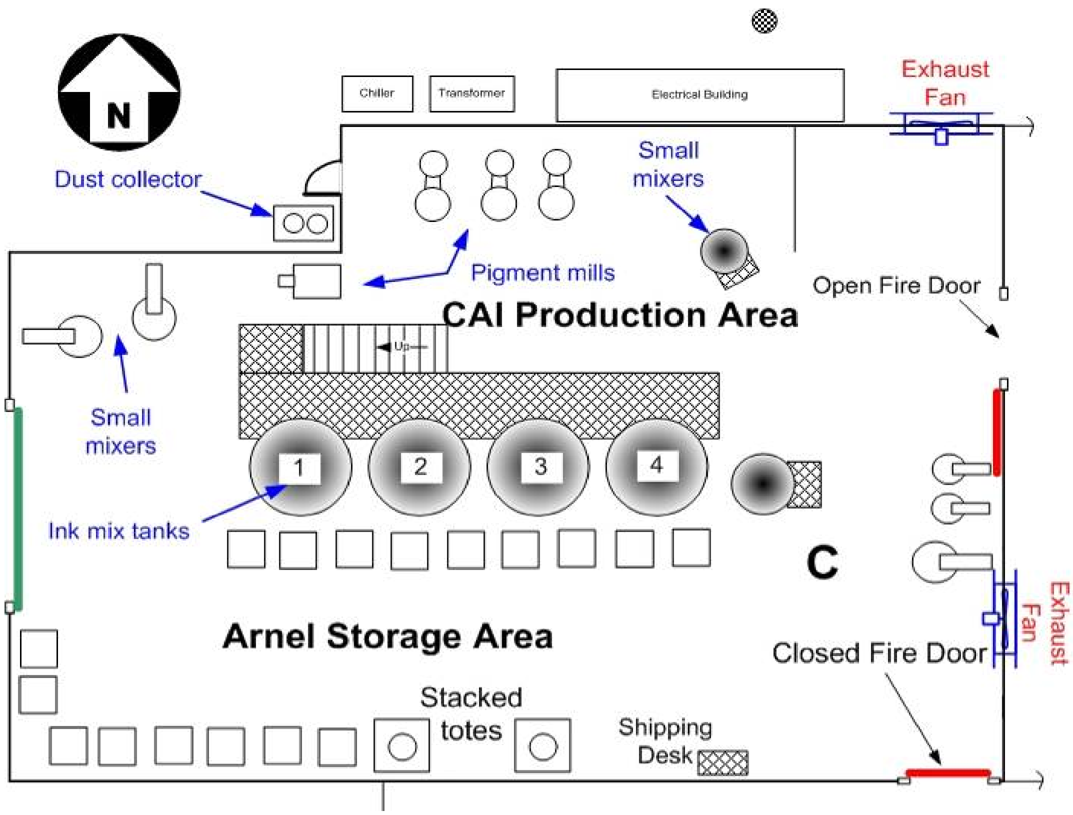

Figure 6. CAI production and Arnel materials storage, area C.

1.4.4 Building Fire Control System

The production area had three fire doors (see Figure 3), each suspended from roller tracks and moved parallel to the wall to open or close. One fire door was located in the southeast corner of area C, which isolated the office/laboratory areas from the production area. CAI and Arnel employees said this door remained closed at night when the building was unoccupied. A second fire door was on the wall between areas C and E, and the third was located on the wall between areas E and F. Although a few employees told the CSB investigators that they thought all three fire doors were routinely closed at night, the last employee to leave the building the night before the explosion said that only the fire door separating the production area from the office/laboratory area was closed the evening before the incident. Considering the employee interviews and where the doors were found in the building debris, the CSB team concluded that the fire doors on the east and west walls of area E were open the night of the explosion.

A foam fire suppression sprinkler system was installed in production areas C, E, and F. In the event of a fire, fusible plugs on the ½-inch orifice standard sprinkler heads would melt to activate the sprinkler head. Water flow in the fire suppression system would trigger the fire alarm box, which would send a signal to the Danvers fire department. The system was not equipped with smoke detectors or other electronic activation devices.

1.5 Process Descriptions

1.5.1 Arnel Materials Storage Scheme

The raw materials Arnel used for paint manufacturing included solvents, resins, pigments, and nitrocellulose. The nitrocellulose was stored in a trailer adjacent to the northeast corner of the building, near production area F. Employees typically maintained an inventory of 10 to 20 fiber drums, each containing 300 pounds of industrial grade nitrocellulose. They stored flammable liquid solvents outside in USTs and inside the production areas in 55-gallon drums as well as in a few 300- to 400-gallon metal intermediate bulk containers (totes).[12] Finished products were stored in the production areas until shipped to customers.

1.5.2 Arnel Paint Manufacturing Process Equipment

Arnel operated a 1000-gallon product mix tank located on the north wall in area E (see Figure 5) and 5- and 55-gallon mixers in areas E and F. Area F contained two rotating-drum grinding mills used to prepare pigments. A flexible hose connected to an overhead duct was installed at the mixers and grinding mills drew airborne dust to the dust collector located in the courtyard during all filling

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[12] The Arnel totes were used as portable tanks. Empty totes were replaced with vendor-supplied full totes.

activities. All of the Arnel equipment was unheated, and Arnel personnel stated that they turned off all mixing and grinding equipment at the end of each workday.[13]

1.5.3 CAI Materials Storage Scheme

CAI used raw materials including solvents, resins, pigments, and nitrocellulose. The nitrocellulose was stored in a trailer adjacent to the southeast corner of the building, near office area A (see Figure 3). Approximately 160 fiber drums, each containing 300 pounds of industrial grade nitrocellulose, were in the trailer at the time of the incident.

CAI stored solvents in the outdoor USTs and in 55-gallon drums in area E. They also used eight 500-gallon steel totes—four rows stacked two totes high—in area E (Figure 7) to store solvents. Operators transferred solvent from the USTs and totes to the mix tanks using a metering pump located at the manifold station. Because the totes were permanently connected to a pipe manifold, fire code requirements addressing fixed storage tanks installed inside a building applied, rather than portable container fire code requirements.

The CSB investigators noted that the solvent storage located in area E was not compliant with certain state fire code or OSHA worker safety requirements. First, the unsealed solvent storage totes vented directly into the room, not outdoors. Second, Class I flammable liquids[14] were discharged through the bottom drain valve outlet on each tote, not pumped out from the top of the tote. Third, the totes had no spill containment system around them to contain a flammable liquid release, such as overflow during a filling operation. Finally, the pipe manifold connected the totes to the pump using combustible elastomeric hoses between each tote and the manifold, not steel pipes.

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[13] Arnel management told the CSB that at the end of each workday they inspected the area using a checksheet to verify equipment status. The explosion and fire destroyed all the records.

[14] Class I flammable liquids are defined as liquids having a flashpoint below 100 °F (OSHA 29 CFR 1910.106).

Figure 7. CAI totes stored flammable liquids in area E. Circled area shows one of the flexible hose connection points to the manifold pipe.

1.5.4 CAI Ink Manufacturing Process Equipment

The largest CAI production equipment, four ink vehicle[15] mix tanks, each approximately 3000 gallons in capacity, was located in area C (see Figure 6). Each tank was about 10 feet tall and eight feet in diameter and had a top-mounted mixer. Mix tanks 1 and 2 were fully open on top, while tanks 3 and 4 were each equipped with a top dome containing a 12-inch diameter access hatch (Figure 8). A hatch cover on each kept debris from falling into the tanks, but did not prevent air or vapor from passing through the opening. Each tank was equipped with a steam heating jacket connected to the steam boiler. Mix tank 3 was insulated on the bottom and sides. The operator controlled the mixture (ink vehicle) temperature by opening and closing a ¼-turn ball valve on the steam pipe connected to the tank jacket.

[15] The printing ink "vehicle" is a mixture of solvents, water, or resin that carries the colorant and other additives.

Operators accessed the tank tops, weight and temperature display consoles, mixer control switches, and steam valves from a steel-grated mezzanine deck on the north side of the tanks (see Figure 8). They pumped liquids from the manifold station in area E directly into the appropriate mix tank. Dry materials and the nitrocellulose pellet drums were lifted to the mezzanine platform with a forklift, then hand-loaded into the appropriate mix tank. The operator opened the slide valve on the dust collector suction line during the addition of dusty materials to the mix tank and closed it afterward.

CAI's production manager was responsible for operating the four mix tanks. He told the CSB investigators that he typically heated the mixture in mix tank 3 to 90 to 120°F to help dissolve the resin and then closed the steam supply valve. He said he did not leave the steam on during non-work hours, although he routinely left the mixer running. However, CAI did not have written procedures for the operation of process equipment; rather, they used ink vehicle recipes. These recipes listed the materials and quantities needed for each specific batch, but did not include checklists or other written instructions to ensure that equipment was operated correctly and consistently.

After the ink vehicle passed a quality control check, operators pumped the liquid out of the bottom of the mix tank into one or more of the smaller pigment mixers, as needed. Unused ink vehicle would remain in the large mix tank for days or possibly weeks until it was all utilized in specific ink products.

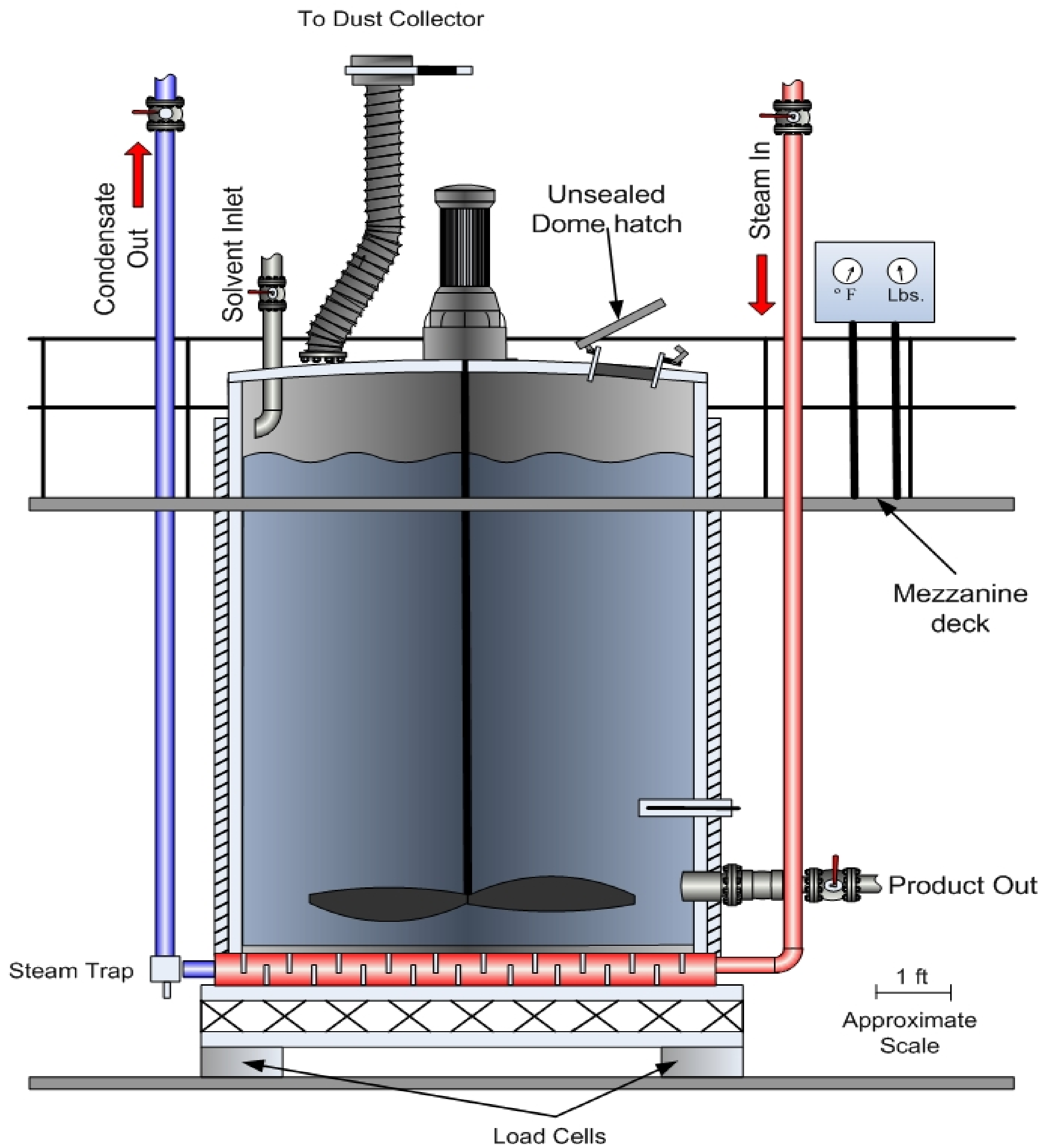

Figure 8. CAI ink vehicle insulated mix tank 3.

2.0 Incident Description

2.1 Normal Workday Activity

On Tuesday afternoon, November 21, 2006, Arnel employees ended their workday before CAI employees. Arnel employees told CSB investigators that they used a checklist to perform an end-of-workday walk-down to verify that all of their equipment was turned off and that Arnel office doors and storage trailers were locked. The Arnel employees then left the facility.

CAI employees told the CSB investigators that they began mixing a 2000-gallon ink vehicle batch in mix tank 3 at approximately 1:00 pm. The CAI production manager said he opened the steam valve at about 3:00 pm to begin heating the mixture. While waiting for the mixture temperature to increase to the 90°F target, he said he and other employees unloaded a shipment of resin and pigment from a truck then loaded the day's ink production into the truck, finishing shortly after 5:00 pm.

The production manager told investigators that before he left for the day he returned to the work platform to check the mixture temperature, which he recalled was about 90°F. He told CSB investigators, "I believe I closed the steam valve." He also said he left the mixer on to prevent undissolved resin from settling to the bottom of the tank, then left the facility at around 5:30 pm.

Shortly before 6:00 pm, the last CAI employee in the building turned off the dust collector fans, wall-mounted exhaust fans, and fresh air supply fan, then locked the building and left for the night.

2.2 Explosion and Emergency Response

The Danvers fire department is located about one mile from the CAI/Arnel facility. At 2:46 am on Wednesday, November 22, the fire department alarm signal began sounding. However, the alarm transmitter at the CAI/Arnel facility malfunctioned before the signal code was completed.[16] A few seconds after the alarm began sounding, fire department personnel heard and felt an explosion. They immediately saw a bright fireball in the sky south of the station as they prepared to dispatch the response team.

Arriving in Danversport, they observed people fleeing from heavily damaged houses and extensive structural damage and debris throughout the surrounding community. The Danvers fire department Incident Commander (IC) immediately launched a comprehensive search-and-rescue operation. Residents and emergency responders helped the injured exit their homes and a nearby bakery that had been extensively damaged (Figure 9). Some of the organizations that participated in the emergency response included:

- Salem, Peabody, and Beverly fire and police departments,
- Massachusetts Environmental Police,
- U.S. Environmental Protection Agency (EPA),
- U.S. Coast Guard,
- U.S. Bureau of Alcohol, Tobacco, Firearms, and Explosives (ATF),
- Massachusetts Department of Environmental Protection,
- Massachusetts Office of the State Fire Marshal, and
- Massachusetts State Police.

The IC ordered an evacuation of about 300 residents and 10 businesses within the incident area. At about 6:30 am he ended the search-and-rescue operation. Shortly afterward, fire crews ceased firefighting activities on the fire that remained burning on the CAI/Arnel property. They continued applying water to a propane storage tank located behind the bakery to disperse propane vapors that were escaping from a pipe damaged by the explosion. At about 1:00 pm on Wednesday afternoon,

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[16] The electronic alarm should have sounded a series of tones that identified the location of the alarm, then continually repeat the code sequence. However, after sending only the first few tones, the signal began randomly sending a tone, which indicated a fault in the electrical connection that was most likely the result of the explosion.

fire crews began spraying foam on the fire that continued burning at CAI/Arnel. Finally, at about 8:00 pm—17 hours after the explosion—the IC declared the fire extinguished.

Figure 9. Search and rescue activities after
CAI/Arnel building explosion (Boston Globe photo).

The explosion and fire leveled the CAI/Arnel facility (Figure 10). One hundred and fifty to 300 feet to the north, the force thrust windows and doors, with their frames, into houses (Figure 11). Ceilings inside houses collapsed on sleeping occupants. Large appliances and kitchen cabinets were thrown across rooms. One hundred feet northwest of the CAI/Arnel building, the bakery's roof and second story collapsed (Figure 12). Brick chimneys as far as 500 feet from the facility were knocked down or heavily damaged. Seventy-seven families were forced to relocate to temporary housing because their homes were heavily damaged; 24 homes were later declared damaged beyond repair.

Figure 10. Aerial view of CAI/Arnel facility after explosion and fire (bakery/pizzeria building lower left) (ATF photo).

Figure 11. Houses destroyed by the explosion.

Figure 12. Bakery/pizzeria building destroyed by the explosion
(CAI/Arnel building far rear on right).

Explosion damage was widespread: 800 feet south of the facility, nearly every window and door facing the CAI/Arnel facility at the New England Home for the Deaf was shattered or blown in (Figure 13), forcing the evacuation of 60 assisted living residents.

Figure 13. Shattered windows and doors boarded up at the
New England Home for the Deaf,
800 feet from the explosion.

Inch-thick pieces of concrete as large as 10 inches in diameter were thrown hundreds of feet into the surrounding community and marina. Large pieces of wood and other debris littered Bates Street, some 200 feet away. The blast wave shattered windows and buckled doors and panels on vehicles parked as far away as 300 feet (Figure 14).

Figure 14. Shattered windows and buckled panels on vehicles.

Remarkably, only 10 people were injured; all of them were treated for cuts and bruises then released from the local hospital. The low number of injuries and absence of fatalities are attributed to the time of the explosion, 2:46 am, when most occupants were in their houses lying in their beds, covered with blankets that protected them from flying glass and debris. The few occupants who were not in bed and the employees working in the bakery happened to be in rooms shielded from the explosion rather than standing or sitting in rooms directly facing the facility. It is likely that fatalities, or at least life-threatening injuries, would have resulted had the explosion occurred when people were outdoors or standing at rear-facing windows or doors in houses abutting the property (Figure 15).

Figure 15. Bates Street home 150 feet north of CAI/Arnel facility destroyed by the explosion.

Pipe joints on the underground cast iron natural gas distribution pipe more than 200 feet away (on Water Street to the west of the facility and Bates Street to the north of the facility) began leaking natural gas.[17] Although the explosion damaged natural gas pipes at a few houses, none of the leaking natural gas ignited, and only the CAI/Arnel building burned (Figure 16).

[17] The Worcester Polytechnic Institute seismograph, 30 miles from the explosion scene, reported that the ground motion from the explosion measured 0.5 on the Richter scale.

Figure 16. Explosion and fire destroyed the CAI/Arnel building.

Most of the CMU walls in the CAI/Arnel building were destroyed (Figure 17). The Arnel storage trailer on the east side of the facility was knocked on its side. Other 40-foot long semi-truck trailers parked on the north and south sides of area C were displaced more than 30 feet and their explosion-facing sides caved in under the force of the explosion. Thousands of gallons of solvent, paint and ink products, the building's heating oil, and more than 50,000 pounds of nitrocellulose burned for many hours.

Figure 17. Debris from shattered CMU walls and collapsed roof trusses in area C.

3.0 Explosion Analysis

In its 10-year history, the CSB had not observed such extensive community damage from any incident prior to the Danversport event. Understanding what caused such a violent deflagration is critical to identifying changes in management and regulatory programs that local and state governments and industry can implement to prevent similar incidents.

CAI employees told the CSB investigators that they had loaded mix tank 3 with a more than 2000-gallon liquid mixture of heptane, isopropyl alcohol, and normal propyl alcohol the day before the explosion. To understand the vaporization characteristics of the mixture, the CSB investigators commissioned laboratory analyses to determine the actual boiling temperature of the mixture and the constituents of the vapor. The investigators calculated the volume of flammable vapor that could have been released into the closed building from the tank if the steam-supplied tank heater overheated the mixture during the overnight hours before the explosion.

3.1 Fuel Sources

Heating flammable liquids above their flashpoints[18] in open containers inside buildings is likely to generate significant combustible vapor, which must be continuously removed to prevent accumulation to an ignitable concentration in air. Both companies stored flammable liquids in portable containers and stationary tanks in the production area of the building. The Arnel processes did not involve heating flammable liquids, but CAI did heat Class I flammable liquids in open tanks in the building during normal work hours.

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[18] Flashpoint is the minimum temperature at which a liquid releases vapor within a test vessel in sufficient concentration to form an ignitable mixture with air near the surface of the liquid [29 CFR 19140.106(a)(14)].

Employees from both companies acknowledged that the building ventilation system was turned off the night of the explosion. Therefore, the CSB investigators examined the possibility that sufficient flammable vapor was generated from an inadvertently heated flammable liquid in a mix tank or from a leak from a large storage tank. Appendix B contains the vapor generation rate calculations for both of these possibilities. Additionally, the CSB addressed resident concerns by investigating possible sources of natural gas to determine whether it could have been involved in the incident.

3.1.1 Flammable Vapor from a Storage Tank

The CSB evaluated a flammable vapor release scenario that could result if heptane were released from one of the CAI storage totes in area E. The team ruled out a flammable liquid release from a steel tote or steel pipe rupture because there was no credible failure mechanism. However, if a flexible elastomeric hose used by CAI to connect the tote outlet valves to the steel pipe manifold (see Figure 7) were to suddenly fail with the tote valve open, heptane would spill onto the floor. Because the totes had no spill containment, heptane would rapidly spread throughout area E and flow into areas C and F (see Figure 3). With the building ventilation off and the area heater fans on, more than 850 pounds of heptane vapor, enough to fuel the explosion, could be released from the liquid spill within a few hours and mix with the air in the production area.

This scenario was ruled out because CAI employees reported, and visual examination confirmed, that all the tote drain valves were closed. Furthermore, because the flexible hoses were isolated from the totes, a hose failure preceding the fire would not have released the contents of a tote.

3.1.2 Flammable Vapor from a Production Tank

On the afternoon of November 21, approximately 13 hours before the explosion, the CAI production manager prepared a 2000-gallon ink vehicle batch containing more than 10,000 pounds of flammable liquid in mix tank 3. The activity required him to pump specific quantities of three flammable liquids from storage tanks into the mix tank, start the agitator, and add powder resin and other dry chemicals. He then opened the steam valve to heat the mixture. While waiting for the mixture's temperature to rise to between 90°F and 120°F, the range used to dissolve the resin, he left the mezzanine area to help other employees unload a truckload of resin bags and other raw materials, then reload the truck with the day's ink production. He planned to return to the mezzanine to check the tank temperature on the display panel and close the steam valve (see Figure 8).

Although the production manager told investigators that he believed he closed the steam valve, the CSB investigators concluded that he most likely simply forgot to perform this critical step before he left for the day at 5:30 pm. Other work activities might have distracted him; in addition, he had no written procedure or checklist to remind him to close the valve, and the tank had no alarms or indicators to alert him that the steam valve was open. His apparent mistake is a common human error known as "loss-of-activation," a type of "slip" error (Norman, 1988). An individual "will make occasional errors, such as forgetting to close or open a valve, even if the person is well-trained and well-motivated" (Kletz, 2001).

Because mix tank 3 was not vented to the building's exterior, uncontrolled tank heating could cause the mixture to rapidly vaporize and release enough vapor into the production area to fuel the explosion. The ink vehicle mixture properties and tank heating capacity were analyzed to determine how much heptane could have been released into the unoccupied building.

3.1.2.1 Mixture Boiling Point

In testing the hypothesis that flammable liquids boiled in the unsealed production mix tank and released flammable vapors, the CSB investigators first determined the boiling point of the ink vehicle as prepared the day before the incident. The CSB tested the mixture in accordance with ASTM method D86, "Standard Test Method for Distillation of Petroleum Products at Atmospheric Pressure."

The boiling temperature was measured by heating a mixture of heptane, isopropyl alcohol, normal propyl alcohol, water, and solid resin containing the same mass percents as the ink vehicle recipe.

The test revealed that the mixture forms a low-boiling (positive) azeotrope[19] with an average boiling point of 165.6°F, 14 degrees below the mixture boiling temperature reported by CAI on its Material Safety Data Sheets (MSDS). Furthermore, it was almost 42 degrees lower than the boiling point of heptane. Table 1 compares the boiling temperatures of the mixture, heptane, and alcohols.

The results indicate the time required to heat the mixture to the boiling point would be shorter than a mixture having a boiling temperature as listed on CAI's MSDS. Furthermore, in processes using the tank's steam heater,[20] the mixture would initially boil more vigorously and release vapor faster than a mixture with a higher boiling temperature.

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[19] An azeotrope is a mixture of two or more pure compounds (chemicals) in such a ratio that its composition cannot be changed by simple distillation. The boiling point of an azeotrope is either less than the boiling points of any of its constituents (a positive azeotrope), or greater than the boiling point of any of its constituents (a negative azeotrope).

[20] The boiler steam pressure ranged from 7 to 10 psig, producing 232 to 239°F steam.

Table 1. CAI ink vehicle component and mixture boiling temperatures.

Flammable Liquid	Boiling Temperature (°F)
n-propyl and iso-propyl alcohols	180-207
Heptane	208
As tested ink vehicle recipe (Alcohols / Heptane / water / resin mix)	165.6
As reported in CAI co-solvent vehicle MSDS	180-207

As part of the mixture test protocol, the relative composition of distillate and vapor phase constituents was analyzed at three temperature points using gas chromatography. The results indicated heptane was the predominant solvent vapor initially released. As the mixture continued to vaporize, the heptane vapor concentration began to decrease and the alcohol vapor concentration increased.

3.1.2.2 Flammable Vapor Generation

The CSB team hypothesized that overheated solvent inside the tank would generate flammable vapors, which would escape through the unsealed hatch into the building. The analysis of solvent mixture temperature rise and boiling rate models concluded that steam flowing through the mix tank heating jacket would have increased the mixture's temperature to boiling point within a few hours. The CSB investigators concluded that an open steam valve would have caused the liquid to boil. As long as the steam valve was open, the boiling mixture would continue to release many hundreds of pounds of flammable vapor into the unventilated production area.

3.1.2.3 Vapor Accumulation in the Unventilated Building

Mixing flammable liquids in tanks that vent directly into buildings requires special precautions to prevent dangerous flammable vapor accumulation. OSHA worker safety standards and

Massachusetts fire code regulations require adequate ventilation around process equipment to remove flammable vapor from a building. Although heating flammable or combustible liquids above their flashpoints is not prohibited by OSHA or the Massachusetts fire code, the CSB stresses that heating should only be done in sealed vessels that are safely vented outside the building.

A CAI employee told the CSB investigators that he turned off the building ventilation fans when he left for the night. As the heptane and alcohol mixture boiled in mix tank 3, the heavier-than-air vapors flowed out of the unsealed dome cover and accumulated at the base of the mix tanks. As discussed, the employees left heater fans on at night, which likely provided enough airflow to thoroughly mix the heptane and alcohol vapor throughout the production area (see Figure 4). Since few possible ignition sources were present in the area, the flammable vapor concentration increased above the lower flammability limit without igniting. Ultimately, a near-homogeneous flammable vapor/air mixture at a concentration above the stoichiometric ratio but below the upper flammability limit was ignited by an unidentified source (see Section 3.2).

3.1.3 Natural Gas Leak into the Building

Many Danversport residents and a few CAI and Arnel employees told the CSB investigators that they had smelled an odor they believed to be natural gas near the facility the day before the incident. The CSB investigated possible sources of natural gas to determine if a leaking gas pipe could have released a large volume of natural gas into the CAI/Arnel building.

Neither the Danvers fire department nor KeySpan, which operates and maintains the odorized natural gas utility system that supplies residents and businesses in Danvers, had any record of gas odor complaints in or around the Danversport homes or in the CAI/Arnel facility in the days leading up to the incident.[21] Furthermore, it is highly unlikely that a natural gas leak from a buried pipe could travel at ground level hundreds of feet such that a person would smell the odorant or it would enter and accumulate inside a building. Because natural gas is lighter than air, a natural gas leak rises into the atmosphere, especially when the wind is calm, as it was the day before the explosion.

Propane and natural gas use odorants that have similar smells; thus, the smell community members described as gas could have been from propane. Eastern Propane and Danversport Bottle Gas filled propane tanks a few hundred feet west of CAI/Arnel facility. The propane odorant is heavier than air, so if the wind is nearly calm a leaking odorant can travel hundreds of feet close to the ground. Residents' claims to CSB investigators that they had smelled gas could have been the result of propane releases when either of the two companies filled propane tanks. In fact, the CSB learned that at about 11:30 am Tuesday, the day before the explosion, a significant propane release occurred when a buried pipe was damaged at Eastern Propane.[22] The leak was stopped within about 20 minutes and pipe repairs were completed in a few hours. Propane released from the damaged pipe might have been the source of the strong odors reported that morning in the Danversport community.

Although the CAI/Arnel facility did not have natural gas service, two natural gas underground pipelines were located within a few hundred feet (Figure 18):

- The Maritimes and Northeast pipeline, a high-pressure interstate gas transmission pipeline, which does not provide gas service to any homes or businesses in Danvers, and
- The KeySpan gas distribution system, which provides natural gas to the homes and some businesses in the area.

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[21] The CSB reviewed the KeySpan leak and repair records and natural gas odor complaints on file at KeySpan and the Danvers Fire Department for the three months preceding the incident.

[22] A worker at Eastern Propane punctured a 1-¼ inch diameter underground pipe during excavation on their property the day before the CAI/Arnel incident. The leak was quickly isolated and repaired.

The CSB investigated the possibility that natural gas from a leak in either buried pipeline could accumulate inside the CAI/Arnel building.

3.1.3.1 Maritimes and Northeast Pipeline

The Maritimes and Northeast pipeline is 215 feet south of the facility and operates at a maximum pressure of about 1400 psig. The pipeline is 30 inches in diameter and has 0.618-inch wall thickness. The pipeline is all-welded steel and has been in operation less than four years.

Figure 18. Buried natural gas lines near the CAI/Arnel property (circled).
Solid line – Maritimes and Northeast pipeline.
Dashed line – KeySpan utility pipeline.

Photo: Office of Geographic and Environmental Information (MassGIS), Commonwealth of Massachusetts, Executive Office of Energy and Environmental Affairs.

Natural gas leaking from this pipeline would have had to travel underground more than 200 feet to reach, then flow into the closed CAI/Arnel building. Even a small leak in such a high-pressure natural gas pipeline would have blown the soil away from the pipe and escaped to the atmosphere close to the leak rather than traveling underground hundreds of feet, and the high velocity of the escaping gas would create a telltale crater at the leak site above the pipe.

In addition, had there been a high-pressure pipe leak, a natural gas fire would almost certainly have resulted and burned until the leak was contained; however, no post-incident natural gas fire occurred. Furthermore, Maritimes and Northeast Pipeline reviewed operating records and conducted post-incident leak surveys and found no evidence of a pipeline leak. In conclusion, there was no evidence that a leak from the high-pressure pipe operated by Maritimes and Northeast Pipeline fueled the explosion.

3.1.3.2 KeySpan Gas Distribution System

KeySpan operates and maintains the odorized natural gas utility system that supplies residents and businesses in Danvers. Some of the underground distribution pipes along Water Street and Bates Street, installed in the 1920s and 1930s, are cast iron with bell and spigot joints (Figure 19) and operate at 0.36 psig (10.8 inches water column). Even at this extremely low pressure, old joints are prone to leaking when the ground shifts due to freezing and thawing or other ground disturbances. Because old systems are prone to frequent leaks, federal government regulations require gas companies to routinely survey buried gas pipes to identify leaks and fix them in a timely manner.[23] KeySpan monitors this distribution system as the regulations require.

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[23] KeySpan categorized detected gas leaks as follows: Grade 1 – existing or probable hazard to persons or property, immediate repair is required; Grade 2 or 2A – non-hazardous when detected but repair to prevent future hazard; Grade 3 – not hazardous, not expected to change.

Figure 19. Old 4-inch cast iron buried gas distribution bell and spigot pipe joint partially separated by the explosion (KeySpan photo).

The branch lines from the KeySpan distribution pipe to the two vacant buildings on Water Street, 150 feet west of the CAI/Arnel building (Abby Fence and Danversport Bottle Gas), were disconnected more than 20 years ago. Furthermore, the underground gas distribution pipes are 150 to 200 feet from the CAI/Arnel building. However, to address community concerns, the CSB considered the possibility that natural gas might have leaked from the KeySpan system and entered the CAI/Arnel building through the sewer system or underground along the outside of a buried pipe.

The Bates Street sewer main and sewer pipes from the CAI/Arnel building and the houses abutting the CAI/Arnel property are buried below the natural gas pipes. Being much lighter than air, natural gas tends to rise through the soil if a leak occurs; as such, gas leaking from a distribution pipe is unlikely to enter the sewer system in any appreciable quantity. In the improbable event that natural gas did enter the sewer pipe, it would most likely vent harmlessly into the atmosphere through the sewer vent pipes on the houses and CAI/Arnel building.

KeySpan found some leaks in the underground distribution pipe on Water and Bates Streets after the incident, and told the CSB investigators that the leaking joints most likely resulted from ground movement caused by the explosion. Even if gas had been leaking from the KeySpan system prior to the explosion, the extremely low gas system pressure could not have caused the gas to flow through the soil to the CAI/Arnel building nearly 200 feet away. And, as discussed, no post-explosion natural gas-fueled fire occurred. Therefore, the CSB concluded that natural gas did not leak from the KeySpan system into the CAI/Arnel building to cause or contribute to the explosion.

3.1.4 Most Likely Fuel

Through a detailed scientific investigation of all of the available evidence, rigorous analysis of the available fuel sources, and process of elimination, the CSB investigators concluded that heptane and propyl alcohols were the most likely solvents to have fueled the explosion. Natural gas and propane were ruled out because there was no credible flow path for natural gas or propane to enter the CAI/Arnel building in any significant volume.

The building contained enough air to support a heptane or alcohol vapor cloud explosion sufficient to cause the resultant damage. Although a large solvent spill inside the building could generate enough heptane vapor, there were no credible storage system leak scenarios. But the day before the explosion, CAI employees transferred more than 2000 gallons of heptane/alcohol into mix tank 3 and opened the steam valve to heat the mixture. The CSB concluded that the mix tank 3 heater steam valve was left open, allowing the flammable mixture to boil in the unsealed tank. The boiling mixture released enough heptane/alcohol vapor into the unventilated building to fuel the explosion.

3.2 Explosion Severity and Damage Characterization

3.2.1 Community Damage Survey

The CSB conducted a community damage survey focused on characterizing the damage sustained in the area surrounding the explosion site. The CSB survey teams photographed and catalogued more than 260 damaged buildings and vehicles. Structures damaged by the blast wave overpressure were observed as far as two miles from the CAI/Arnel facility. The survey data were overlaid on a pre-event satellite photograph of the Danversport peninsula to display the extent of documented community damage (Figure 20).

Figure 20. Aerial view showing some damage data points and estimated explosion overpressures out to about 600 feet from the facility (double circle, center). Google Earth Pro

3.2.2 Explosion Overpressure

Analysts estimated the blast wave overpressure at various distances from the CAI/Arnel explosion site by comparing the observed damage in Danversport to US Department of Defense (DoD) explosives safety data. The results indicated the explosion generated a symmetrical blast wave. Overpressure values were estimated to be 2.3 psi at 365 feet away and 1.2 psi at 581 feet away from the CAI/Arnel building, as shown in Figure 20. Appendix A contains a detailed description of the explosion characterization.

3.2.3 Explosion Severity Factors

The pressure generated from a flammable vapor ignition depends, among other things, on the amount of fuel in the air. Figure 21 shows the pressure generated as a function of a generalized fuel-air mixture in a closed test chamber; however, actual pressure and concentration depend on the fuel type. The maximum generated pressure typically occurs slightly above the stoichiometric fuel-air ratio.[24]

Other important variables affecting explosion pressure are the burning velocity rate—which is a property of the particular fuel—and the degree to which the flame accelerates inside the vapor cloud after ignition. The latter is substantially affected by two factors: the degree to which the vapor cloud is confined and the extent of congestion within the cloud. Confinement allows the concentration of flammable vapor in air to increase. Rigid obstacles such as process equipment located within the vapor cloud interfere with the advancing flame front, causing it to become more turbulent. That causes the flame to accelerate.

In this case, the vapor cloud accumulated and was confined inside the closed CAI/Arnel building. Because the facility was unattended, and because electrical equipment in the process area was for the most part explosion-proof, it is likely that the concentration of the flammable vapor in air increased beyond the lower explosive limit and continued to increase above the stoichiometric range. Additionally, obstacles such as process equipment, raw material storage racks and containers, and

[24] The stoichiometric ratio is the fuel-air ratio wherein all of the available oxygen in the air exactly reacts with all of the available fuel. At fuel-air ratios above the stoichiometric ratio, more fuel than oxygen is available.

interior walls within the confined volume imposed considerable congestion. These factors combined to increase the severity of the explosion and the resulting overpressure and impulse.

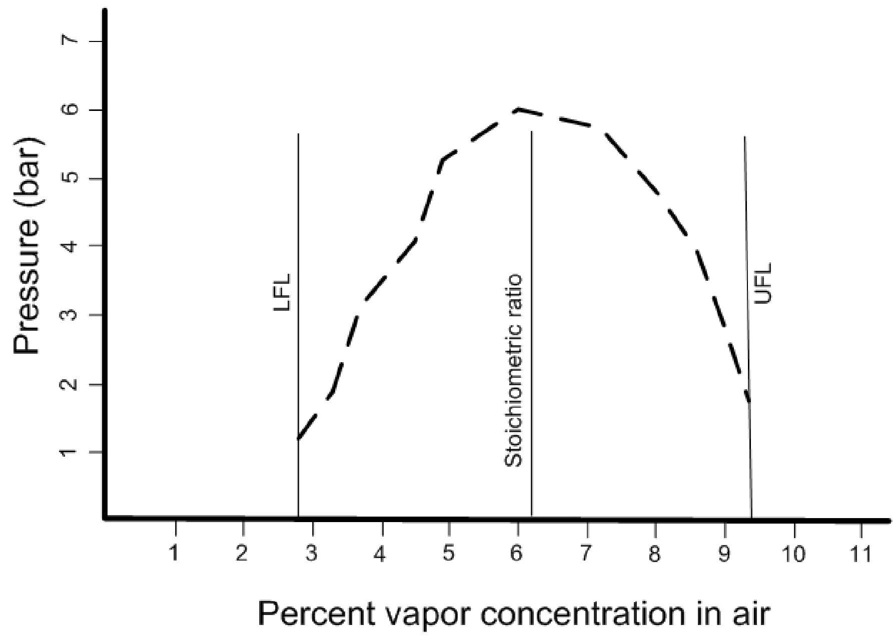

Figure 21. Example of maximum pressure vs. flammable vapor volume concentration in air in a standard test apparatus.

Analytical methods are available to estimate the overpressure as a function of distance from an explosion. Appendix A provides a more detailed discussion of these methods. The CSB's analysis of the CAI/Arnel event concluded that the flammable liquids in the facility could fuel an explosion sufficient to generate overpressures consistent with the surveyed community damage.

3.3 Ignition Sources

The National Fire Protection Association provides criteria for manufacturers to rate electrical devices that might be exposed to flammable atmospheres. The CSB, by interviewing workers and examining electrical devices found in the debris, determined that permanently installed production area electrical equipment was likely rated for use in flammable liquid production and dispensing areas (see Section 1.4.1). Therefore, the CSB concluded that this equipment was most likely not the ignition source.

Even though the explosion and subsequent fires prevented the CSB from identifying the specific ignition source, the team located some equipment in the debris that could have ignited the vapor inside the building. The CSB investigators recovered non-rated electrical equipment in the debris, including a consumer-type box fan (Figure 22) that might have been inside the production area, which was likely equipped with a thermostat control.[25] These simple bi-metallic thermostats typically generate a spark when the contacts open and close, which could ignite a flammable vapor. However, the explosion and intense fires destroyed any evidence establishing the pre-explosion location and operating status of these devices.

Figure 22. Box fan, a possible ignition source recovered from the debris near area E.

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[25] This type of fan frequently is equipped with an adjustable thermostat. The recovered metal frame contained two manufactured holes, most likely for the on/off switch and a thermostat.

Another possible ignition source may have been one of the three heater fan motors on the walls in the production area (see Figure 4). With the building ventilation turned off, the flammable vapor could have accumulated, drifted into an operating fan, and ignited.

The office and laboratory areas also contained various energized electrical devices. Some, like the area heater fans, automatically started and stopped. Flammable vapor might have migrated into the area, contacted one of these devices, and ignited.

The CSB team ruled out static electricity as a possible ignition source, as both CAI and Arnel took precautions to prevent static charge accumulation. Both companies grounded and bonded process equipment and periodically tested electrical conductivity. Operators also controlled the addition of the flammable liquids into the mix tanks to minimize static charge accumulation. Although a static charge will accumulate in heptane, the alcohols and water in the process mixture increased its conductivity, reducing the likelihood that a charge would accumulate. It is also unlikely that slow-speed mixing would promote sufficient charge accumulation in the flammable liquids within the tank. Finally, on the night of the explosion, no liquid was transferred and there were no mixing activities inside the building that could have generated a static charge.

4.0 Regulatory Analysis

4.1 Massachusetts Regulations

4.1.1 Land Use Involving Hazardous Materials

For more than 65 years, the General Laws of Massachusetts[26] have prohibited using a building or structure for keeping, storing, manufacturing, or selling "crude petroleum or any of its products…or inflammable [sic][27] fluids or compounds" unless the local authority has granted a license to use the land for such purpose. The Massachusetts Board of Fire Prevention Regulations is responsible for establishing the threshold quantities of fluids or compounds above which a license is required.

The land use licensing application process requires a public hearing, with all "owners of real estate abutting the land or directly opposite the land on any public or private street" notified of the hearing by registered mail. If issued by the local government, the license is "a grant attached to the land." The law further requires the owner or occupant of the licensed land to annually file a certificate of registration with the clerk of the local government, setting forth the name and address of the licensee. However, it does not require the applicant to list the specific materials or their respective quantities on the registration.

The law also contains provisions for denial or revocation of a license. If a fire or explosion hazard exists or is liable to exist due to the exercise of the license, the fire marshal or head of the local fire department "shall issue an order to the licensee to cease and desist…and shall direct that reasonable measures to ensure safety to the public be undertaken…" The local licensing authority or state fire

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[26] Article 1, Title XX, Chapter148, Section 13.

[27] "Flammable" is the preferred spelling in modern scientific writing. The word "inflammable" is usually used in nontechnical and figurative contexts. [Inflammable. (n.d.). *Dictionary.com Unabridged (v 1.1)*. Retrieved March 25, 2008, from Dictionary.com website: http://dictionary.reference.com/browse/inflammable.]

marshal may revoke the license for cause after notice and a hearing. Additionally, the law provides that "any person aggrieved by the granting of a license…may, within ten days of [the] granting [of] the license, appeal to the marshal…" The law further states that "the local authority shall revoke the license if the fire marshal determines a hazard would exist."

However, the long-standing licensing law has a significant shortcoming: it and the associated regulations mandate review of the potential impact on public safety only when a company first proposes to store or handle large quantities of flammable materials. It contains no provisions requiring the owner or operator to apply for a revised license if the quantity or type of hazardous material changes.

The CSB also identified deficiencies in the standard forms issued by the Department of Fire Services. The license application form[28] only prompts the applicant to list the total quantity of flammable liquids on the property and does not provide for listing flammable solids or the other hazardous materials required to be licensed, such as the nitrocellulose stored at the CAI/Arnel facility. Furthermore, the Department of Fire Services annual registration form[29] does not require listing any of the licensed hazardous materials or quantities. These inconsistencies can result in understating the actual quantity of hazardous materials at a licensed facility, as was the case at CAI/Arnel.[30] Hazardous materials not listed on the license application will most likely be overlooked by town regulators and abutting property owners during any subsequent license approval process.

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[28] Application for License, Massachusetts form FP-2.

[29] Certificate of Registration, Massachusetts form FP-5.

[30] The CAI/Arnel facility license and registration documents did not list the flammable solid nitrocellulose, which exceeded 50,000 pounds stored on site.

The license on file for the CAI and Arnel property was issued in December 1944 and authorized 250 gallons of flammable liquids. The CAI/Arnel facility registration certificate on file in Danvers at the time of the incident listed "11,500 gallons miscellaneous."[31] Although Danvers Board of Selectmen[32] meeting minutes documented two changes to the license, which increased the total licensed quantity to 6000 gallons, there was no record that any adjacent landowners were formally notified of the planned increases as would be required if the land were being licensed for the first time. Furthermore, no Board of Selectmen meeting record(s) existed that addressed an increase of the registered quantity of flammable liquids from 6000 gallons to the registered quantity of 11,500 gallons at the time of the incident. Finally, CAI and Arnel had more than 50,000 pounds of nitrocellulose on site at the time of the incident but had never applied for a license to store more than 100 pounds of the flammable solid.

The CSB also found that Massachusetts property licensing laws and regulations do not address storing or using toxic chemicals, such as those listed in the OSHA Process Safety Management (PSM) standard. The Massachusetts General Laws provide local governments with authority to regulate toxic chemicals,[33] but contain no toxic chemical licensing requirements. Omitting the total quantities of hazardous materials from the application is a significant weakness in the state's laws addressing land use planning.

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[31] The CAI/Arnel property license was originally issued to Essex Finish Co. in 1944. Since then, the licensed quantities have increased from "250 gallons lacquer" to "11,500 gallons miscellaneous" merely by updating the annual registration and paying the appropriate fees to the Town of Danvers.

[32] The Board of Selectmen is a board of officials elected to administer the public business of a Massachusetts town.

[33] Massachusetts General Laws Chapter 148, Section 28.

4.1.2 Massachusetts Department of Fire Services

The Department of Fire Services is an agency within the Executive Office of Public Safety[34] responsible for promoting firefighter safety through written policy and training program development and implementation, and for directing policy and legislation addressing "all fire related matters."

4.1.2.1 Office of the State Fire Marshal

The State Fire Marshal heads the Department of Fire Services. The department is responsible for statewide compliance with the Massachusetts General Laws Chapter 148 and Section 527 of the Code of Massachusetts Regulations. Code Compliance officers provide regulatory compliance support to local fire departments. The office also provides fire protection engineering support and fire code interpretations to local authorities, and prepares and distributes fire safety advisories to the public and fire professionals.

The Fire and Explosion Investigation Section is responsible for investigating the causes and origins of fires and explosions under the direction of the fire marshal. The Public Education Unit provides technical assistance and fire safety awareness training to local fire departments, health educators, and other public service organizations. The Fire Data Unit is responsible for maintaining the Fire Incident Reporting System and the Burn Injury Reporting System.

4.1.2.2 Board of Fire Prevention Regulations

The Department of Fire Services Board of Fire Prevention Regulations is a 14-member board responsible for promulgating the fire safety code: 527 Code of Massachusetts Regulations (527 CMR). Board members include registered professional engineers and fire chiefs from large, medium, and small population areas. The board provides technical assistance to local fire departments.

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[34] www.mass.gov, January 2008.

4.1.2.3 Flammable Liquids and Solids Storage

527 CMR 14.03 provides rules for storing and handling flammable liquids and solids such as those used at the CAI/Arnel facility. It contains the threshold quantity for each material type (Table 2) that triggers the land licensing requirements discussed in Section 4.1.1. The regulation requires a separate license for each material type that exceeds its threshold quantity.[35] Furthermore, each material type is considered separately when determining the total quantities at a facility.

Table 2. Board of Fire Prevention Regulations Material Threshold Quantities (Partial List).

Flammable Material	License required
Class I liquids[36] in containers 60 gallons or less, and portable tanks (e.g., totes)	793 gallons
Class I liquids in non-process, fixed installation storage tanks greater than 60 gallons capacity (e.g., USTs)	10,000 gallons
Flammable solids	100 pounds

CAI and Arnel stored three different material types subject to the land use license. The total quantity of Class I flammable liquids stored at the facility in totes, drums, and five-gallon and smaller containers likely was less than the 11,500 gallon limit as specified on their facility license.[37] The total aggregate quantity in the three USTs and eight fixed tote tanks used to store Class I flammable liquids was 13,000 gallons. A separate license was required for this flammable liquid storage but was not obtained.

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[35] 527 CMR 14.03 Table 1, Note 2

[36] 527 CMR 9.02 defines Class I flammable liquids as any liquid having a flashpoint below 100°F and vapor pressure not exceeding 40 psia at 100°F.

[37] The fire code bases the permitted quantity on the total aggregate capacity of all tanks, containers, and transport vehicles, regardless of the fill level in each [527 CMR 14.01 (3)].

The mix tanks were excluded from license requirements.   Even though the tanks contained in excess of 10,000 gallons of flammable liquid in aggregate, process vessels are excluded from the license requirement.

Additionally, the companies had more than 50,000 pounds of nitrocellulose, a flammable solid, on site at the time of the incident. However, the companies had not obtained the required license for this type of material.

In addition to the license and annual registration requirements, the state fire code requires the owner to obtain a permit from the local fire department to store more than the threshold quantities of flammable liquids and solids [527 CMR 14.03 (1)]. Unlike the license or registration documents, this permit must list the amounts stored at the facility.

Contrary to the permit requirements, the Danvers fire department had no record of having issued a permit to CAI/Arnel for the storage of the nitrocellulose or the Class I flammable liquids in the portable containers. The only permit on file at the fire department applied to the USTs as required by 527 CMR 9.07; that permit was more than two years overdue for renewal.

The state fire code requires "the head of the fire department to periodically inspect tanks and equipment" at facilities that store and use flammable materials [527 CMR 14.03 (9)(c)], but does not define or specify an inspection frequency. Inspection records on file in the Danvers fire department showed that the most recent inspection of CAI/Arnel was in 2002, during which fire department personnel reviewed the foam fire suppression system installation and recommended minor changes to the nitrocellulose storage. The fire department did not inform the companies that they lacked the permits required to store the flammable materials at the facility.

Although fire department records did not identify any fire code compliance deficiencies involving the flammable liquid storage inside the building, the CSB investigators noted that flammable vapor control and spill containment in the CAI flammable liquid storage area did not conform to the fire code. For example, the totes were not vented outside the building [§9.07 (B)(1)] nor enclosed by a fire resistant rated assembly [§14.03(16)], and Class I flammable liquids in the totes were dispensed by gravity [§14.04(2)].

Representatives from the Department of Fire Services told the CSB investigators that few local fire departments have personnel on staff with specialized process knowledge sufficient to inspect chemical manufacturing facilities, even those that only mix chemicals, as did CAI and Arnel. They also said that the Department of Fire Services is limited in its ability to provide technical support to the more than 200 local fire departments located throughout Massachusetts. However, the CSB believes the fire code violations related to flammable liquid storage inside the building did not require specialized knowledge of process equipment or expertise in flammable liquids storage. Fire department personnel qualified to perform life safety inspections should also be capable of reviewing flammable liquids storage areas for compliance with the state fire code.

4.2 Local Government Ordinances

The CSB contacted local governments in Massachusetts to inquire how each applies the flammable materials licensing and registration regulations. The number of licensed manufacturing facilities in the sample towns ranged from zero to more than 200.

In each of the six towns contacted, either the town clerk or the fire department administers the license application for new licensees and annual registrations. Three towns reported that they require facilities to obtain a new license if the registered quantity is increased; however, this requirement was not documented in any town ordinance or bylaw. The registered flammable material quantity was listed in most licenses and in a few annual registrations. Table 3 summarizes the survey results.

Table 3. Local government flammable materials license survey results.

	Boston	**Worcester**	**Springfield**	**Leominster**	**Danvers**	**Georgetown**
Population	590,000	175,000	154,000	41,000	29,000	7,500
Number of licensed manufacturing facilities (Note 1)	25	~100	~200	80	3	0
History of denying facility license	Yes	No	Yes	No	No	No
History of existing license appealed by an aggrieved person	No	Yes	No	No	No	No
Fire permits at each licensed facility	Yes	Yes	Yes	Yes	No (Note 2)	Yes
Certificate of registration lists quantity and type of material	Yes	Yes	No	No	Yes	No
Licensing and registration process in town by-laws	No	No	No	Yes	No	No
Controls in place to address an increase in registered quantity (Note 3)	Inspection and new license	Inspection and new license	Inspection and new license	Engineering study and inspection	New license application	Inspection

Notes:

1. Excludes gas stations, retail sales businesses, and propane distributors.
2. No record of fire department permits issued to CAI/Arnel for the flammable liquids inside the building and the nitrocellulose stored outside existed.
3. Listed controls based on discussions with town officials. Town ordinances do not regulate increases in the licensed quantity.

The survey results indicate significant variability in how the towns apply the licensing and registration laws. For example, registration documents in only three of six towns list the registered chemicals and quantities, and only one town has bylaws addressing the licensing process. The six towns combined issued more than 400 licenses; however, only two towns reported having denied a license application. Most importantly, although all six towns stated that controls up to and including new license applications are in place to review increases in the quantity of a licensed material, none of these requirements are contained in town bylaws. Many town governments may not be effectively using the Massachusetts flammable materials licensing law to control hazardous materials use within their jurisdictions.

However, in 2007, one local jurisdiction amended the town ordinance addressing the flammable materials license application process to require companies to submit to the town "process safety management analysis information" that they prepared as required by the OSHA PSM standard (see Section 4.3.2). This town also requires the licensee to submit updated process information coincident with the PSM five-year process hazard analysis review and update requirement.[38] The ordinance further requires each licensee to obtain the services of "a Massachusetts registered Professional Engineer in the field as determined and selected by the City Council…" to review the plan.[39] License applications for non-PSM covered processes must also contain a registered Professional Engineer-reviewed safety plan based on the PSM standard.[40]

These regulatory changes improve the local government's ability to manage flammable materials licensing and registration. Requiring specific management safety program elements already

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[38] 29 CFR 1910.119 (e)(6).

[39] City of Leominster, Revised Ordinances, Chapter 12.

[40] The CSB noted that although the language in the Leominster ordinance suggests it applies to all PSM-regulated facilities, the specific language links the requirement only to flammable and explosive materials. Toxic chemicals covered by PSM and reactive chemicals are not addressed in the town ordinance.

established in federal regulations is an effective method for improving facility safety performance. Furthermore, the safety program documents that are submitted by the licensee provide a basis for the decision to approve or deny the application.

4.3 Occupational Safety and Health Administration

Federal OSHA administers and enforces worker safety and health standards in Massachusetts; however, OSHA had never inspected the CAI/Arnel facility before the November 2006 incident. Two important OSHA standards applicable to the use of flammable liquids at CAI/Arnel included the Flammable and Combustible Liquids standard and the Process Safety Management (PSM) standard.

4.3.1 Flammable and Combustible Liquids Standard

The OSHA Flammable and Combustible Liquids standard[41] establishes requirements for storing and using flammable and combustible liquids. This standard requires general area ventilation to maintain a flammable vapor concentration below 25 percent of the lower flammable limit when flammable liquids are stored and used inside buildings [§1910.106 e (3)]. In addition to general area ventilation, this standard requires local ventilation to remove any flammable vapors that might escape open process equipment.

In 1998, CAI and Arnel upgraded the building ventilation system to increase airflow in the production areas; however, CAI employees turned off the ventilation fans before leaving at the end of each day. On the night of the explosion, vapor flowed out of the top of heated mix tank 3 and accumulated to an explosive concentration inside the building. Had the ventilation system continued operating, the vapor would likely have been exhausted out of the building, thereby either preventing the buildup of

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[41] 29 CFR 1910.106.

an explosive atmosphere or limiting the buildup so that a subsequent ignition might have been less catastrophic.

The CSB investigation also found that CAI's storage of flammable liquids in the totes in area E did not comply with other OSHA requirements (Table 4). These deficiencies show that the two companies did not adequately review the OSHA Flammable and Combustible Liquids standard when the indoor solvent storage tanks were installed.

Table 4. CAI flammable liquids storage deficiencies.

29 CFR 1910.106	Requirement	Finding
b(4)	Unsealed storage containers must be vented to building exterior Overflow prevention is required	Installed totes vented directly inside production area E Unsealed totes could overflow onto floor during filling
c(2)	Piping material shall be steel, nodular iron, or malleable iron	Flexible elastomeric hoses connected tote drain outlet to manifold pipe (see Figure 7)
d(4)	Spill containment is required around unsealed containers Gravity or mechanical exhaust (ventilation) is required	No spill containment around unsealed totes in area E Building ventilation system turned off at night
h(4)	Storage tanks shall be separated from processing areas with two-hour rated construction	CAI and Arnel mixing equipment and CAI storage totes co-located in area E

4.3.2 Process Safety Management Standard

The OSHA PSM standard[42] requires employers to implement a management program to prevent or minimize the consequences of catastrophic releases of certain highly hazardous chemicals. PSM

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[42] 29 CFR 1910.119.

applies to facility processes that include 10,000 pounds or more of flammable liquids or gases in one location, and to listed toxic chemicals at or above certain threshold quantities. For regulated flammable liquid and toxic chemical processes, the standard requires employers to implement a management system to minimize the hazards. Key elements of the system include requirements for conducting process hazard analyses, implementing and maintaining written operating procedures, conducting periodic operator training, and implementing a management of change program. Even if the OSHA PSM regulations do not apply to a given process, the 14 elements codified in the standard offer a comprehensive safety management program framework for hazardous chemical facility operations.

The CSB concluded that the Arnel processes did not contain any listed hazardous chemical and did not contain more than 10,000 pounds of flammable liquids. Arnel was therefore not required to implement a PSM program.

The CSB concluded, however, that CAI was required to implement a PSM program because the mixture in mix tank 3 exceeded the flammable liquids threshold quantity (10,000 pounds). Additionally, the four side-by-side CAI production mix tanks could, on occasion, contain more than 10,000 pounds of flammable liquid in aggregate. CAI management told CSB investigators that they were unaware of this important OSHA standard.

Had CAI implemented a PSM program, a process hazards review likely would have identified the need for the installation of automated temperature controls and safety devices on their mix tanks. The review might also have identified the importance of maintaining building ventilation whenever flammable liquids were stored in the open mix tanks, or the need to use sealed mix tanks vented to the building exterior. Furthermore, all of the fire code requirements applicable to indoor flammable liquid storage might have been identified and applied.

4.4 The Emergency Planning and Community Right to Know Act[43]

In 1986, Congress passed the Superfund Amendments and Reauthorization Act (SARA). SARA established a national baseline for planning, response, management, and training for chemical emergencies. Title III of SARA, the Emergency Planning and Community Right-to-Know Act (EPCRA), is intended to promote state and local government hazardous chemical emergency preparedness and response capabilities through better coordination, planning, and access to chemical information.

EPCRA Section 302 requires the governor of each state to establish a State Emergency Response Commission (SERC), which is responsible for implementing EPCRA provisions. The SERC designates emergency planning districts and appoints local emergency planning committees (LEPC) for each district.

The SERC supervises and coordinates the LEPC activities, establishes procedures for receiving and processing public requests for information collected under EPCRA, and reviews local emergency response plans. Although the EPA has no mandatory oversight authority, their regional response teams may review and comment on an emergency response plan or other issues related to preparation, implementation, or exercise of the plan when requested to do so by an LEPC.

4.4.1 Local Emergency Planning Committee

Each LEPC is responsible for developing an Emergency Response Plan as set forth in EPCRA Section 303. LEPCs use chemical inventory information, known as Tier I or Tier II reports, from

[43] Reprinted from the CSB investigation report on the 2004 toxic chemical release at MFG Chemical, Inc. in Dalton, GA (CSB, 2006). Comments on applicability to CAI/Arnel have been added.

facilities handling hazardous chemicals to participate in the development of comprehensive local emergency response plans. The EPA requires participants in the LEPC to include emergency response authorities and representatives of facilities that use covered chemicals, and community representatives such as local hospital personnel, the media, environmental groups, and residents. Broad participation in the LEPC ensures that emergency response planning takes into account all of the community issues in the event of an actual chemical emergency. The LEPC may also participate in natural disaster emergency response planning.

Section 303 of EPCRA requires each LEPC to prepare an emergency response plan (ERP) and submit a copy to the SERC for review and comment. The ERP must:

- Document the name and location of each business in the community that has more than specified quantities of "extremely hazardous substances,"
- Develop procedures for the business and local emergency and medical personnel to use when responding to a hazardous chemical release,
- Assign emergency coordinators for both the business establishment and the community,
- Develop procedures for notifying the community that there has been a hazardous chemical release,
- Develop evacuation plans that include effective notification methods and evacuation routes, and
- Be reviewed, tested, and updated each year.

Facilities covered under EPCRA, such as the CAI/Arnel facility, are required to submit emergency and hazardous chemical information to the LEPC, the SERC, and the local fire department.[44] LEPCs

[44] CAI and Arnel did submit their EPCRA Tier II lists of hazardous chemicals to the Danvers fire department. However, the Arnel list was incomplete.

are to have access to the facility Risk Management Plans[45] and to work with industry and local officials to improve local emergency response plans and to inform the public about chemical accident hazards and risks.

The town of Danvers did not have an active LEPC at the time of the incident. At the urging of the Danversport residents, the Danvers Board of Selectmen reestablished the LEPC in early 2008.

[45] Neither CAI nor Arnel were required to prepare a Risk Management Plan (40 CFR 68).

5.0 Model Fire Codes

5.1 National Fire Protection Association

5.1.1 The Flammable and Combustible Liquids Code

The National Fire Protection Association's *Flammable and Combustible Liquids Code* (NFPA 30) is a consensus standard applied to the safe handling, storage, and processing of flammable and combustible liquids. It establishes criteria for the design and protection of indoor flammable liquid storage tanks, ventilation, and flammable liquids processing. This code allows flammable liquids in unsealed containers to be heated indoors as long as adequate exhaust ventilation is provided to prevent flammable vapor accumulation within the building. However, it does not specify automatic shutdown, isolation, or emergency cooling measures if the process overheats or the ventilation system does not control flammable vapor accumulation.

The Massachusetts Building Code (780 CMR) requires permit applicants for new or modified buildings and structures that use flammable liquids to apply NFPA 30; however, pre-existing facilities, such as the CAI/Arnel facility, are not required to retroactively apply NFPA 30. The Massachusetts Fire Code, 527 CMR 14, *Flammable and Combustible Liquids, Flammable Solids or Flammable Gases,* incorporates only a few specific NFPA 30 requirements, such as Section 3.2 for portable tank and container design.

5.1.2 The Standard for the Manufacture of Organic Coatings

The Standard for the Manufacture of Organic Coatings (NFPA 35) applies to facilities that use flammable and combustible liquids to manufacture organic coatings for automotive, industrial, institutional, household, marine, printing, transportation, and other applications. Representatives from the National Association of Printing Ink Manufacturers (Section 6.1) told CSB investigators that organic coatings manufacturing industry risk insurers and engineering professionals use NFPA 35 as the primary standard for fire prevention at member company facilities that use flammable and combustible liquids. However, the Massachusetts Fire Code does not require organic coatings manufacturers like CAI and Arnel to use NFPA 35.

Although NFPA 35 covers fire safety management practices in most areas, the CSB identified some deficiencies. Certain devices or components are specifically discussed, for example, "kettles and thin-down tanks," but are not defined. An appendix establishes flammable vapor hazard zones inside buildings based on whether tanks are "open," "closed," or "sealed and vented," yet these terms are not defined or used elsewhere in the standard. It also contains vague language such as "mixing tanks shall be designed to safely manufacture the products assigned to them."

Most importantly, the standard does not prohibit heating flammable liquids inside buildings in unsealed tanks—one root cause of the CAI/Arnel incident. The NFPA should revise the standard to prohibit indoor process heating of flammable and combustible liquids above their flashpoints, unless heating occurs in sealed tanks that are vented outside the building. Furthermore, the standard should require process safety controls to prevent overheating and stop the heating process if the flammable vapor control equipment (e.g., building ventilation system or heater tank vent) malfunctions.

5.2 International Code Council – International Fire Code

The International Fire Code (IFC) is a model fire code adopted by many state and local jurisdictions that provides criteria for the safe storage, use, and handling of hazardous materials. The standard includes chapters on a variety of fire safety subjects and hazard categories. Chapters covering operations similar to those in place at CAI/Arnel include:

- Chapter 20 – Manufacture of Organic Coatings,
- Chapter 27 – Hazardous Materials-General Provisions, and
- Chapter 34 – Flammable and Combustible Liquids.

Chapter 27 includes a Hazardous Materials Management Plan (HMMP) and a Hazardous Materials Inventory Statement (HMIS). The HMMP must clearly define the storage areas, maximum inventory in each area, and location and type of emergency equipment. The HMIS must include detailed information on hazard classification, maximum quantities stored, and storage conditions. Local permitting authorities can require companies to submit and maintain these documents as part of the hazardous materials permitting process.

Chapter 27 also specifies continuous exhaust ventilation of indoor storage areas and emergency power backup for mechanical ventilation systems; it also specifies explosion (deflagration) prevention systems designed to "prevent unacceptable structural damage."

Like NFPA 35, the IFC Chapter 20 scope statement does not specifically include ink manufacturing. Also, important terms used in Chapters 20, 27, and 35, such as "open, closed, and sealed process tanks," are not defined. Adding these and other definitions, such as the definition of "storage tank," will reduce the possibility of misinterpretation. Finally, the International Code Council should revise applicable chapters to prohibit indoor heating of flammable and combustible liquids above their flashpoints, unless heating occurs in sealed tanks that are vented outside the building.

6.0 Trade Associations

6.1 National Association of Printing Ink Manufacturers

Established in 1917, the National Association of Printing Ink Manufacturers (NAPIM) is the only trade association representing printing ink manufacturers in the United States. Operating within the International Paint and Printing Ink Council (IPPIC), NAPIM is comprised of 55 ink manufacturing companies representing more than 70 percent of the total U.S. production of printing inks. NAPIM membership also includes 78 supplier companies. NAPIM representatives noted that companies similar in size to CAI constitute the majority of the NAPIM membership; CAI was not a member.

While its principal mission is to advance the business interests of its membership, NAPIM provides industry-specific environmental, health, and safety information to member companies through electronic communications and yearly conferences. The NAPIM website provides regulatory and safety information such as EPA reporting requirements, hazardous chemical exposure information, and ink-manufacturing equipment safety information. Annual NAPIM conferences include presentations on workplace safety.

Representatives from the NAPIM attended the CSB public meeting in Danvers, MA, on May 9, 2007. They distributed the CSB's preliminary findings of the CAI/Arnel incident investigation and offered to help their member companies review operations for similar hazards.

6.2 The National Paint and Coatings Association

Established in 1887, the National Paint and Coatings Association (NPCA) serves a membership of more than 400 paint and coatings manufacturers, suppliers, and distributors, and is part of the IPPIC. Paint and coatings manufacturers, suppliers, and distributors operating in the United States are eligible for NPCA membership. To encourage participation from small companies, NPCA membership fees are based on annual sales and company membership classification.[46]

The NPCA Occupational Health and Safety Committee develops and distributes safety information to member companies through newsletters and electronic publications. These communications address safety topics such as exposure assessments, fire risk reduction, and static electricity control guidance. Companies also have access to the NPCA Coatings Care program.

The NPCA initiated the development of the Coatings Care program in 1996 to serve as the environmental health and safety management program for coatings manufacturers.[47] Representatives from large paint and coatings manufacturers developed the program for use by smaller member companies. The Coatings Care program includes five modules to assist member companies in implementing safe and environmentally sound operations: Transportation, Product Stewardship, Manufacturing Management, Community Responsibility, and Security.

Arnel did not participate in NPCA. Although Arnel processes did not directly contribute to the explosion, participation in the NPCA might have helped Arnel to identify and control hazards at the facility, especially those involving indoor storage and building ventilation.

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[46] The NPCA offers several membership classifications to companies based on the desired level of participation and interest area.

[47] The Coatings Care program is modeled on American Chemistry Council Responsible Care (ACC) program. ACC recognizes Coatings Care as an alternative to Responsible Care membership requirements for painting and coating manufacturers.

7.0 Similar Incident

7.1 Universal Form Clamp

The CSB investigated a similar incident that occurred on June 14, 2006, at the Universal Form Clamp Company (UFC) facility in Bellwood, Illinois, 14 miles west of Chicago. The CSB investigation (CSB, 2007) determined that an open-top tank containing a mixture of heptane and mineral spirits was inadvertently heated to its boiling point. Vapors generated from the boiling liquid escaped through the open top of the tank and spread along the floor. The flammable vapor cloud accumulated in the building for approximately 10 to 15 minutes before reaching an ignition source and igniting.

Like the CAI process, the UFC process involved adding a solid resin to a solvent mixture in a 2200-gallon tank that was heated with steam. Unlike the CAI process, a thermostat controlled the steam valve position on the UFC process. However, the thermostat was found to be incorrectly installed and poorly maintained. Like the CAI tank, the UFC tank was not equipped with an automatic shutdown system or over-temperature alarm, and the ventilation system that removed flammable vapor accumulation around the tank was not working the day of the incident.

The CSB estimated that the vapor ignited about 15 minutes after it began spreading in the UFC building. Unlike the CAI/Arnel incident, however, the flash fire at UFC caused significantly less facility—and no offsite—damage. Tragically, one person was killed.

8.0 Key Findings:

1. The steam valve on the mix tank 3 heater was inadvertently left open overnight. High-temperature steam continued flowing through the heating jacket and heated the mixture to its boiling temperature.

2. The mix tanks were not equipped with automatic controls to prevent overheating the mixture when the process was unattended.

3. The mix tanks were not designed to be sealed and were not equipped with piping to direct flammable vapor safely out of the building. Flammable vapor flowed unabated out of the top hatch into the production area.

4. CAI personnel turned off the building ventilation system at night when the building was unoccupied, allowing flammable heptane vapor, alcohol vapor, or a combination of the two to accumulate to a near-ideal explosive concentration that was ignited by an unknown ignition source.

5. CAI and Arnel did not have fire department-issued permits for storing the flammable liquids inside the building or the flammable solids outside, as required by the Massachusetts Board of Fire Prevention Regulations.

6. CAI flammable liquids storage inside the building did not conform to OSHA and Massachusetts fire code requirements.

7. The Massachusetts fire code does not specify a frequency for local fire department inspection of indoor flammable liquids storage areas. More than four years had elapsed since the CAI/Arnel facility storage was inspected by the Danvers fire department.

8. The Massachusetts fire code does not require companies that handle flammable and combustible liquids to apply the *Flammable and Combustible Liquids Code* (NFPA 30), or require organic coatings manufacturers that use flammable and combustible liquids to apply *The Standard for the Manufacture of Organic Coatings* (NFPA 35).

9. Massachusetts law does not require re-licensing the land, convening a public hearing to consider the risks to the public, or notifying affected landowners when a licensee increases the quantity of flammable materials above the licensed amount.

10. The CAI ink manufacturing process was covered by the OSHA Process Safety Management Program; however, because CAI was unaware of the OSHA standard, CAI management did not apply any of the generally recognized best practice management elements, such as process hazards analysis, to their hazardous chemical processes.

11. The CAI/Arnel facility was not inspected by the local fire department to evaluate the status of compliance with state fire code requirements, including fire department permit applications and safe storage of flammable liquids inside the building.

12. At the time of the incident, the Town of Danvers did not have a functioning LEPC.

9.0 Incident Causes

1. CAI management did not conduct a process hazards analysis or similar systematic review of processes involving hazardous materials:

    - CAI heated Class I flammable liquids in unsealed tanks inside a closed building,
    - CAI did not install or use automated process controls, alarms, or safeguards when heating flammable liquids in process equipment inside a closed building,
    - CAI did not maintain adequate building ventilation during all flammable liquids process operations.

2. CAI management did not use written procedures or checklists to facilitate safe process operations.

10.0 Recommendations

The CSB makes recommendations based on the findings and conclusions of its investigations. Recommendations are made to parties that can affect change to prevent future incidents, which may include the companies involved, industry organizations responsible for developing good practice guidelines, regulatory bodies, and organizations that have the ability to broadly communicate lessons learned from the incident, such as trade associations and labor unions.

10.1 General Court of the Commonwealth of Massachusetts

2007-03-I-MA-R1 Revise the General Laws of Massachusetts addressing flammable materials licensing and registration:

- As part of the annual registration renewal, require new and existing product manufacturing registrants to submit written certification to local governments stating that the facility complies with, at a minimum, all state and local fire codes and hazardous chemical regulations.
- Require all companies holding a license and current registration to apply for an amended license and re-register the facility before increasing any flammable material quantity above the licensed amount or adding a different regulated chemical. Include a requirement in the approval process to solicit input from affected landowners, similar to the requirement for obtaining the original license and registration.

2007-03-I-MA-R2 Amend the General Laws of Massachusetts to require the Office of the State Fire Marshal to audit local governments for compliance with the flammable materials licensing regulation and audit fire departments for compliance with permit issuance and inspection of manufacturing facilities licensed to store and handle flammable liquids and solids. The audits should be conducted at least once every five years.

10.2 Commonwealth of Massachusetts Office of Public Safety, Department of Fire Services

2007-03-I-MA-R3 Incorporate the *Flammable and Combustible Liquids Code* (NFPA 30) and *Standard for the Manufacture of Organic Coatings* (NFPA 35) into the Massachusetts Board of Fire Prevention Regulations.

2007-03-I-MA-R4 Revise 527 CMR 14 to specify the maximum interval (such as annually) for local fire departments to conduct inspections of manufacturing facilities holding one or more licenses and permits to store and handle flammable materials.

2007-03-I-MA-R5 Develop mandatory written inspection criteria to be used by the local fire departments when performing manufacturing facility inspections. Develop inspection training material and provide training to the local fire departments.

2007-03-I-MA-R6 Revise the license and registration forms (FP-2 and FP-5) to require listing each hazardous material type and quantity. Identify the requirement that a separate license and permit are required for each of the eight classes of flammable material when the facility possesses more than the listed threshold quantity specified in 527 CMR 14.03 (2).

10.3 Town of Danvers

2007-03-I-MA-R7 Pending revision of the Massachusetts Fire Safety Code (527 CMR), revise the town bylaws addressing 527 CMR 14 requirements applicable to facility licensing and annual registration to:

- Require new and current product manufacturing registrants to certify in writing that the facility complies with, at a minimum, all state and local fire codes and hazardous chemical regulations as part of the annual registration renewal.
- Require companies holding a license and current registration for any of the eight classes of flammable materials specified in 527 CMR 14.03 (2) to re-register the facility before increasing any chemical quantity above the registered amount or adding a different regulated chemical at the facility. Include a requirement in the approval process to solicit input from affected landowners, similar to the requirement for obtaining the original license and registration.
- Revise the license and registration forms to require listing each hazardous material type and quantity, and require a separate license and permit for each of the eight classes of flammable materials specified in 527 CMR 14.03 (2) .
- Require the fire department to annually inspect licensed manufacturing facilities for compliance with the fire code.

10.4 CAI, Inc.

2007-03-I-MA-R8 Develop a written safety program to manage hazardous process operations. The program should:

- Prohibit heating flammable or combustible liquids above their flashpoints in tanks inside buildings unless the tanks are sealed and vented to the building exterior.
- Require safety controls to prevent overheating of flammable or combustible liquids.
- Apply the process safety management program elements as contained in the American Institute of Chemical Engineers (AIChE) Center for Chemical Process Safety (CCPS) *Guidelines for Implementing Process Safety Management Systems* to all processes that use flammable, toxic, or reactive chemicals.
- Comply with the following, as applicable:
    - OSHA Flammable and Combustible Liquids standard (29 CFR 1910.106),
    - OSHA Process Safety Management standard (29 CFR 1910.119),
    - National Fire Protection Association *Flammable and Combustible Liquids Code* (NFPA 30), and
    - National Fire Protection Association *Standard for the Manufacture of Organic Coatings* (NFPA 35).

10.5 National Fire Protection Association

2007-03-I-MA-R9 Revise *Flammable and Combustible Liquids Code* (NFPA 30):

- Prohibit heating flammable and combustible liquids above their flashpoints in tanks inside buildings, unless the tanks are sealed and vented to the building exterior.
- Require heated tanks and vessels containing flammable and combustible liquids to have equipment to prevent overheating, such as:
  - Devices to stop the heating process if the temperature exceeds the safe operating limits,
  - Devices to stop the heating process if the flammable vapor control equipment malfunctions (e.g., building ventilation system or heated tank vent), and
  - A heating medium that is unable to heat the tank above safe operating temperatures.

2007-03-I-MA-R10 Revise *The Standard for the Manufacture of Organic Coatings* (NFPA 35):

- Define equipment specifically discussed in the standard, such as kettles and thin-down tanks.
- Define the terms "open," "closed," and "sealed and vented."
- Prohibit heating flammable and combustible liquids above their flashpoints in tanks inside buildings unless the tanks are sealed and vented to the building exterior.
- Require heated tanks and vessels containing flammable and combustible liquids to have equipment to prevent overheating, such as:
    - Devices to stop the heating process if the temperature exceeds the safe operating limits,
    - Devices to stop the heating process if the flammable vapor control equipment malfunctions (e.g., building ventilation system or heated tank vent), and
    - A heating medium that is unable to heat the tank above safe operating temperatures.

10.6 International Code Council

2007-03-I-MA-R11 Revise the International Fire Code:

- Chapter 20 –
  - Specifically include "printing inks" in the definition of "organic coating."
  - Define equipment specifically discussed in the standard, such as open and closed kettles.
  - Require heated tanks and vessels containing flammable and combustible liquids to have equipment to prevent overheating, such as:
    - Devices to stop the heating process if the temperature exceeds the safe operating limits,
    - Devices to stop the heating process if the flammable vapor control equipment malfunctions (e.g., building ventilation system or heated tank vent), and
    - A heating medium that is unable to heat the tank above safe operating temperatures.

- Chapters 20, 27, and 34 –
  - Define "open," "closed," and "sealed and vented" process tanks.
  - Define "non-listed" process tanks.
  - Prohibit heating flammable and combustible liquids above their flashpoints in tanks inside buildings unless the tanks are sealed and vented to the building exterior.

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Appendix A

Explosion Reconstruction Analysis

1.0 Community Damage Survey

The CSB investigation team surveyed the community to characterize the damage sustained in the area surrounding the explosion site. The CSB survey teams photographed and catalogued more than 260 buildings and vehicles using global positioning satellite (GPS) coordinates to ensure accurate positioning. The damage data were displayed in a format that overlaid the consequence information on a pre-event satellite photographic image of the area (Figure A-1). Damage was observed as far as 9000 feet from the explosion site.

Figure A-1. Aerial view showing damage data points and estimated explosion overpressures. CAI/Arnel facility is in the double circle, center. (graphic: Google Earth Pro)

2.0 Explosion Pressure and Impulse Estimates

An explosion produces effects (such as pressure and impulse), which result in consequences (damage) to encountered "targets" or obstacles. Consequences may be defined based on the type of obstacle involved as shown in Table A-1. Approximations of the pressure necessary to cause various levels of damage have been published. Table A-2 shows estimated building overpressure damage thresholds.

Table A-1. Typical explosion consequence descriptions

Obstacle Type	Minor	Moderate	Severe
Building	Glass breakage, shingles blown off, etc.	Deformation of panels (such as garage doors) or siding, cracking of wood framing elements	Displacement of heavy components (such as brick or concrete sections)
Tree	Leaves blown off, small branches broken	Large branches broken, permanent bending	Entire tree uprooted or snapped at base
Human	Eardrum rupture, minor lacerations	Broken bones, concussion, severe lacerations	Lung rupture, organ failure, death

On a more advanced level, the U.S. Department of Defense tests explosive events and characterizes the response of a given structure by placing well-defined target structures at predetermined distances from the explosive device. The results of such tests provide data for developing pressure-impulse (P-I) diagrams for various structures (Figure A-2).

Table A-2. Typical structure explosion damage thresholds (Crowl, 2003)

Overpressure (psi)	Observed Damage
0.15	Glass window breakage
0.4	Minor structural damage
1.0	Partial building demolition, uninhabitable
2.0	Partial wall/roof collapse
5.0 – 7.0	Nearly complete destruction of wood frame structures

As shown in the P-I diagram, different combinations of pressure and impulse may cause the same degree of damage to a structure. Therefore, reconstructing pressure and impulse from observed damage is difficult, and may be infeasible given multiple combinations of pressure and impulse can cause similar damage.

Nonetheless, it is possible to develop some reconstructive estimates especially when multiple blast markers are available. For example, breakage of types of glass windows may be related to some bracketed threshold pressure while the extent to which glass shards are thrown might then be related to impulse. Additionally, the P-I curves are asymptotic and therefore have a pressure sensitive range and an impulse sensitive range.

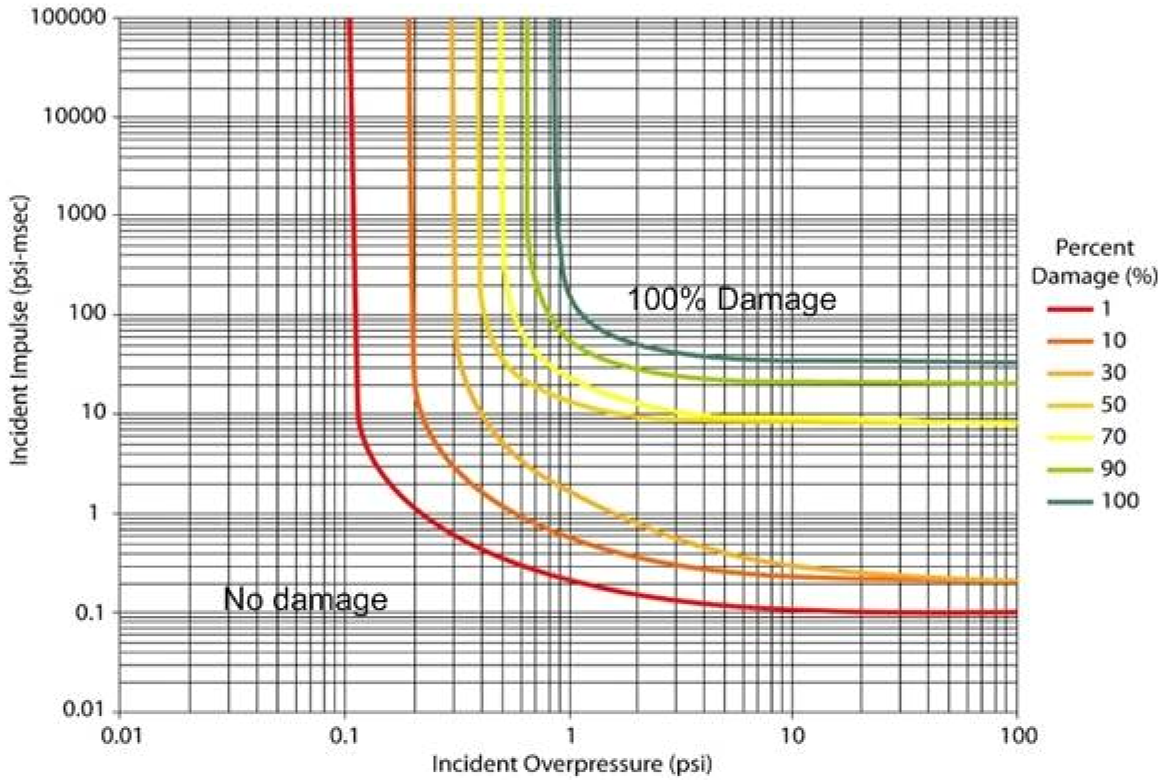

Figure A-2. Pressure – impulse (P-I) diagram of a sample structural object

CSB retained blast experts from APT Research, Inc. (APT)[1] to assist with the Danvers community damage survey and reconstruction. APT analysts selected a set of blast markers from among the many available. There were numerous premises where annealed single-pane windows were broken, while stronger tempered double-pane windows were not. Some other blast markers considered included the following:

- The bakery/pizzeria located 158 feet northwest of the explosion - Damage to this building was severe.

[1] APT developed and maintains the Safety Assessment for Explosive Risks model for Department of Defense Explosives Safety Board. The model computes explosive effects and risks.

- Eastern Propane Gas, Inc., located 410 feet southwest of the explosion - Single-paned annealed windows broke but double-paned tempered windows did not. Glass projectile data were also obtained from this facility.

- A residence on Riverside St., 878 feet north of the explosion - The garage door facing the blast was deformed.

- Bishop Fenwick High School, 2265 feet south of the explosion - Approximately one third of the windows on the side of the building facing the blast were broken while only five to 10 percent of windows on the east and west sides were broken. This provided some discrimination between the reflected (dynamic) overpressure and the side-on overpressure.[2]

Analysts estimated the pressure and impulse that acted on these buildings. Because such estimates involve some subjective judgments, multiple analysts prepared estimates independently, and then compared their work to form a consensus estimate. The set of estimates were integrated to create a composite assessment of the effects that caused the observed consequences as a function of distance from the facility. These results were then checked for consistency with damage guidelines for scaled charges reported for TNT blasts in Department of Defense Explosive Safety Standard 6055.9. This check was qualitative; the damage guidelines in the standard are only generally defined and solely related to overpressure. Impulse is not considered in the standard.

The analysts concluded that the explosion resulted in a symmetrical blast wave producing overpressures of approximately 1.2 psi at 580 feet and 2.3 psi at 365 feet from the CAI/Arnel building

[2] The side-on overpressure is that which is observed normal to the blast wave. The reflected overpressure is that which is observed in the face of the approaching pressure front. The reflected overpressure is higher due to kinetic effects.

as shown in Figure A-1.[3] In light of the previously described limitations of the methodology these figures can only be considered estimates. Higher overpressures occurred closer to the blast but their magnitude is less certain.

[3] These overpressures correspond to the expected effects for risk factors K=40 and K=24 from Department of Defense Explosive Safety Standard 6055.9.

3.0 Hypothetical Explosion Estimates

The damage to the CAI/Arnel building and the open or closed status of the fire doors as reported by employees, suggest that flammable vapor most likely accumulated only in areas C, E, and F, the production areas (Report, Figure 3). From layout drawings provided by CAI, the CSB estimated that the available air volume in these zones of the building was 110,000 cubic feet.

The CSB selected three fuels for hypothetical explosion modeling: propyl alcohol, normal heptane, and methane.[4] The heptane and alcohol were constituents of the mixture in the process tank. Methane was evaluated due to the possibility that if natural gas leaked from a buried natural gas distribution pipe, gas might have migrated into the building.

The TNO Multi-Energy Method[5] was then applied to predict overpressures at the aforementioned ranges of interest (365 and 580 feet) for various fuel-air mixtures, each having an aggregate volume of 110,000 cubic feet. The amount of fuel was varied until the predicted overpressures corresponded to 2.3 and 1.2 psig at the respective ranges of interest. The results are presented in Table A-3.

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[4] The flammability characteristics of methane are representative of natural gas.

[5] The blast strength parameter in the model was set at 7. At pressure range of interest the model is insensitive to parameters greater than 7.

Table A-3. Hypothetical Fuel Scenarios for 110,000 Cubic Foot Production Building

Fuel	Fuel Volume cu.ft.	Fuel / (Fuel+Air) Ratio, Vol. %	Stoichio-metric Ratio, Vol. %	Fuel Mass lb	LEL, Vol. %	UEL, Vol. %	% of UEL [6]
Methane	14,740	13.4%	9.5%	622	5%	15%	84%
Propyl alcohol	7,700	7.0%	4.5%	1220	2%	12%	50%
Heptane	3,190	2.9%	1.9%	843	1.2%	6.7%	31%

The figures presented in Table A-3 suggest that the explosion of near-ideal mixtures of propyl alcohol or heptane are consistent with the observed consequences of the explosion.

The results presented in Table A-3 appear to suggest that an explosion involving a rich mixture of methane might also produce the observed consequences. However, it is known that the severity of confined fuel-air explosions peaks close to, but somewhat above, the stoichiometric condition. Severity then drops off markedly as the upper explosive limit is approached. Not only does the pressure produced decrease, but the rate of pressure generation decreases as well. At 84 percent of the upper explosive limit this effect is highly significant. The maximum pressure achieved decreases by 56 percent and the rate of pressure generation K_g decreases by 85 percent.[7, 8] Because the TNO Multi-Energy method does not incorporate this phenomenon, and because there is no credible way such a large volume of natural gas could enter the building, the methane scenario in Table A-3 is not realistic.

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[6] For purposes of discussion herein the lower explosive limit is considered 0% and upper explosive limit (UEL) 100%.

[7] K_g is defined by the expression $(dP/dt) \cdot V^{1/3}$ where pressure increase is measured in a test cell of constant volume V.

[8] See Gieras et. al. (2006) for discussion of the explosion parameters of methane.

In conclusion, while the reconstructive modeling method discussed is based on estimates, it supports the theory that the destructive energy from the explosion at the CAI/Arnel facility was consistent with an explosion fueled by flammable solvents (either alcohol or heptane), but not from natural gas (methane).

Appendix B

Vapor Generation Analysis

1.0 Spill Scenario

1.1 Scenario Description

An instantaneous spill releases 500 gallons of heptane from a tote in Room E of the CAI/Arnel building. The pool spreads to 0.5 cm deep and spreads to the neighboring rooms of the building. Airflow from heater fans provides air movement and a driving force for evaporation over the surface of the pool.

1.2 Scenario Assumptions

Pool Volume = V = 500 gallons = 1.893 m^3

Pool and floor temperature = T = 65°F = 291.5K

Air velocity = 0.1 meters/second

Pool Thickness = x = 0.5 cm

Pool Area = A = 378.6 m^2

Pool is circular

1.3 Calculations

$Q = k_g A p_s M/R T$

Where Q = emission rate (kg/sec) k_g = mass transfer coefficient (m/sec) R = gas constant (8.31 joules/mol K)	A = pool area (m^2) p_s = vapor pressure (N/m^2) M = molecular weight (kg/mol) T = Pool temperature (K)

And:

$k_g = Sh\ D / dp$

Where:

Sh = Sherwood number

D = diffusivity (m^2/sec)

dp = pool diameter (m)

And:

$Sh = 0.023\ Re^{0.8} Sc^{1/3}$

Where

Re = Reynolds number = $u\ d\ \rho/\mu$

Sc = Schmidt number = $\mu/\rho\ D$

And:

$D = 0.01498\ T^{1.81}\ (1/M_A + 1/M_B)^{0.5}/[P(T_{cA}T_{cB})^{0.1405}\ (V_{cA}{}^{0.4} + V_{cB}{}^{0.4})^2\}]$

Where:

$T = 291.5K$

M_A = heptane molecular weight = 101.2 g/gmol

M_B = air molecular weight = 28.95 g/gmol

T_{cA} = Critical temperature for heptane = 540K

T_{cB} = Critical temperature for air = 132.3K

V_{cA} = Critical volume for heptane = 426 cm^3/gmol

V_{cB} = Critical volume for air = 82.71 cm^3/gmol

$D = 0.0649\ cm^2/sec = 6.49 \times 10^{-6}\ m^2/sec$

Find Reynolds Number

Re = Reynolds number = $u\ d\ \rho/\mu$

Where

u = air velocity over pool = 0.1 m/sec

d = pool diameter = 22m

$\rho_{air} = 1.2 kg/m^3$

$\mu_{air} = 0.000018$ kg/m sec

Re = 146, 667

Find Schmidt number

Sc = Schmidt number = $\mu/\rho D$

Where

$D = 6.49 \times 10^{-6}\ m^2/sec$

ρ and μ for air listed above

$Sc = 2.31$

Find Sherwood number

$Sh = 0.023\ Re^{0.8} Sc^{1/3}$

$Sh = 413$

Find mass transfer coefficient

$k_g = Sh\ D / dp$

$k_g = 1.22 \times 10^{-4}\ m/sec$

Find Emission Rate

$Q = k_g A p_s M/R T$

$A = 378.6 m^2$

$p_s = 4202 N/m^2$

M = 100.2 g/gmol

R = 8.31 N m/mol K

T = 291 K

Q = 8.04 g/s = 63.81 lb/hr

Therefore

Time to evaporate 850 pounds of heptane = **13.3 hours**

2.0 Boiling Tank Contents Scenario

2.1 Scenario Description

Steam continues to flow to the tank's jacket after the facility is closed for the night. Steam at up to 144,000 BTU/hour heats the mixture to boiling then liberates the necessary vapor to create the flammable atmosphere within the building.

2.2 Scenario Assumptions

Two boilers are operating for a total available heat flux of 288,000 BTU/hour

All of the heating area (38.5 ft^2) is available for heat transfer.

The time necessary to heat from 65°F to 100°F, as reported by CAI operators, is 2 hours.

Steam is available at 239°F

2.3 Calculations

$Q = U\ A\ \Delta T$

Starting at 65°F, manipulate this equation such that the temperature difference is 139 degrees after 2 hours.

This gives an overall heat transfer coefficient of 24 BTU/ hr ft^2 F.

Setting U, iterate the temperature increase in the tank by the minute until the boiling point is reached. This occurs at 479 minutes. Once the boiling point is reached, vapor generation can begin. The temperature difference is constant as well as heat input into the system.

Appendix B – Vapor Generation Analysis

Emission Rate = Q/λ

Where

Q = heat flux (BUT/hr)

λ = average latent heat (BTU/lb)

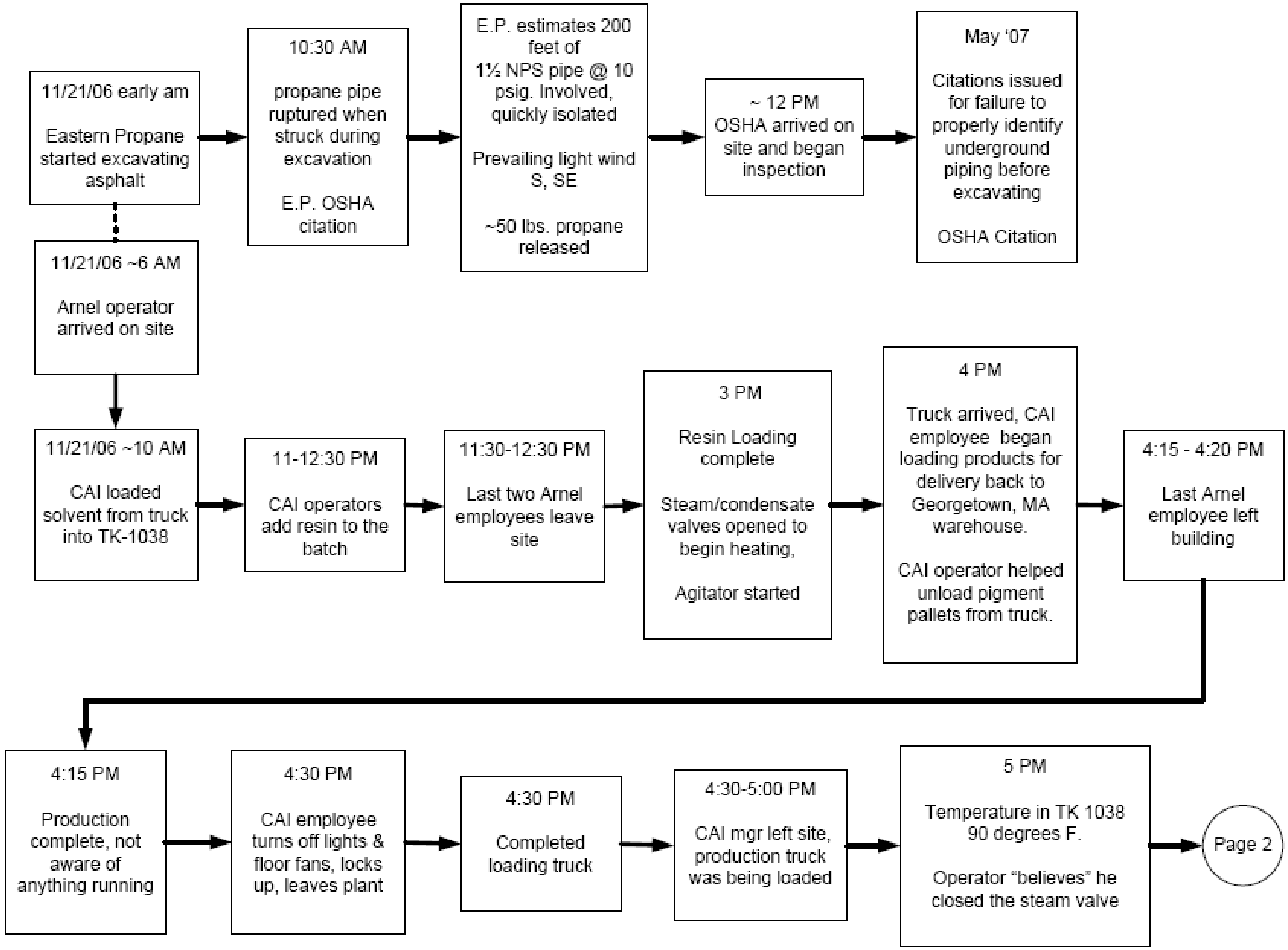
Therefore

Emission rate = 4.4 lb/minute = **264 lb/hr**

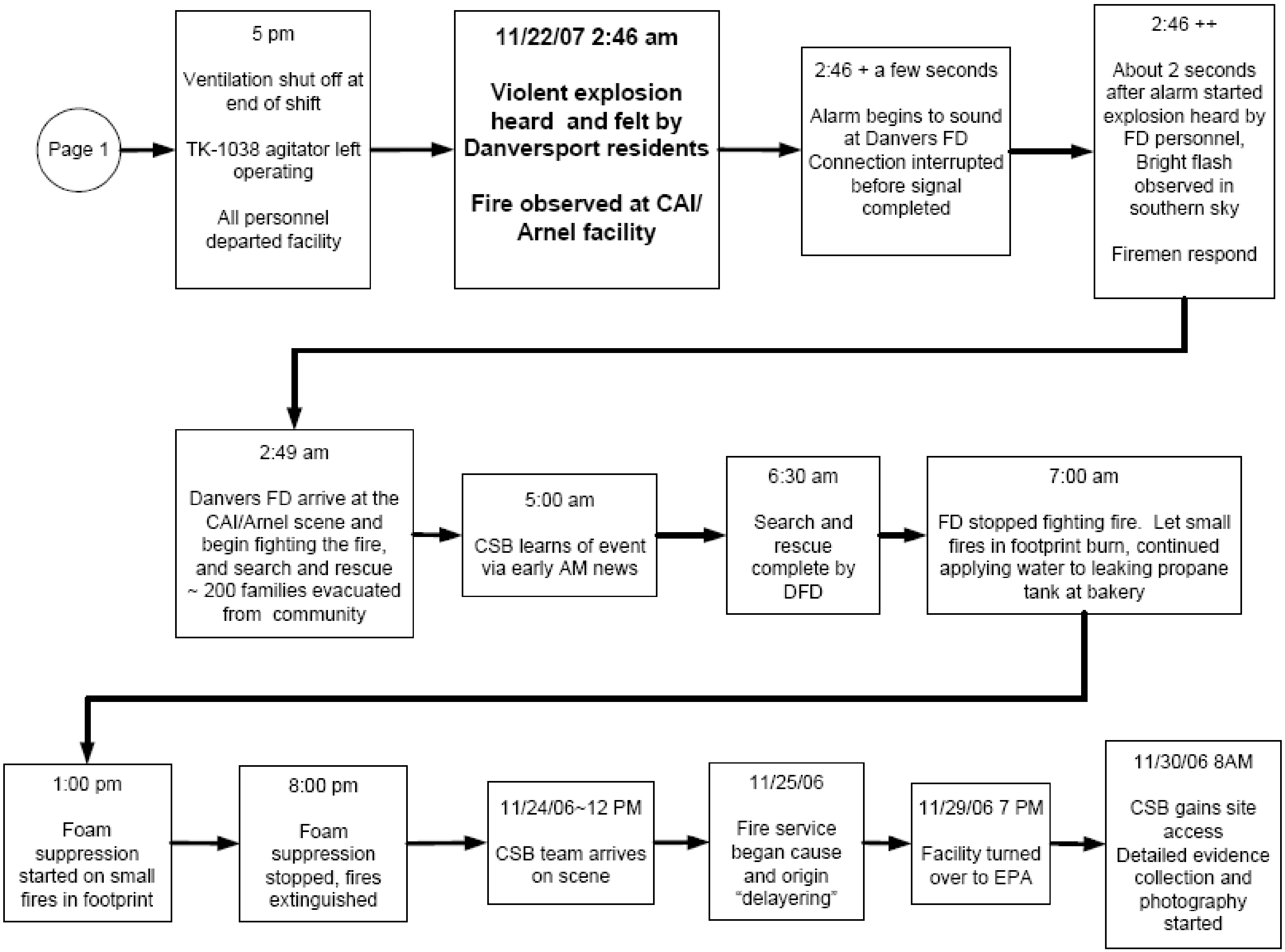
Appendix C

Incident Timeline

Appendix C – Incident Timeline



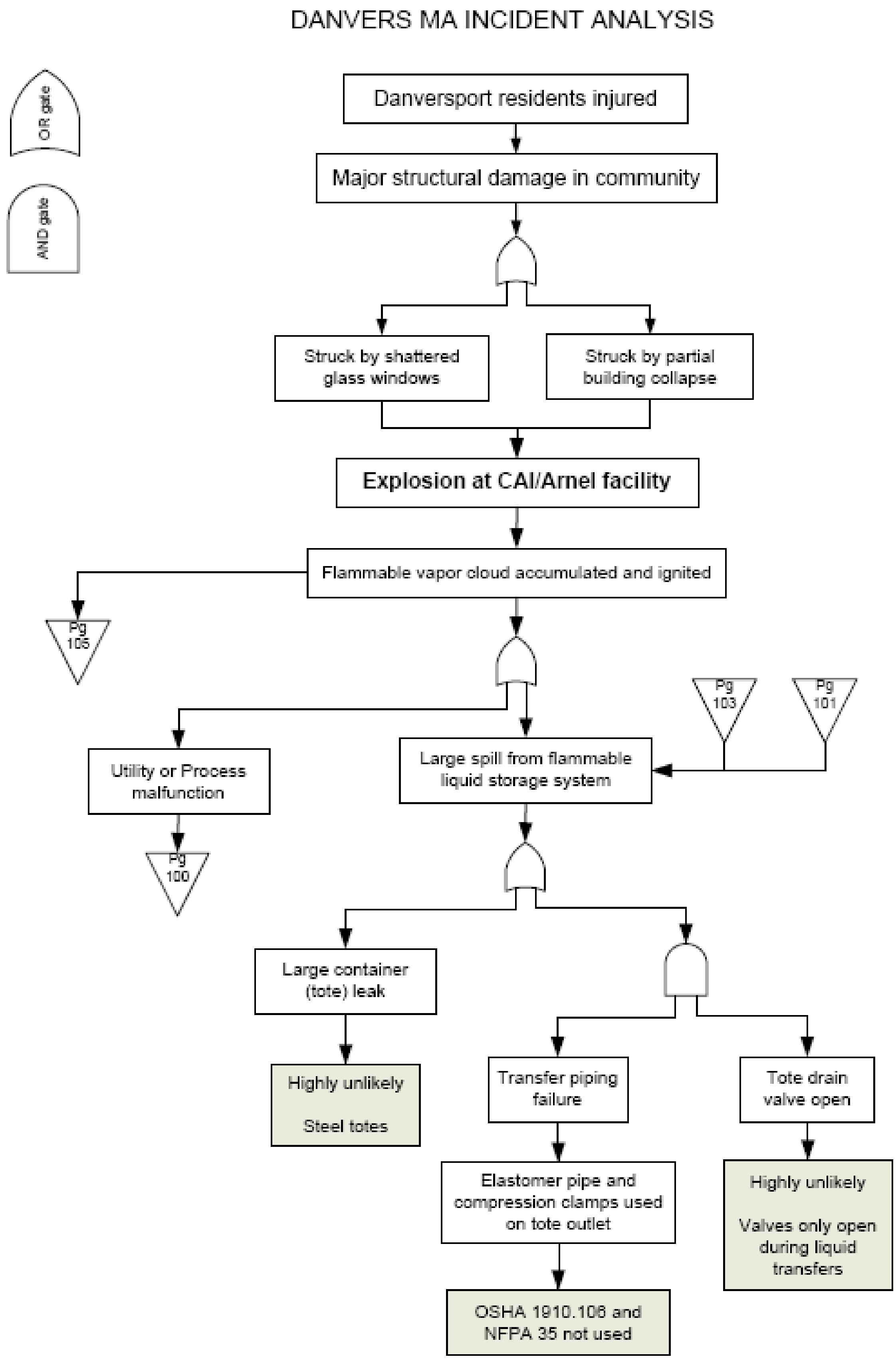
Appendix C – Incident Timeline



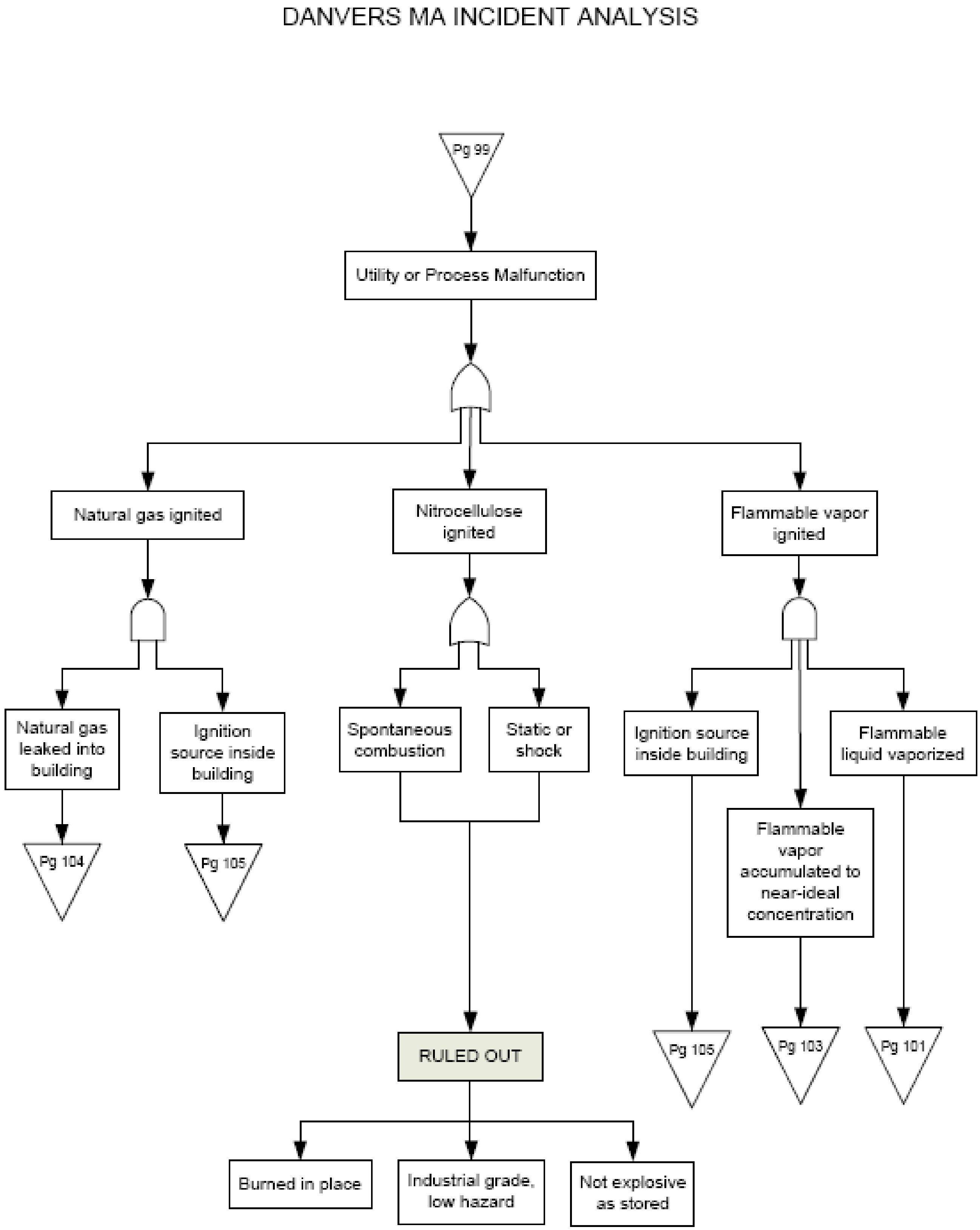
Appendix D

Logic Tree

Appendix D – Logic Tree



Appendix D – Logic Tree



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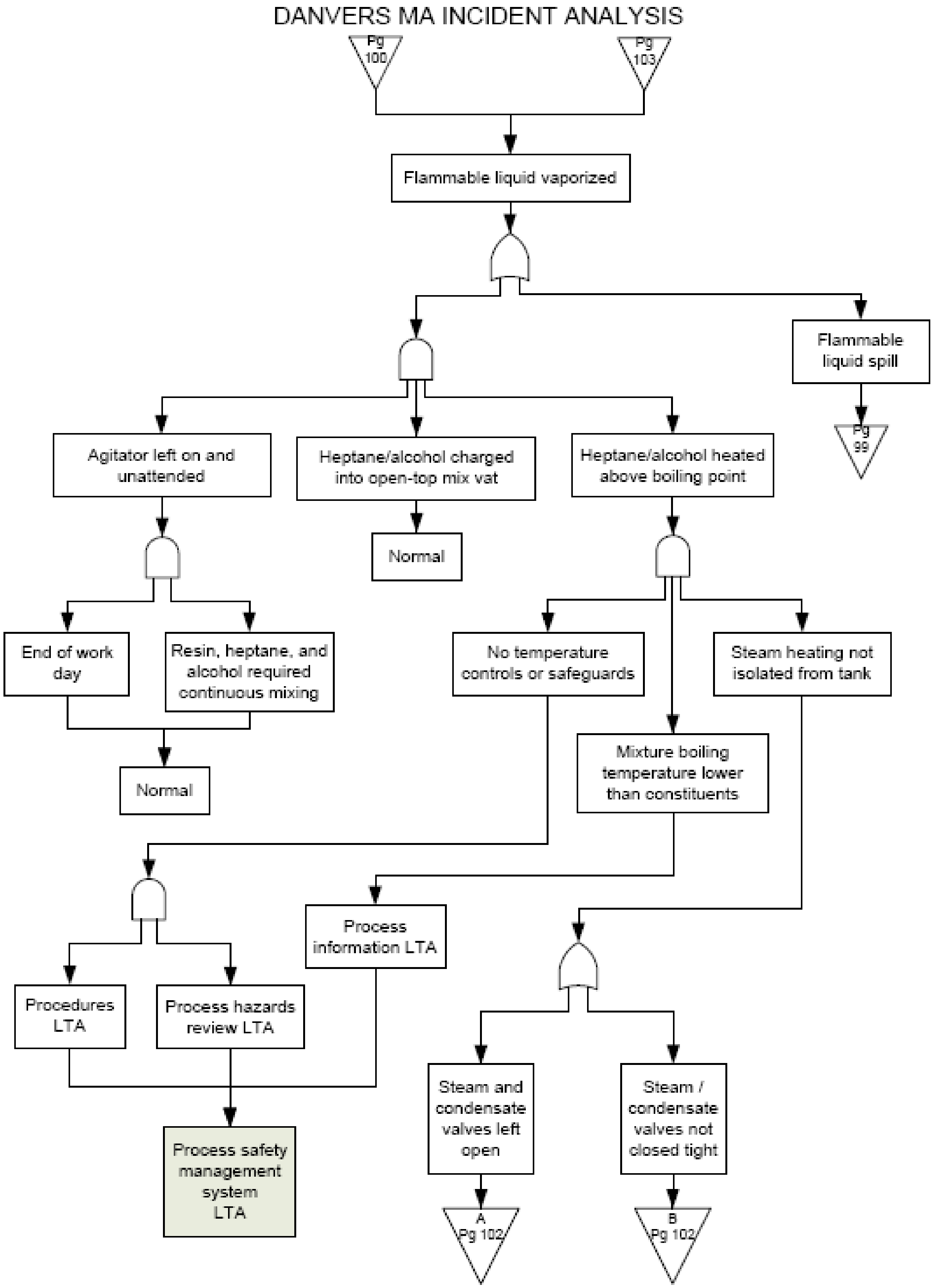

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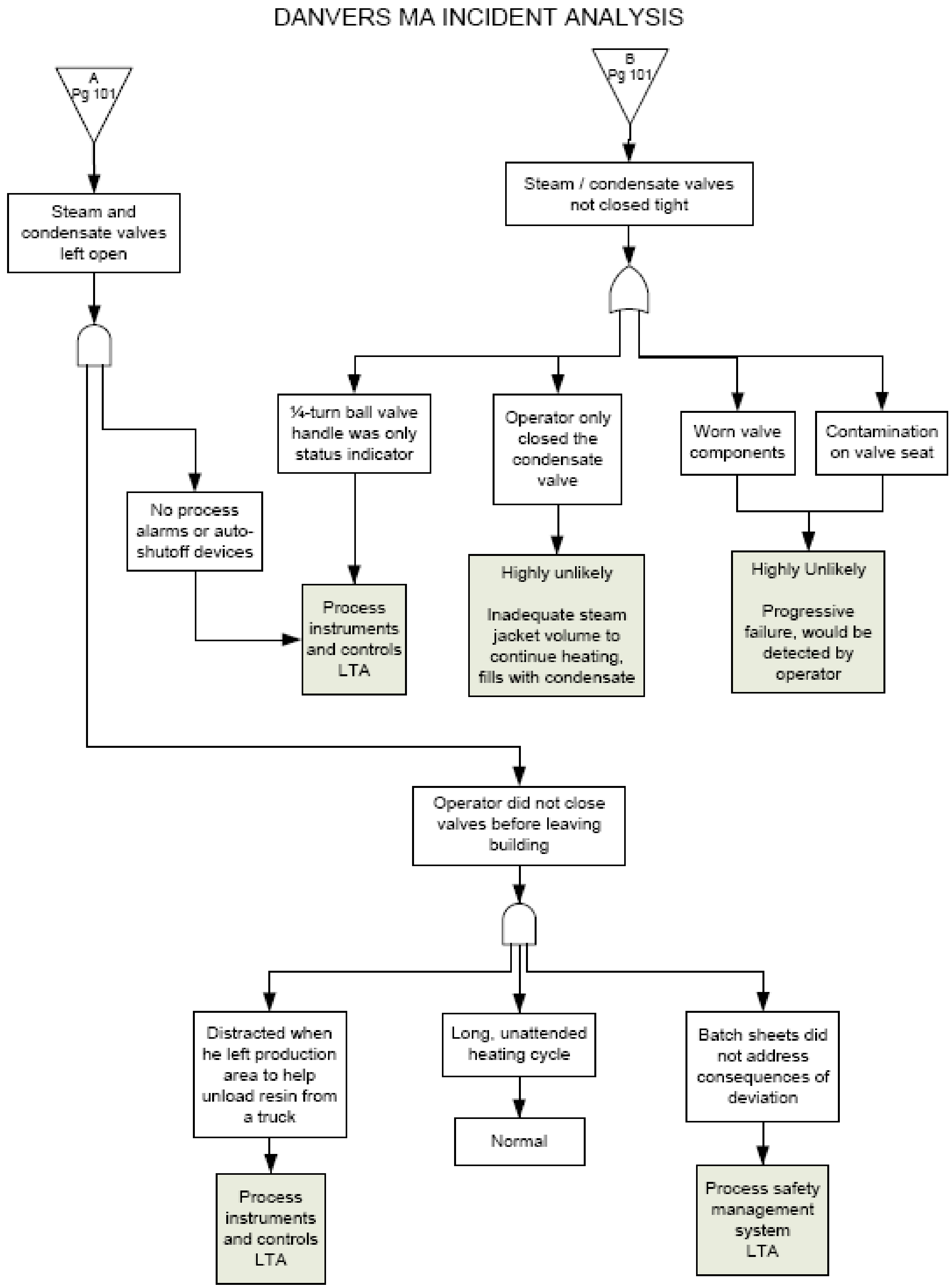
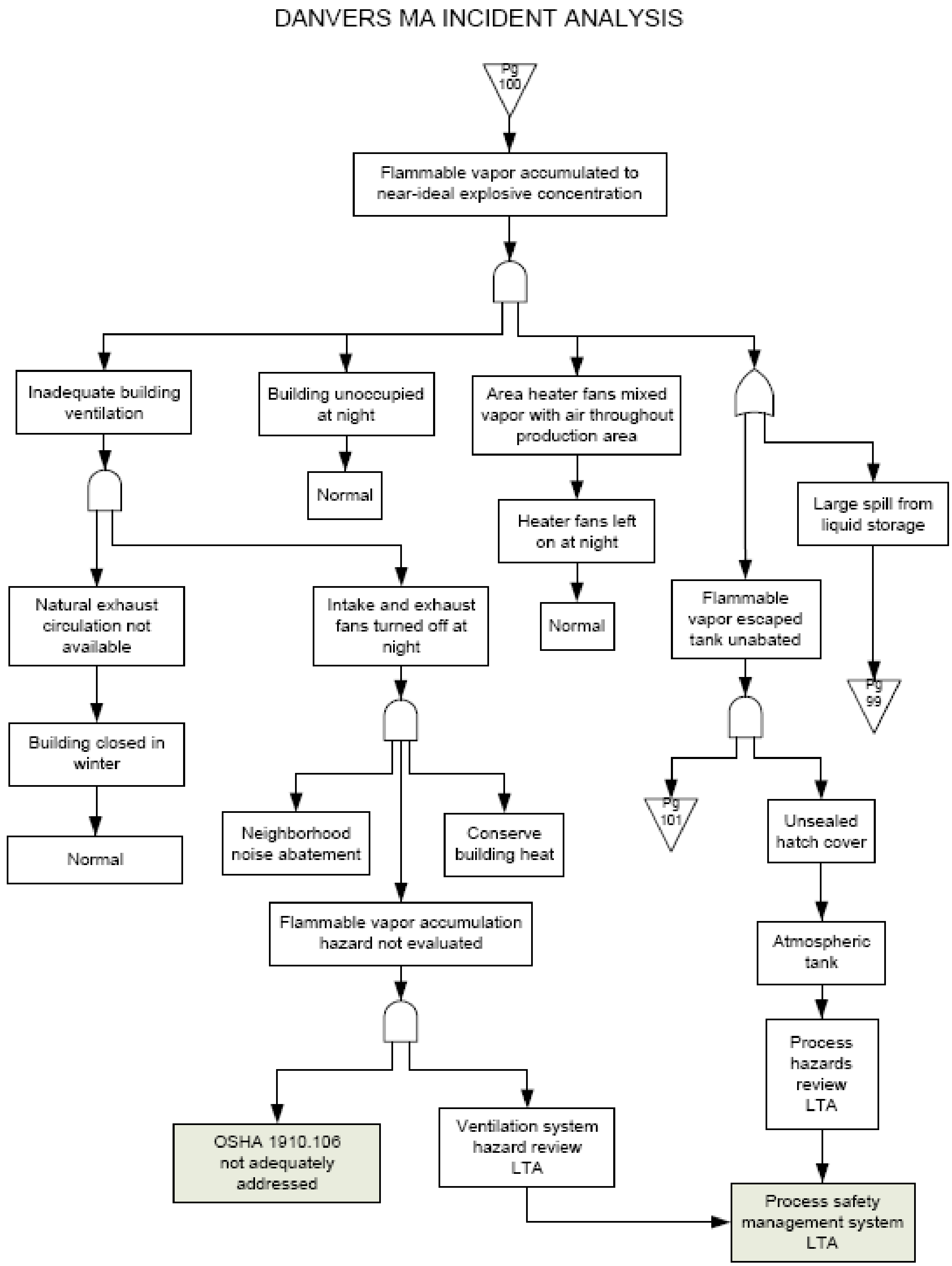
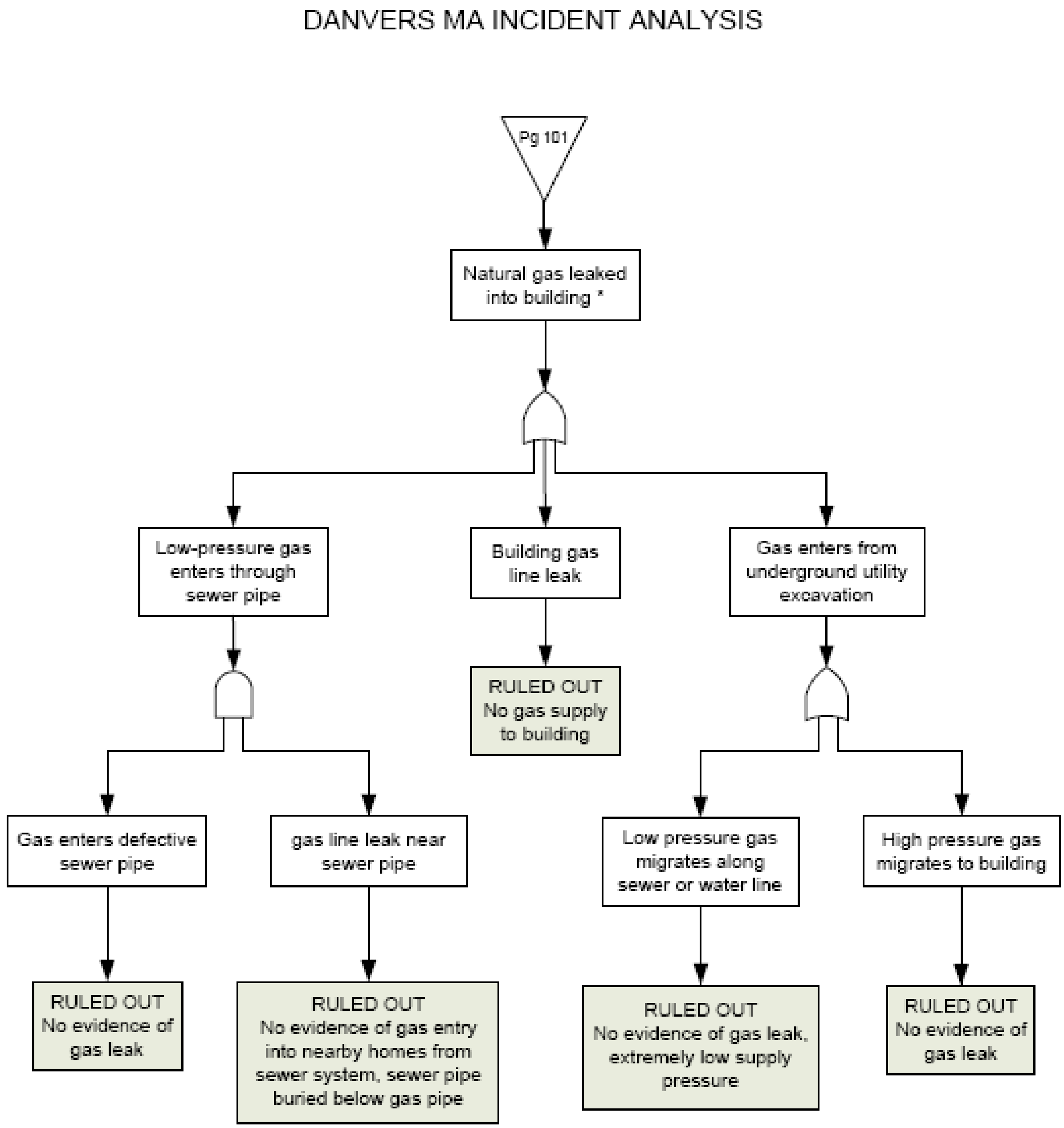
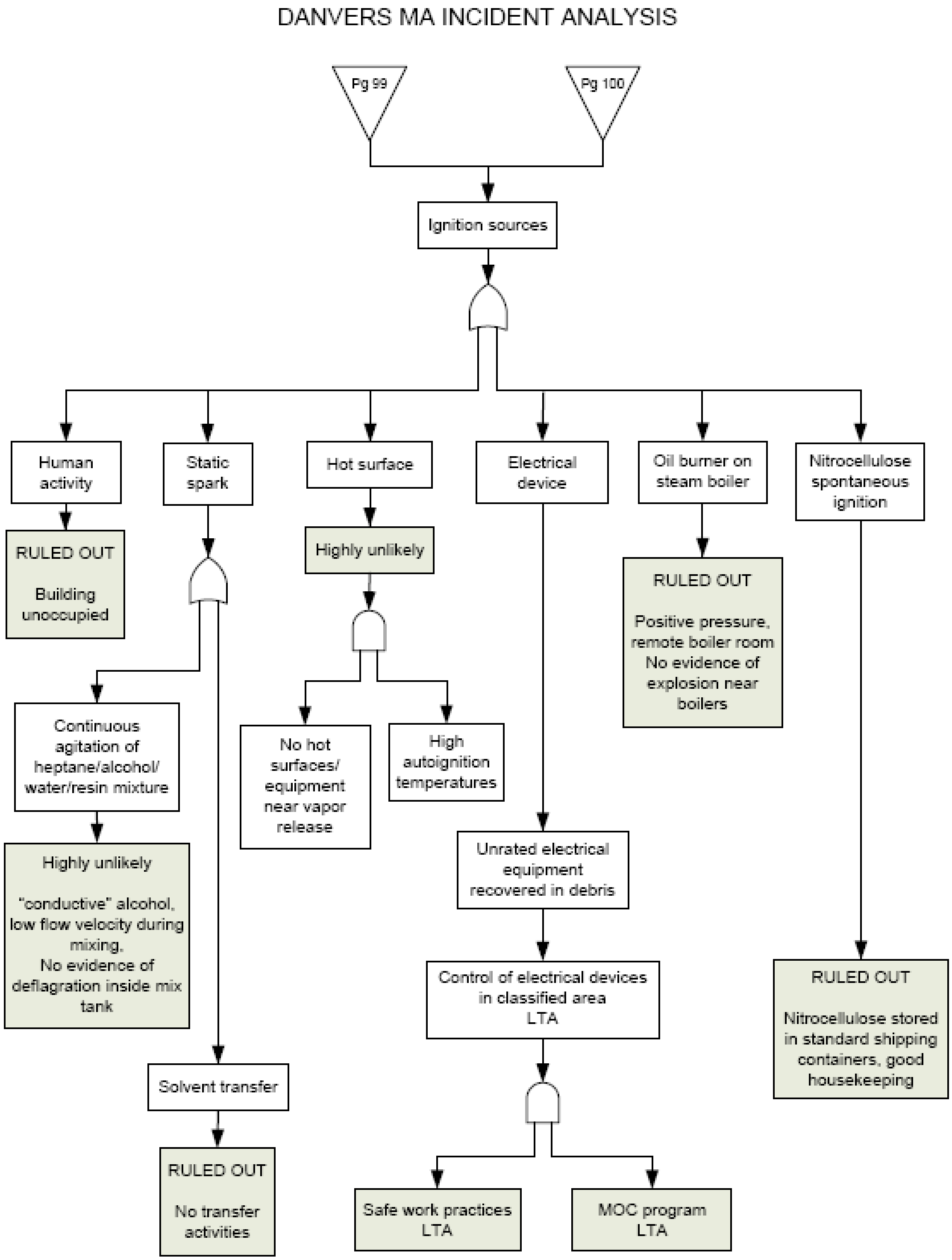


Appendix D – Logic Tree




DANVERS MA INCIDENT ANALYSIS
Pg 101
Natural gas leaked into building *
Low-pressure gas enters through sewer pipe
Building gas line leak
Gas enters from underground utility excavation
RULED OUT No gas supply to building
Gas enters defective sewer pipe
gas line leak near sewer pipe
Low pressure gas migrates along sewer or water line
High pressure gas migrates to building
RULED OUT No evidence of gas leak
RULED OUT No evidence of gas entry into nearby homes from sewer system, sewer pipe buried below gas pipe
RULED OUT No evidence of gas leak, extremely low supply pressure
RULED OUT No evidence of gas leak


DANVERS MA INCIDENT ANALYSIS
Pg 99
Pg 100
Ignition sources
Human activity
Static spark
Hot surface
Electrical device
Oil burner on steam boiler
Nitrocellulose spontaneous ignition
RULED OUT
Building unoccupied
Highly unlikely
RULED OUT
Positive pressure, remote boiler room
No evidence of explosion near boilers
Continuous agitation of heptane/alcohol/ water/resin mixture
No hot surfaces/ equipment near vapor release
High autoignition temperatures
Unrated electrical equipment recovered in debris
Highly unlikely
"conductive" alcohol, low flow velocity during mixing,
No evidence of deflagration inside mix tank
Control of electrical devices in classified area
LTA
RULED OUT
Nitrocellulose stored in standard shipping containers, good housekeeping
Solvent transfer
RULED OUT
No transfer activities
Safe work practices
LTA
MOC program
LTA