U.S. Chemical Safety and
Hazard Investigation Board

Fatal Vessel Leak, Vapor Cloud Explosion, and Fire at Yenkin-Majestic Resin Plant

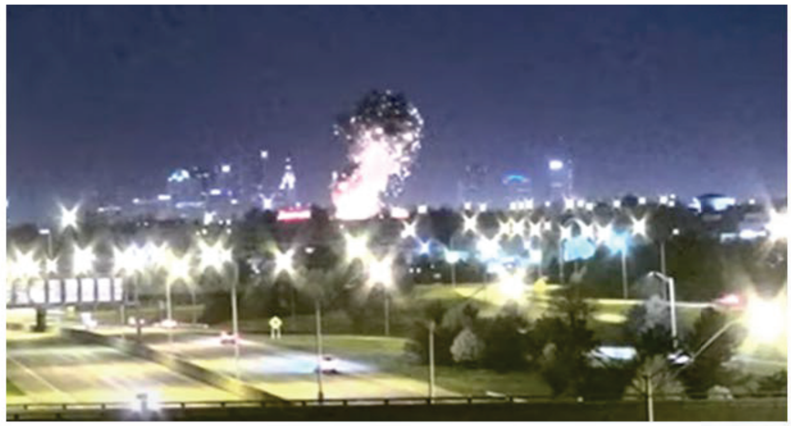
Columbus, OH | *Incident Date: April 8, 2021* | **No. 2021-04-I-OH**

Investigation Report

Published: November 2023

SAFETY ISSUES:

- **Mechanical Integrity of Low-Pressure Vessels**
- **Safeguard Selection and the Hierarchy of Controls**
- **Emergency Preparedness**



U.S. Chemical Safety and Hazard Investigation Board

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The CSB is an independent federal agency charged with investigating, determining, and reporting to the public in writing the facts, conditions, and circumstances and the cause or probable cause of any accidental chemical release resulting in a fatality, serious injury, or substantial property damages.

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The April 8, 2021, vessel leak, explosion, and fire incident at the Yenkin-Majestic resin plant fatally injured Wendell Light.

CONTENTS

ABBREVIATIONS

API	American Petroleum Institute
ANSI	American National Standards Institute
ASME	American Society of Mechanical Engineers
ASSP	American Society of Safety Professionals
BPVC	Boiler and Pressure Vessel Code
CCPS	Center for Chemical Process Safety
CSB	U.S. Chemical Safety and Hazard Investigation Board
FFS	fitness-for-service
FR	flame resistant
HAZWOPER	Hazardous Waste Operations and Emergency Response
HMI	human-machine interface
HSE	Health and Safety Executive
LEL	lower explosive limit
MAWP	maximum allowable working pressure
MDR	manufacturing design range
NBBI	National Board of Boiler and Pressure Vessel Inspectors
NBIC	National Board Inspection Code
Ohio EPA	Ohio Environmental Protection Agency
PED	Pressure Equipment Directive
PHA	process hazard analysis
PIP	Process Industry Practices
PPE	personal protective equipment

PSI	process safety information
psig	pounds per square inch gauge
RAGAGEP	recognized and generally accepted good engineering practices
RMP	Risk Management Program
SDS	safety data sheet
VM&P	varnish maker and painter’s naphtha

EXECUTIVE SUMMARY

On April 8, 2021, at approximately 12:02 a.m., a mixture of flammable naphtha solvent vapors and resin liquid became pressurized and then released through the seal of a closed manway of an operating kettle at the Yenkin-Majestic Paint Corporation (Yenkin-Majestic) OPC Polymers resin plant in Columbus, Ohio. The naphtha vapor spread throughout the enclosed building and formed a flammable vapor cloud both inside and outside the building. Approximately two minutes later, at 12:04 a.m., the flammable vapor cloud found an ignition source, and an explosion erupted, which ignited additional flammable material, resulting in a large fire that was extinguished after approximately 11 hours. More than 100 firefighters responded to the scene, including hazmat teams. The incident damaged buildings on the Yenkin-Majestic site and caused a fire in a commercial property adjacent to the site. Local news outlets reported that the explosion shook nearby homes and was seen, heard, or felt throughout parts of Columbus.

One employee was fatally injured from thermal injuries and inhalation of products of combustion and was found partially covered by rubble inside the second floor of the resin plant. Eight other employees were transported to area hospitals for injuries suffered during the explosion and building collapse, including third-degree burns and limb fractures, with one employee requiring a leg amputation after he was crushed under collapsed debris.

In addition, firefighting water runoff entered the nearby Alum Creek through a storm drain. The Ohio Environmental Protection Agency (Ohio EPA) reported that it observed offsite impacts from this incident, including firefighting water runoff, through at least April 11, 2021. Yenkin-Majestic has estimated its total property damage from the accident at over $90 million and demolished the severely damaged resin plant after the incident.

SAFETY ISSUES

The CSB's investigation identified the safety issues below.

- **Mechanical Integrity of Low-Pressure Vessels.** Yenkin-Majestic did not adequately ensure the mechanical integrity of a new 20-inch manway that was installed on a process vessel (Kettle 3) approximately three months before the incident. Kettle 3 normally operated at or near atmospheric pressure but was known to potentially build pressure up to 15 pounds per square inch gauge (psig) during some upset conditions. After the new manway was added, Yenkin-Majestic performed a leak check up to 4 psig and allowed Kettle 3 to continue operating for approximately three months until the incident. On the day of the incident, Kettle 3's new manway did not withstand more than 9 psig of pressure during a process upset and leaked hot resin and flammable solvent vapor into the facility. The CSB determined that Yenkin-Majestic did not follow basic quality assurance practices, such as adequately pressure testing equipment after alterations, which led to this release. In addition, Yenkin-Majestic had taken the position that Kettle 3 was exempted from pressure vessel regulation based on its process safety information documenting that it would not exceed 15 psig. Although pressure vessels that can operate over 15 psig are subject to pressure vessel safety codes, there is little guidance specifically for the design, construction, and alteration of pressure vessels not exceeding 15 psig. The CSB details the gaps in safety guidance for pressure vessels not exceeding 15 psig and provides recommendations for improvement in this report. (Section 4.1)

- **Safeguard Selection and the Hierarchy of Controls.** The hierarchy of controls is a risk management principle based on ranking hazard controls from most effective to least effective. On the day of the incident, the system design allowed an operator to add solvent to the hot-resin-filled kettle while, unknown to the operator, the agitator (which was supposed to mix the liquids in the kettle) was off. The subsequent activation of the agitator caused the liquid solvent to rapidly vaporize as it contacted the hot resin, leading to the pressure increase in the kettle and the subsequent release through the closed manway. Yenkin-Majestic had not installed or configured interlocks to prevent solvent addition to the kettle when the agitator was off during normal batch operations and relied upon computer panel status indicators, that were not equipped with alarms, to communicate the agitator status to the operator. Although administrative controls are essential for reducing risk, they depend on human actions, perception, and judgment. Administrative controls should not be relied on alone, without additional robust design and engineering controls in highly hazardous chemical processes. (Section 4.2)

- **Emergency Preparedness.** Yenkin-Majestic did not have adequate mitigative safeguards to minimize the consequences of the incident. For example, Yenkin-Majestic did not effectively utilize flammable gas detection systems and associated alarms to audibly notify onsite personnel of a hazardous gas release and the need to evacuate. During the incident, some of the gas monitors installed within the Yenkin-Majestic facility detected the flammable solvent release approximately one minute after the release began and sent an email to an offsite employee, but the monitors did not sound audible alarms to warn employees of the hazard. Additionally, Yenkin-Majestic did not specifically train its employees to recognize and respond to the presence of a flammable solvent vapor cloud and its associated hazards. During the incident, this overall lack of hazard recognition led to some personnel approaching the hazardous gas to investigate the release instead of initiating a plant-wide evacuation. Finally, Yenkin-Majestic allowed resin plant operators to wear cotton short-sleeved shirts while working in proximity to flammable materials unless they were performing specific tasks. Had the resin plant employees been required to wear flame-resistant personal protective equipment (PPE), multiple employee burn injuries resulting from the explosion and fire may have been reduced or prevented. (Section 4.3)

Cause

The CSB determined that the cause of the fatal explosion and fire was the release of flammable solvent vapor through the seal of a closed reactor manway that was not designed, constructed, or pressure tested to a design pressure appropriate for the process. The release through the closed manway occurred after the reactor became pressurized by the rapid vaporization of solvent when the reactor's agitator was turned on.

Contributing to the incident was Yenkin-Majestic's failure to adhere to basic pressure vessel integrity quality assurance practices, as well as the absence of clear industry guidance specifically for the design, construction, and alteration of pressure vessels in highly hazardous chemicals service not exceeding 15 psig. Also contributing to the incident was the absence of engineering controls to prevent the incident sequence and the failure of Yenkin-Majestic's administrative controls (overreliance on operator actions).

Contributing to the severity of the incident was Yenkin-Majestic's inadequate emergency preparedness, which led to a lack of a timely evacuation of all employees from the resin plant, lack of audible alarms to alert employees to the presence of flammable vapor concentrations in the resin plant, and a lack of flame-resistant uniforms to protect employees from fire hazards.

RECOMMENDATIONS

To Yenkin-Majestic

2021-04-I-OH-R1

Update mechanical integrity procedures for all process vessels in highly hazardous chemicals service, including pressure vessels not exceeding 15 psig, to adopt alteration guidance in API 510 *Pressure Vessel Inspection Code* or Part 3 of the *National Board Inspection Code*.

2021-04-I-OH-R2

Assess and document applicable design, construction, and alteration standards for all pressure vessels in highly hazardous chemicals service in new resin plant designs, including pressure vessels not exceeding 15 psig. At a minimum, adopt PIP VESLP001 *Low-Pressure, Welded Vessel Specification* as design and construction guidance for pressure vessels not exceeding 15 psig. Implement a program to assess the pressure vessels against updated applicable recognized and generally accepted good engineering practices, such as those published by API, ASME, PIP, and other organizations, at least once every five years, and address the gaps identified. Develop and implement written procedures to document and maintain records of (i) all inspections of, (ii) all alterations to, and (iii) all maintenance and repairs on all pressure vessels in highly hazardous chemicals service.

2021-04-I-OH-R3

Demonstrate the use of prevention through design using the hierarchy of controls in future resin plant designs. Specifically, prioritize inherently safer design and engineering controls to prevent process safety events. Refer to sources such as *Safety Instrumented Systems: A Life-Cycle Approach* by P. Gruhn and S. Lucchini, *Human Error in Process Plant Design and Operations – A Practitioner's Guide* by J. Robert Taylor, *Guidelines for Preventing Human Error in Process Safety* by the Center for Chemical Process Safety (CCPS), *Guidelines for Inherently Safer Chemical Processes – A Life Cycle Approach* by the CCPS, and *Guidelines for Risk Based Process Safety* by the CCPS for guidance. Demonstration could include documentation of conceptual design safety reviews, hazard analysis and risk assessments of detailed project designs, and a plan to address the recommendations to control the hazards.

2021-04-I-OH-R4

Identify and document all equipment that could release flammable materials and install LEL detectors in accordance with sources and guidance such as *Guidelines for Engineering Design for Process Safety* by the Center for Chemical Process Safety and *Explosion Hazards in the Process Industries* by Rolf K. Eckhoff. Ensure that detection of hazardous conditions automatically triggers both visual and audible alarms to alert plant personnel of the hazard. Develop and implement employee training on actions to take, such as prompt evacuation, when such alarms are activated.

2021-04-I-OH-R5

Develop and implement requirements for personnel to wear flame-resistant uniforms in all operating areas that process flammable chemicals. Update employee training material to include the requirement for and purpose of PPE use.

To American Petroleum Institute (API)

2021-04-I-OH-R6

Develop specific design, construction, and alteration guidance for low-pressure process vessels in flammable and other highly hazardous chemicals service not exceeding an internal pressure of 15 psig in API 510 *Pressure Vessel Inspection Code*, API RP 572 *Inspection Practices for Pressure Vessels*, and/or other appropriate products. At a minimum, include guidance for:

(i) determining and documenting the low-pressure vessel's design pressure (such as through a data sheet and a nameplate affixed to the vessel);

(ii) determining when or if all or parts of the ASME Boiler and Pressure Vessel Code should be applied;

(iii) acceptable alternative engineering methods, if applicable; and,

(iv) alteration requirements, such as design assessments, inspections, and pressure testing.

To American Society of Mechanical Engineers (ASME)

2021-04-I-OH-R7

Assist API in developing design, construction, and alteration guidance for low-pressure vessels in flammable and other highly hazardous chemicals service not exceeding an internal pressure of 15 psig. If any new design and construction guidance is specifically developed for pressure vessels in flammable and other highly hazardous chemicals service not exceeding an internal pressure of 15 psig, reference the design and construction guidance in the Section VIII, Division 1 of the ASME Boiler and Pressure Vessel Code (BPVC).

1 BACKGROUND

1.1 YENKIN-MAJESTIC PAINT CORPORATION

Yenkin-Majestic Paint Corporation (Yenkin-Majestic) is a coatings and resin manufacturer based in Columbus, Ohio. The company was founded in 1920 and moved to its current location (1920 Leonard Avenue) in 1954. At the time of the incident, Yenkin-Majestic employed approximately 180 people and had three divisions at its Columbus facility: Majic Paints, Yenkin-Majestic Industrial Coatings, and OPC Polymers [1]. OPC Polymers develops and manufactures resins for the coatings industry [2]. The incident occurred at the OPC Polymers resin plant within the Yenkin-Majestic facility. At the time of the incident, a total of 21 Yenkin-Majestic employees were onsite, with 12 employees in the resin plant, five employees in the adjacent paint plant, and three maintenance technicians supporting both plants.

A portion of Yenkin-Majestic's resin plant was subject to the U.S. Occupational Safety and Health Administration (OSHA) Process Safety Management of Highly Hazardous Chemicals (PSM) standard due to its usage of flammable liquids present in quantities of 10,000 pounds or more.[a] Yenkin-Majestic is not regulated by the Environmental Protection Agency's (EPA) Risk Management Program (RMP) rule. The part of the process that experienced the incident was PSM-covered.

OPC Polymers is a specialty polymers and resins supplier. As of late 2023, 35 specialty polymers and resins suppliers operated in Ohio, and 340 such suppliers operated within the United States [3].[b]

1.2 RESIN PRODUCTION PROCESS

1.2.1 TYPICAL KETTLE OPERATION

Yenkin-Majestic produced over 120 different products at the resin plant by batch reaction [4]. The resin batch reactions took place inside agitator-stirred[c] reactors, called kettles, that were heated by furnaces or steam.

Figure 1 is a simplified drawing of a furnace-heated kettle. Liquid raw materials used in the batch process were piped from storage tanks into the top of the kettle. Solid ingredients could be dropped into the kettle from a

[a] Yenkin-Majestic considered the resin plant's PSM-covered process as the kettle systems and their associated scale tanks, including piping to the scale tanks and piping up to the filtration system. Yenkin-Majestic did not consider finished goods storage tank systems and raw material storage tank systems to be part of the covered process. The paint plant, warehouses, and other buildings were not PSM-regulated. Yenkin-Majestic managed separate PSM and non-PSM policies to comply with the regulatory requirements.

[b] Not all companies listed in GlobalSpec's specialty polymers and resins supplier directory are manufacturers like OPC Polymers. GlobalSpec's "suppliers" category includes manufacturers, service providers, and distributors [3].

[c] An agitator, or a mechanical mixer, is a shaft-mounted impeller system that is connected to a drive unit (such as a motor).

hopper through a designated opening on the kettle. Operators could also add solid material into the kettle in smaller quantities through the manway.[a]

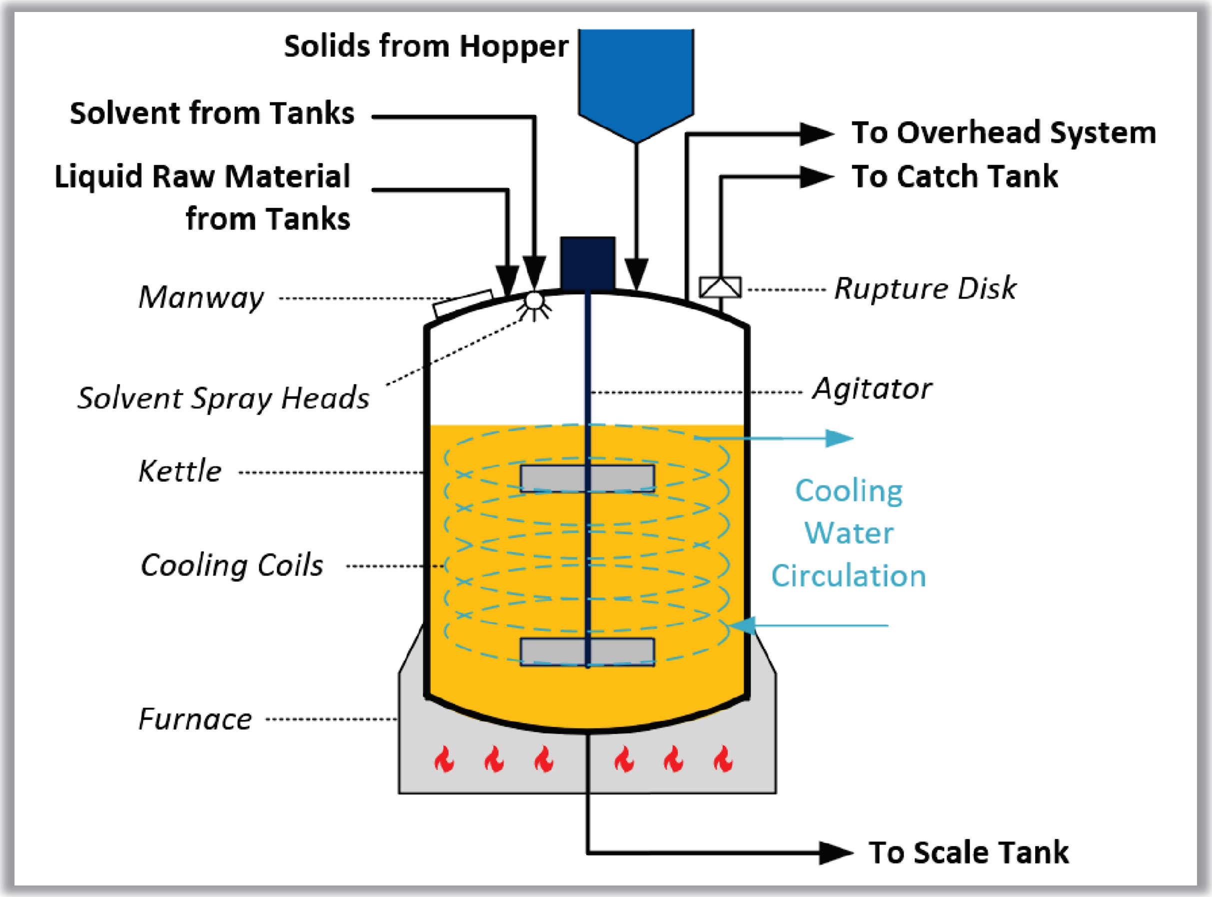

Figure 1. Simplified kettle drawing (not to scale). (Credit: CSB)

Yenkin-Majestic used its proprietary recipes for the kettle batch operations, which typically involved blending and reacting various chemicals inside the heated, stirred kettles. Toward the end of each batch operation, the kettle operators would analyze samples of the kettle's contents approximately every 20 minutes to monitor the batch's progress. After the operator determined that the reaction was completed, based on laboratory sample results, the operator would push a "Batch Done" button at the kettle's control panel. This action would shut down the furnace and begin water circulation through the cooling coils to cool the kettle's contents.

While water circulated through the cooling coils, solvent, which did not chemically react with the resin, was also typically added to the kettle to aid in cooling.[b] After the kettle contents were cooled down to a target temperature, the resin would be transferred to a separate finishing vessel, called a scale tank, where it would be

[a] The available technical literature indicates that at least one other resin manufacturing company reported requiring fully-enclosed solids loading systems due to the risk that "[a]ccidental introduction of moisture in raw materials into a hot reaction mass can generate superheated steam, which can be ejected with solvent vapors out of an open manhole or loading port possibly forming a vapor cloud in the operating area" [49, p. 10]. Yenkin-Majestic had recently implemented a project to install a fully-enclosed solids loading system into Kettle 3, described in *Section 4.1.1*).

[b] The solvent varied based on the product.

blended with additional solvent to a final product specification.[a] Solvent lowered the resin mixture's overall density and viscosity.

1.2.2 Kettle 3 Process Equipment

On the night of the incident, a kettle used for the batch reactions, called Kettle 3, was being operated to produce an alkyd resin, which is a component used in some paints and clear coatings [5]. Kettle 3 was a cylindrical reactor with a diameter of 8 feet and a height of 7 feet. **Figure 2** shows most of the major equipment associated with Kettle 3 (valves and valve configuration not shown).[b] Kettle 3 was heated by a furnace located directly underneath it,[c] and the system also included auxiliary equipment to cool, separate, and recirculate process streams as needed for the resin production process. The Kettle 3 system operated open to the atmosphere, first passing through a bubble cap column acting as a scrubber and then through the total condenser, where any non-condensable gases, such as nitrogen, were directed through 3-inch atmospheric vent piping that was routed to the outside of the building.

[a] The solvent's primary purpose was to bring the resin mixture to a target product specification.

[b] Process flow in the overhead system, which included the bubble cap column, condenser, decanter, and reflux tank, could be routed in several different configurations based on preset automated valve settings.

[c] It was not uncommon for some older alkyd resin reactors to be heated by furnaces. Currently, according to multiple textbooks on resin manufacture, alkyd resin reactors are typically heated and cooled through jackets around the reactors and/or coils immersed in the reactors [53, p. 118, 54, pp. 103-104, 55, p. 1604]. One source describing alkyd resin manufacture states, "High-pressure steam and gas-flame heating have been used but are less satisfactory and more hazardous" [55, p. 1604]. For example, one company told the CSB that it no longer operated its furnace-fired resin reactors, opting for jacket heating and cooling for reactors in all its sites. A 2015 source describes more efficient heating alternatives now available for new resin plant designs: "In the past, heating was accomplished by direct fire such as a kerosene or fuel oil flame or by electrical heating. [...] The best heating technique now used is to circulate hot silicon oil through the jackets. If very big reactors are used for high-capacity production, heating coils may be immersed into the reactor to improve the rate of heat transfer to the materials in the reactor" [54, p. 104].

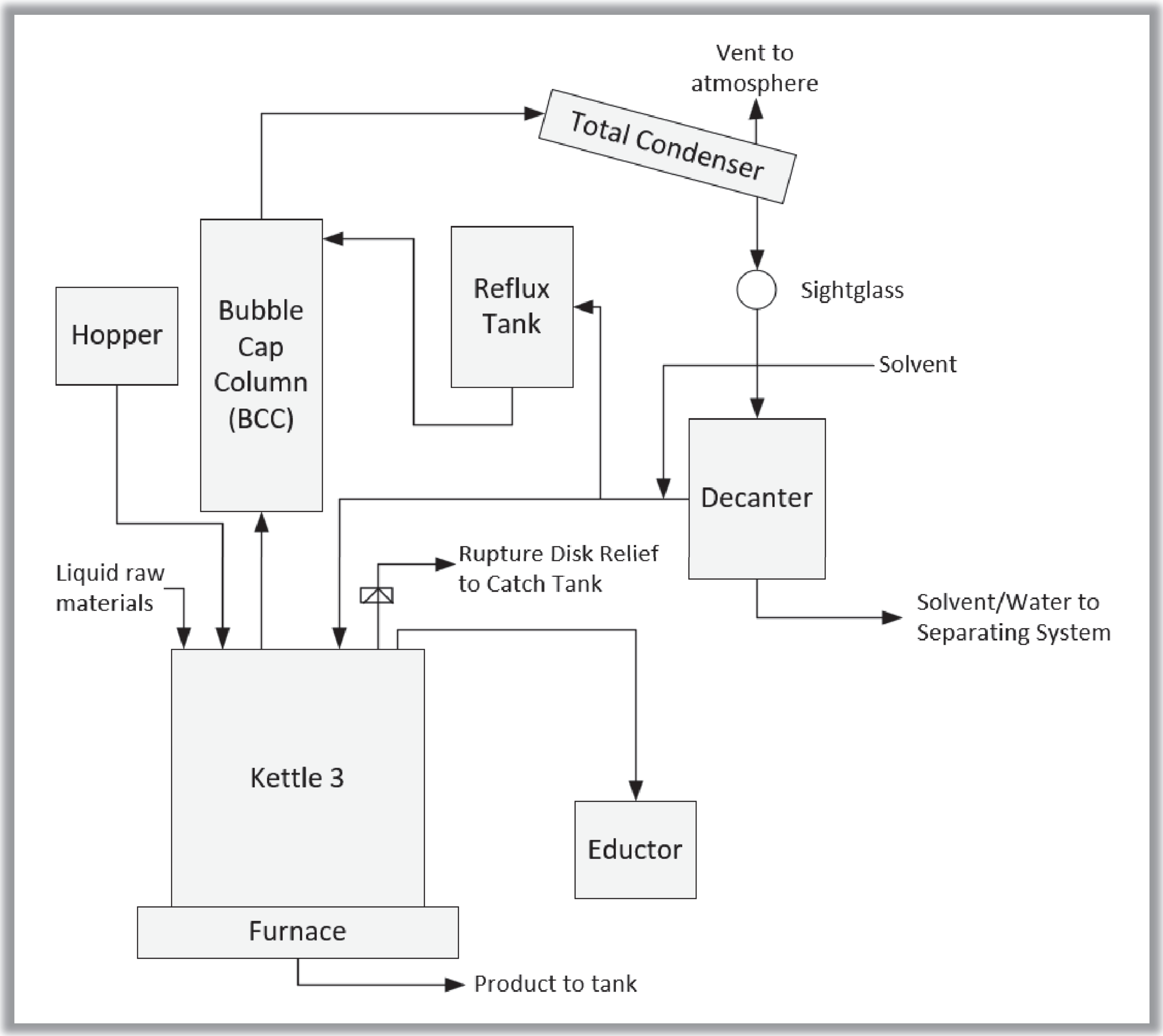

Figure 2. Simplified block diagram showing major equipment in the Kettle 3 system. (Credit: CSB)

Kettle 3 was typically operated at or near atmospheric pressure. The kettle was configured with a high-pressure alarm at 2 pounds per square inch gauge (psig), and an automatic high-pressure trip at 4 psig. The high-pressure trip activated the "emergency cooling" safety interlock,[a] which was designed to shut down the furnace and turn on cooling water to the coils to aid in reducing the temperature and pressure inside the kettle. The Kettle 3 emergency pressure-relief system also included one 8-inch rupture disk, used to protect the vessel from high-

[a] Safety interlocks take automatic action to achieve or maintain a safe state of the process when a process variable reaches a defined limit. In this instance, some of the interlocks were hard-wired into the devices, while others were achieved by software programming of process logic controllers that regulated the devices on Kettle 3.

pressure conditions, which Yenkin-Majestic documented as having a burst pressure between 13.5 and 15 psig.[a] In the event of high pressure inside the kettle, the rupture disk was intended to open and direct the pressurized contents of the kettle into a catch tank.[b] During the April 8, 2021, incident, the high-pressure alarm and trip activated after Kettle 3's pressure began to rise, and the rupture disk did not burst (discussed further in *Section 2*).

The April 8, 2021, incident initiated in Kettle 3 during the production of a batch of resin, which was in its final cooling step. The release occurred from a closed manway that had been added three months prior to the incident, discussed further in *Section 3.2.*

1.2.3 Resin Plant Layout

The resin plant was a multi-story enclosed building that housed six kettles and other process equipment. The kettles were enclosed in various rooms, as illustrated in **Figure 3**. The kettles spanned two stories of the resin plant; the kettles rested on the furnaces on the first (ground) floor, and the equipment on and near the top of the kettles to control the process was accessible on the second floor (**Figure 4**). Some of the kettles were set up to be controlled and monitored via a control panel next to the kettle inside the kettle room, while others were controlled from adjacent control rooms. The laboratory, where operators analyzed samples during the batch runs, was on the third floor.

On the day of the incident, the release of flammable solvent vapors and resin liquid occurred at a manway on top of Kettle 3, located on the second floor of the resin plant. **Figure 3** shows the general layout of the second floor, where red circles indicate kettle locations, and other circles indicate auxiliary equipment such as tanks.

[a] The tag on Kettle 3's recovered rupture disk post-incident indicated a marked burst pressure of 16.5 psig. According to purchase records, Yenkin-Majestic had been ordering rupture disks whose marked burst pressure fell within a manufacturing design range of 15.3-17 psig for Kettle 3, which did not match Kettle 3's documented process safety information (discussed further in *Section 4.1.2*).

[b] In some kettle high-pressure events, some liquid material would also leave the system through the condenser's atmospheric vent onto the roof.

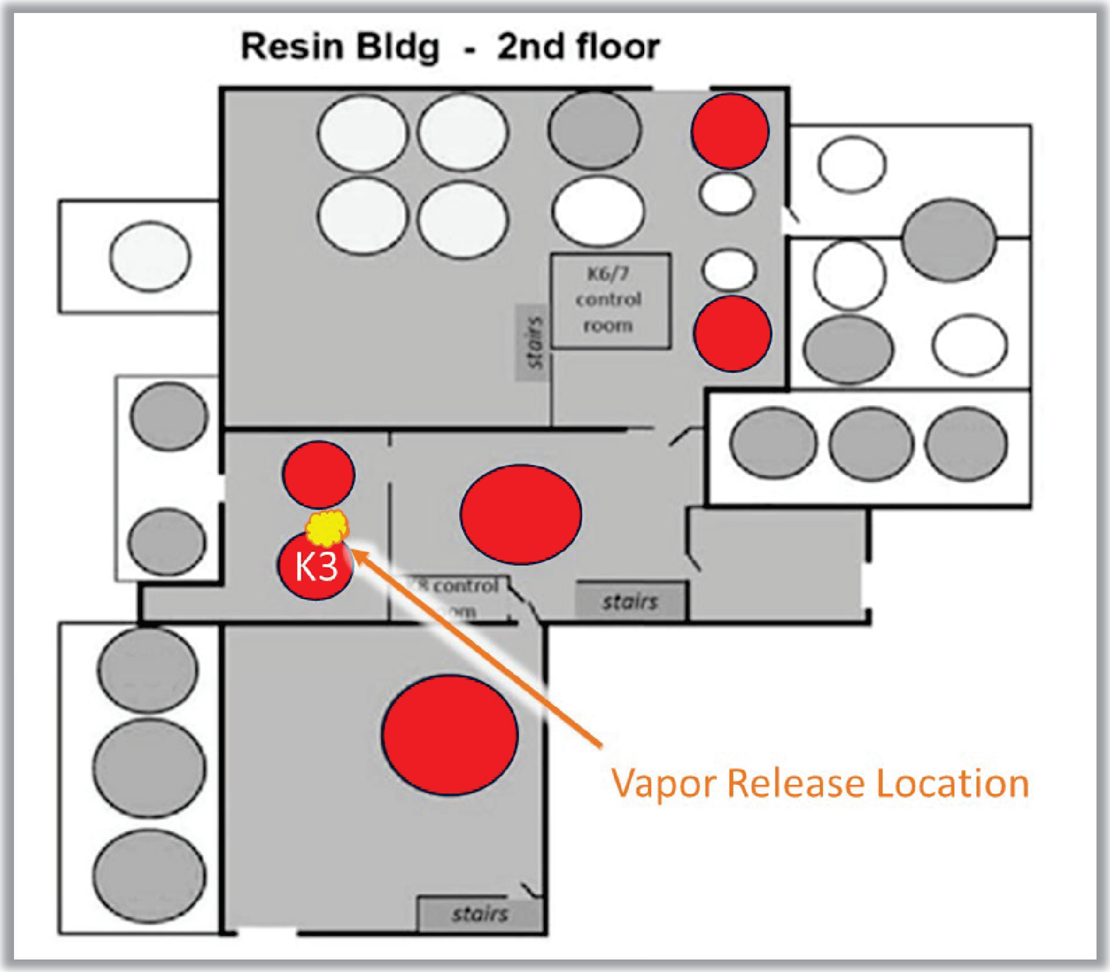

Figure 3. Flammable solvent vapor release location. (Credit: Yenkin-Majestic with modifications by CSB)

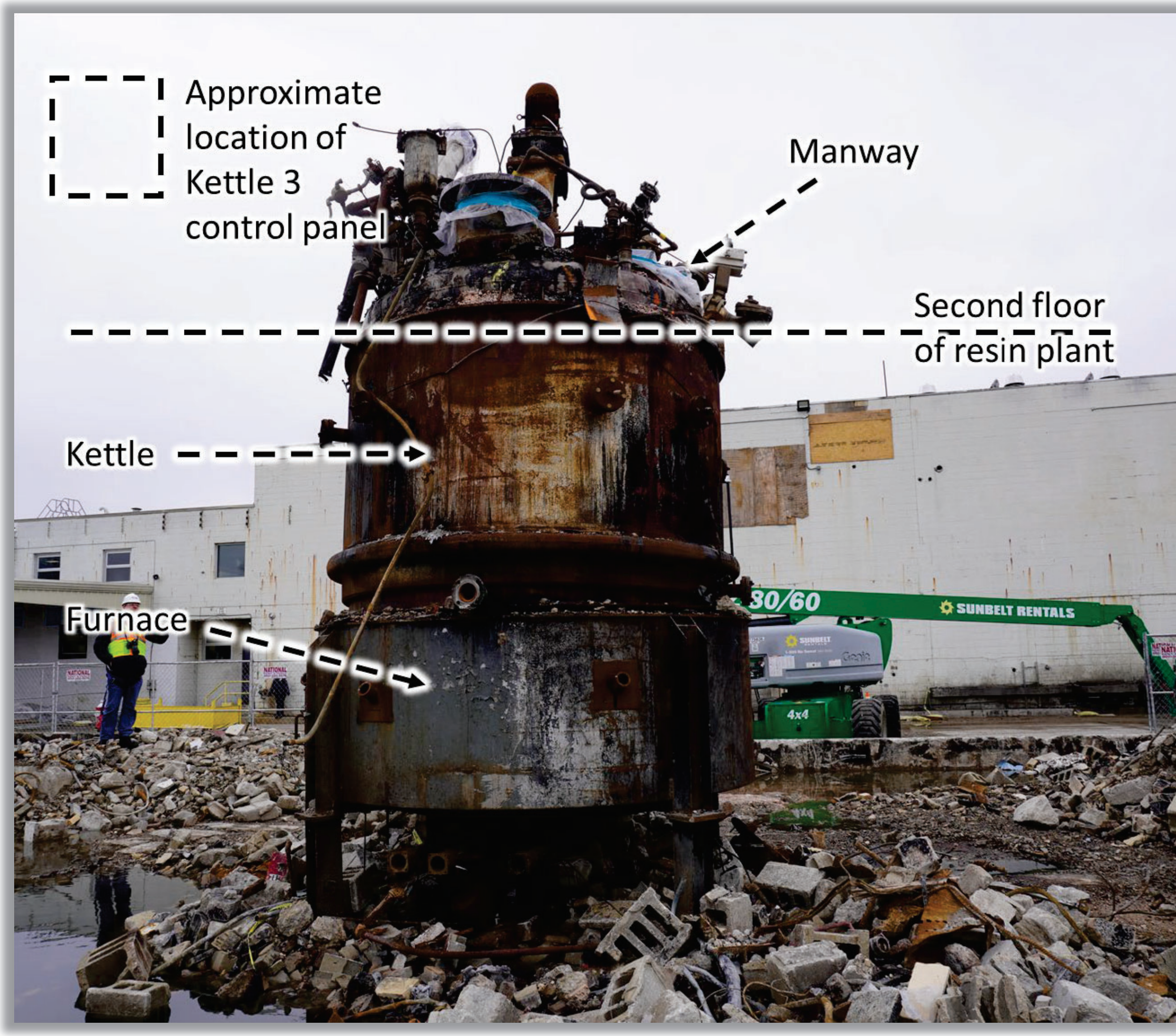

Figure 4. Photo of Kettle 3 during demolition. (Credit: CSB)

1.2.4 VM&P Naphtha (Solvent)

In resin production, a solvent is typically added as a "thinner" to the resin mixture to lower the final product's viscosity, as well as affect its drying and film formation properties [6, pp. 12, 71]. Yenkin-Majestic used varnish maker and painter's naphtha (VM&P) as the solvent for the resin batch that was in production in Kettle 3 on the day of the incident [7]. VM&P is a petroleum-derived hydrocarbon solvent, also known as hydrotreated light straight run naphtha. According to the safety data sheet (SDS) from the vendor that provided VM&P to Yenkin-Majestic, VM&P can cause skin irritation and may cause drowsiness or dizziness. The vendor's SDS describes VM&P as a highly flammable liquid with a flashpoint of 69 °F that boils (vaporizes) between 264 °F and 291 °F. As a vapor, VM&P is about four times heavier than air, meaning that it will accumulate in low or confined areas and spread along the ground.

1.3 DESCRIPTION OF SURROUNDING AREA

Figure 5 shows the Yenkin -Majestic facility and depicts the areas within one, three, and five miles of the facility boundary. Summarized demographic data for the approximately one-mile vicinity of the Yenkin-Majestic facility is shown below in **Table 1**. There are over 33,127 people residing in over 14,751 housing units, most of which are single units, within the census blocks in which a portion of the block(s) are within one mile of the Yenkin-Majestic facility. Detailed demographic information is included in Appendix B.

Yenkin-Majestic's resin plant was located approximately three miles from downtown Columbus. Columbus is Ohio's state capital and had a population of approximately 907,000 in 2021 [8].

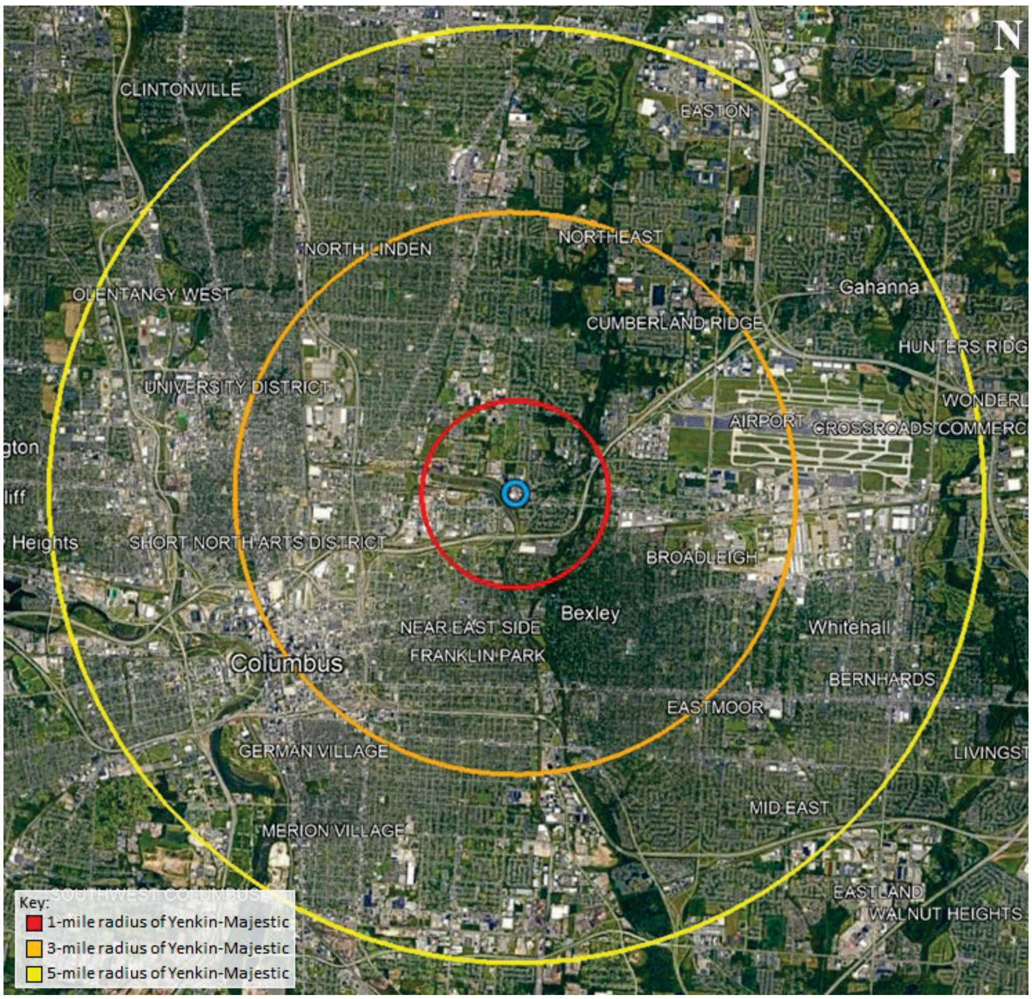

Figure 5. Overhead satellite image of the Yenkin-Majestic facility and the surrounding area. (Credit: Google Earth, annotated by CSB)

Table 1. Summarized demographic data for approximately one-mile vicinity of Yenkin-Majestic facility.[a] (Credit: CSB using data obtained from Census Reporter)

Population	Race and Ethnicity		Per Capita Income	% Persons Below Poverty Line	Number of Housing Units	Types of Housing Units	
33,127	White	27%	$ 27,368	30%	14,751	Single Unit	63%
	Black	56%				Multi-Unit	35%
	Native	2%				Mobile Home	2%
	Asian	4%				Boat, RV, Van, etc.	0%
	Islander	0%					
	Other	1%					
	Two+	4%					
	Hispanic	6%					

[a] Census Reporter reports that Ohio's per capita income was $35,119 and that the overall per capita income for the United States was $38,332 [8].

2 INCIDENT DESCRIPTION

The incident occurred during the April 8, 2021, night shift[a] toward the end of Kettle 3's operating sequence, which had been progressing normally. During the incident, a total of 21 Yenkin-Majestic employees were onsite, with 12 employees in the resin plant, five employees in the adjacent paint plant, and three maintenance technicians supporting both plants. Employee A was the operator overseeing the Kettle 3 batch operation in the resin plant.[b] At 10:19 p.m., Employee A departed the kettle room to review sample results at the laboratory. While he was gone from the kettle room, at 10:22 p.m. the Kettle 3 agitator unexpectedly shut down.[c,d] Employee A returned a few minutes later, at 10:25 p.m., and did not realize that the agitator had shut down while he was away; no alarms were active at the time to indicate a process abnormality, either.

At 10:33 p.m., with the batch temperature at approximately 455 °F, Employee A pushed the control system's "Batch Done" button to begin cooling the kettle's contents.[e] At this point in the procedure, the Kettle 3 agitator should have been running, but unknown to Employee A, it remained stopped.

At approximately 11:06 p.m., Employee A began adding solvent (VM&P) into the kettle through the spray heads at the top of the kettle (**Figure 1**). According to the solvent flow totalizer data, about 300 gallons[f] of solvent flowed into the kettle at a steady rate over about 26 minutes, from approximately 11:06 p.m. to 11:32 p.m. Control system records showed that the batch temperature measured inside the kettle during this time was about 430 °F, while the temperature of the solvent being added was approximately 70 °F. Employee A finished adding the solvent to Kettle 3, and he waited for the kettle temperature to cool down to less than 325 °F.[g]

Around midnight, about 90 minutes after Employee A pushed the Batch Done button, the kettle temperature was recorded as 424 °F—approximately 100 °F higher than he expected after 90 minutes of cooling.[h] At this time, Employee A began to investigate potential causes for this process abnormality. He looked into the kettle through the glass window of the manway and noticed for the first time that the agitator was off (not turning). He then checked the HMI screens to confirm that it was off. He later told the CSB that he did not know why or when it had turned off; however, knowing that the agitator was supposed to stay on for the duration of a batch, he turned it back on at 12:02 a.m.

While the agitator was off, the solvent and the hot resin were not mixing and remained mostly separated, explained further in *Section 3.1.* When the agitator began mixing the kettle's stagnant layers at 12:02 a.m., the liquid solvent began to vaporize, increasing the pressure inside the kettle from approximately 0 to 4 psig in 15

[a] The night shift started at 7:00 p.m.

[b] Some kettle operators were qualified for multiple kettles, and were assigned a batch, or kettle, for each shift based on the resin plant's production schedule.

[c] The furnace also shut down at this time, because it was programmed to automatically shut down when the agitator shut down.

[d] The CSB was unable to determine the cause of the agitator shutdown. Although not definitively confirmed by the CSB, the temporary power loss to the agitator may have occurred during unrelated concurrent maintenance work in the electrical room.

[e] The cooling water flow did not start, because it was programmed to activate only while the agitator was running.

[f] Kettle 3 could contain up to almost 3,000 gallons of liquid. Based on the kettle's geometry, 300 gallons of liquid would add approximately 9-10 inches to the liquid level inside the kettle.

[g] After the kettle reached this temperature, Employee A's next step would be to transfer the resin to another tank.

[h] Employee A told the CSB that he expected the resin to cool down to 325 °F in approximately 45 minutes to an hour. Since January 2020, the time it took to cool this resin product (time from the start of cooling to the start of pumping) ranged from 55 minutes to one hour and 40 minutes, averaging approximately one hour.

seconds (**Figure 6**). The pressure continued to increase even after triggering the kettle's high-pressure alarm and safety interlock.[a] Two seconds later, when the kettle's pressure reached approximately 9 psig, Kettle 3's closed manway could no longer contain the pressure and began to release a mixture of hot resin liquid and flammable solvent vapor through the sealing surface around its lid into the kettle room (**Figure 7**). At this point, Kettle 3's pressure was still below the rupture disk's marked burst pressure, so it did not relieve Kettle 3's pressure.

Within seconds, the entire room filled with white vapor, obscuring visibility. Employee A was sprayed by the hot, releasing material and could smell what he later identified to the CSB as flammable VM&P naphtha inside the room.

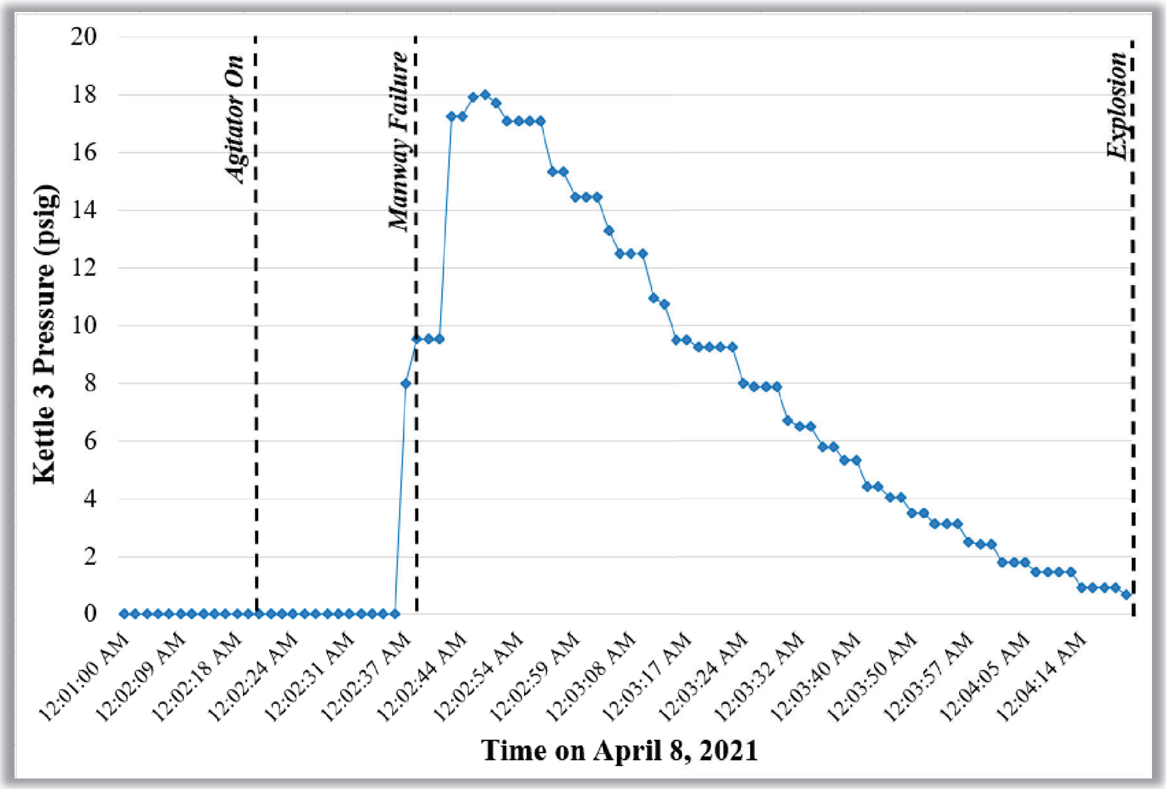

Figure 6. Kettle 3 pressure trend during April 8, 2021, incident. (Credit: CSB)

[a] The safety interlock was designed to shut down the furnace and turn on cooling water to the coils. Since the furnace was already shut down, only the cooling water was activated by this action.

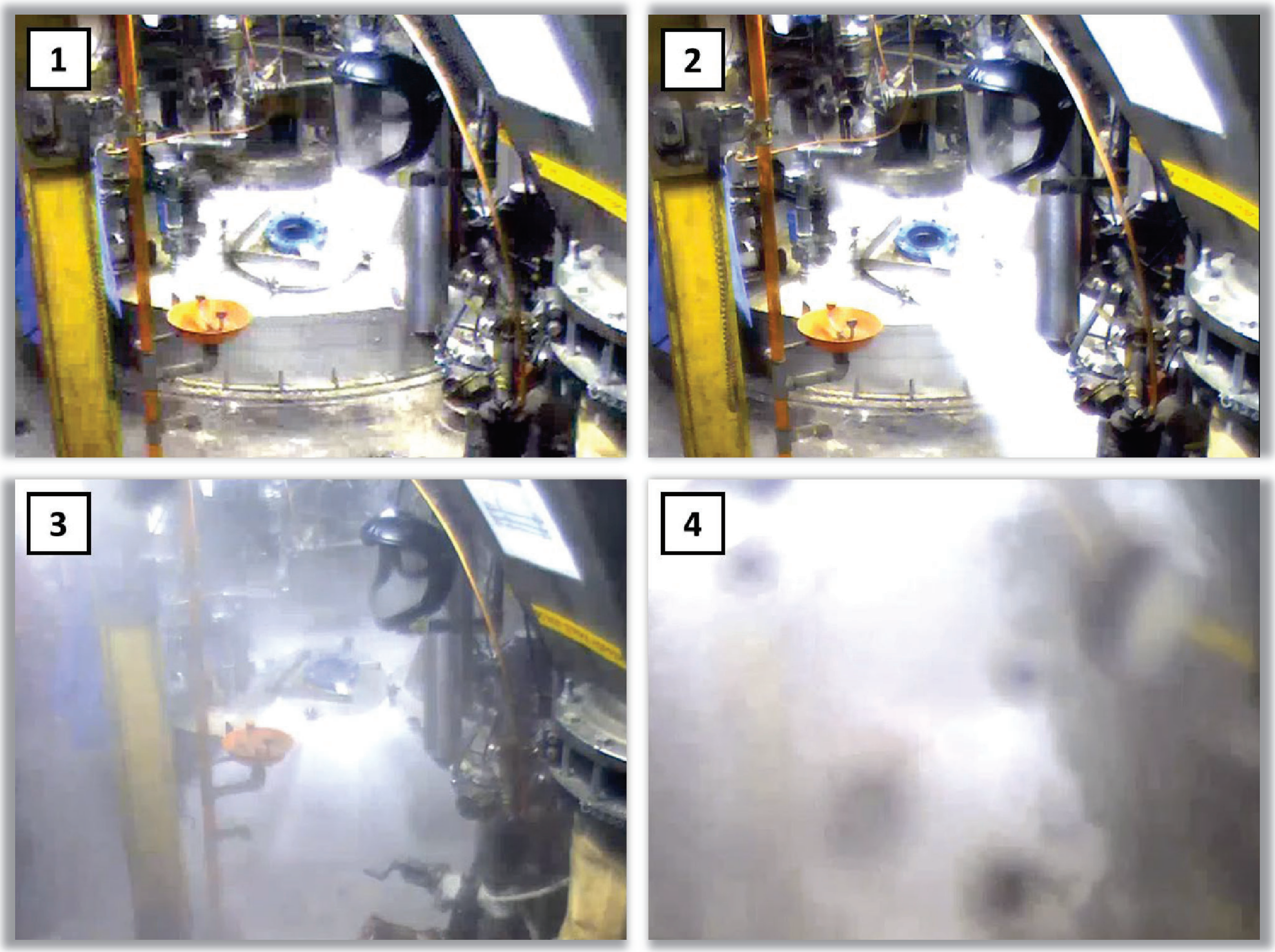

Figure 7. Initial six seconds of the vapor release from Kettle 3. (Credit: Yenkin-Majestic, annotations by CSB)

Employee A informed the CSB that after the flammable release started, he tried to reverse his actions and turn off the agitator, but he could not see through the white vapor and had difficulty breathing. Employee A stated that he tried to hit the emergency-stop button with his eyes closed, but he was not able to reach it. About 20 seconds after the release started, Employee A evacuated from the kettle room.

Employee B, who was in a nearby kettle room, saw Employee A screaming in pain and helped him evacuate from the building. Surveillance cameras show Employees A and B emerging from the resin plant at approximately 12:03:50 a.m., about 80 seconds after the release began, and approximately 30 seconds before the explosion.

The agitator continued stirring the contents of Kettle 3, and the pressure inside the kettle continued to climb until it peaked at 18 psig, according to control system records (**Figure 6**). At this peak pressure, Kettle 3's pressure was above the rupture disk's marked pressure setting but still within its burst tolerance range, and it did not burst to relieve Kettle 3's pressure.[a] Flammable solvent vapor continued leaking from the manway sealing

[a] Based on the Kettle 3 rupture disk's marked burst pressure of 16.5 psig and the manufacturer's burst tolerance of plus or minus 2 psi, the rupture disk's maximum burst pressure could have been as high as 18.5 psig, which was higher than the peak pressure of 18 psig observed during the incident.

surface, and over the next minute after the pressure peak, the kettle's pressure gradually decreased to less than 1 psig.

Surveillance cameras recorded a cloud of flammable solvent vapors moving into adjacent operating areas of the plant. Eventually, the flammable vapor cloud began to flow out of the second floor onto the ground level, where it could be seen from outside of the building. **Figure 8** shows the extent of the ground-hugging flammable vapor cloud pouring out of the west side of the resin plant, just before the vapor cloud exploded at 12:04:23 a.m. The arrow points in the direction of the kettle room where the release occurred on the second floor.

Figure 8. Vapor cloud just before the explosion. (Credit: Yenkin-Majestic)

Multiple flammable gas detectors inside the furnace room on the first floor started detecting an increasing concentration of flammable vapors during the release. The flammable gas detectors triggered automatic furnace shutdowns; however, they were not configured to sound an audible alarm.

Many employees inside or near the resin plant were not aware of the dangerous situation. For instance, at 12:03:30 a.m., an employee saw the white vapor from the outside of the building and began running into the resin plant to investigate what he thought was a steam leak.[a] According to witness accounts, no one used the resin plant's intercom communication system to call for an evacuation or otherwise warn workers of the imminent danger. Post-incident, Yenkin-Majestic also confirmed that the fire alarm system had not been activated to warn workers to evacuate prior to the explosion.[b] Employees working at or near the resin plant that night told CSB investigators that they did not hear any alarms or other warnings before the explosion.

[a] Steam and solvent vapors are typically both white in appearance.

[b] According to Yenkin-Majestic's fire emergency and evacuation plan, the fire alarm system starts a general evacuation alarm if a manual pull station is activated, a water flow is detected, or a smoke detector is set off.

At 12:04 a.m., the released flammable vapors found an ignition source[a] and exploded.[b] Local news outlets reported that the explosion shook nearby homes and was seen, heard, or felt throughout parts of Columbus [9, 10]. The image in **Figure 9** is captured from traffic camera footage approximately two miles away from the resin plant.

Figure 9. Explosion seen from a traffic camera. (Credit: WKYC Channel 3 [10])

The explosion ignited additional flammable material present at the resin plant, resulting in a large fire that was extinguished after approximately 11 hours. More than 100 firefighters responded to the scene, including hazmat teams [9].

Several of the 15 resin plant employees working that night had to evacuate the building by running through flames. Shortly after the explosion, Yenkin-Majestic performed a headcount and determined that three employees were missing. During response efforts on the night of the incident, firefighters rescued two injured employees who were trapped in the collapsed and unstable resin plant building, and eight injured employees were transported to area hospitals. The injured employees sustained trauma associated with the explosion and building collapse such as limb fractures, with one employee requiring a leg amputation after he was crushed under collapsed debris. Four of the injured employees were burned by the fire, two of whom received third-degree burns. The fire department continued the search for the final missing employee in daylight using

[a] The CSB was unable to determine the ignition source.

[b] In the book *What Went Wrong? Case Histories of Process Plant Disasters and How They Could Have Been Avoided*, Trevor Kletz explains "the inevitability of ignition" once a vapor cloud forms, because "the amount of energy required to ignite a flammable mixture can be very small (again, on the order of 0.2-mJ spark energy for most hydrocarbons)" [56, p. 452]. The book concludes: "Mixtures of flammable gas or vapor and air in the explosive range are likely to ignite and explode even though we try to remove all sources of ignition. The probability of ignition is so high that designers and operators should assume that it is inevitable and design and operate accordingly" [56, p. 454].

surveillance drones. The employee was found fatally injured (from thermal injuries and inhalation of products of combustion) and partially covered by rubble inside the second floor of the resin plant.

The incident damaged buildings on the Yenkin-Majestic site and caused a fire in a commercial property adjacent to the site. Yenkin-Majestic has estimated its total property damage from the accident at over $90 million. The resin plant was severely damaged, and Yenkin-Majestic demolished it over a 19-month period after the incident. Reports from neighbors indicated that the blast also shook neighboring buildings [11, 12].

The Ohio EPA responded to the incident and identified that some of the firefighting water runoff had entered the nearby Alum Creek. Within a few hours of the incident, responders vacuumed runoff into tankers and installed booms in the area and at the inlets of other nearby storm drains to contain the release. Yenkin-Majestic also conducted air monitoring around the perimeter of the facility and developed a waste recovery and remediation plan. The Ohio EPA reported that it observed offsite impacts through at least April 11, 2021. Neither the Ohio EPA nor Federal EPA have issued any citations or fines to Yenkin-Majestic related to the incident. Additionally, community members requested an air quality study in the surrounding neighborhood, funding for which the Columbus City Council approved more than two years after the incident [13]. The air quality study is anticipated to continue through at least 2024 [14].

3 TECHNICAL ANALYSIS

3.1 RAPID PRESSURE INCREASE

On the night of the incident, Kettle 3's pressure began to increase rapidly seconds after the kettle operator turned on the agitator. At the time just before the agitator was turned on, the kettle contained two layers of liquid that significantly differed in density, viscosity, boiling point, and temperature, which impeded their ability to mix (stratification) until the agitator started. Density and viscosity differences between two liquids can significantly affect their ability to mix without agitation. According to one source:

> The mixing of miscible liquids with very different physical properties is a common operation in many chemical and food process industries. [...] The two fluids are fully miscible, but the effects of viscous and buoyancy forces must be overcome by the inertial forces generated by the impeller, for homogenisation to take place. When the two fluids have large differences in density and viscosity, very long mixing times can result [15].

According to Yenkin-Majestic's standard operating procedures, proper agitation (or mixing) was required to mix all ingredients and distribute heat optimally inside the kettle.

Since the 1960s, there have been several notable chemical disasters that were precipitated by starting an agitator in a stratified vessel [16, 17, p. 168, 18].[a] In August 2018, the Center for Chemical Process Safety (CCPS) published a safety bulletin titled, *"What if your agitator fails?"* which summarized a 1993 incident and warned against re-starting an agitator without technical assistance [18]. Many of these incidents occurred when at least two chemicals mixed and reacted suddenly, leading to rapid heat and pressure generation. In the case of this incident, it was not a rapid chemical reaction but rather the sudden vaporization of solvent (a phase change from liquid to vapor) that caused a rapid pressure increase inside Kettle 3. Yenkin-Majestic had experienced similar solvent vaporization incidents, but they were on a much smaller scale, typically when blending hot resin with solvent in agitated tanks.

Kettle operators were given the option as a standard practice to either add the solvent through the spray heads at the top of the kettle, or through a submerged line near the bottom of the kettle. On the night of the incident, Employee A added all of the solvent through the spray heads.

The resin inside Kettle 3 was approximately 30% more dense and more than 1000 times more viscous than the solvent added through the top of the kettle. The difference in density and viscosity between the two liquids allowed the solvent to float on top. In addition, the resin, at a temperature of approximately 424 °F around the time of the incident, was significantly above the solvent's boiling point of approximately 290 °F. When a liquid is poured on a hot surface significantly above its boiling point, vapor generated from the rapidly boiling liquid can sometimes form a layer of gas at the interface, insulating the rest of the liquid from the hot surface [19]. This phenomenon, called the Leidenfrost effect or film boiling, could have further contributed to the segregation

[a] A study of 189 industrial batch reactor incidents between 1962 and 1987 attributed 6 of these incidents to "operator either failed to switch on agitator or switched it on too late, the [net] result was en-mass reaction" [16, p. 7].

of the solvent being added at a temperature of 70 °F to the top of the kettle, from the rest of the hot resin at the bottom of Kettle 3, until the agitator was restarted.[a]

Employee A had several options to re-establish agitation inside Kettle 3, as discussed further in *Section 4.2.2*. Once the agitator restarted and could not be subsequently stopped, all of the approximately 300 gallons of solvent quickly vaporized, initiating the rapid pressure increase inside the kettle.[b,c]

The CSB concludes that after Kettle 3's agitator stopped during a routine resin batch production operation, solvent added into the kettle on top of hot resin did not mix with the resin due to differences in the two liquids' physical properties. When Kettle 3's agitator was later started and could not be subsequently stopped, the bulk of the solvent mixed with the hot resin and vaporized, causing a rapid pressure increase inside Kettle 3.

3.2 Release from Manway

Based on surveillance camera footage provided to the CSB by Yenkin-Majestic, the flammable solvent and resin mixture was released through the sealing surface of the newly installed manway on Kettle 3 as pressure increased (**Figure 7**). Process records around the time of the release indicate that Kettle 3's pressure was approximately 9 psig when the release began.

Figure 10 and **Figure 11** show the new manway before and after the incident. The manway's lid was attached to the kettle with a single vertical hinge and could pivot open. A sight glass on the lid allowed operators to see inside the kettle. Four swing bolts tightened down the 3/8-inch thick lid onto a gasket[d] on the kettle's 20-inch nozzle opening.

[a] There appeared to be some solvent vaporization while the kettle operator added solvent to Kettle 3, not knowing at the time that the agitator was stopped. He recalled, "Pressure was low. I mean it didn't even go above 1 psi whenever I was adding solvent. So everything seemed perfectly normal."

[b] Kettle 3 could contain up to almost 3,000 gallons. The amount of each component is estimated at 2000 gallons of resin and 300 gallons of solvent inside Kettle 3 on the night of the incident based on the weight and density information available. Based on the kettle's geometry, 300 gallons of liquid would add approximately 9-10 inches on top of the liquid level inside the kettle. If completely vaporized, 300 gallons of solvent would expand to approximately 6280 cubic feet at atmospheric pressure, which is almost 50 times the volume that remained inside Kettle 3.

[c] Kettle 3 was connected with piping to auxiliary equipment, including a condenser that had an atmospheric vent, which likely relieved some of the pressure building up in the system.

[d] According to Yenkin-Majestic employees, the gasket between the manway's sealing surfaces at the time of the incident was a 1/2-inch-thick gasket that Yenkin-Majestic had cut from a large sheet. Yenkin-Majestic employees also indicated that a spare gasket of the same material had been cut so a replacement would be readily available if needed. While the spare gasket for the manway was retained, no gasket material from Kettle 3 itself could be recovered post-incident due to fire damage.

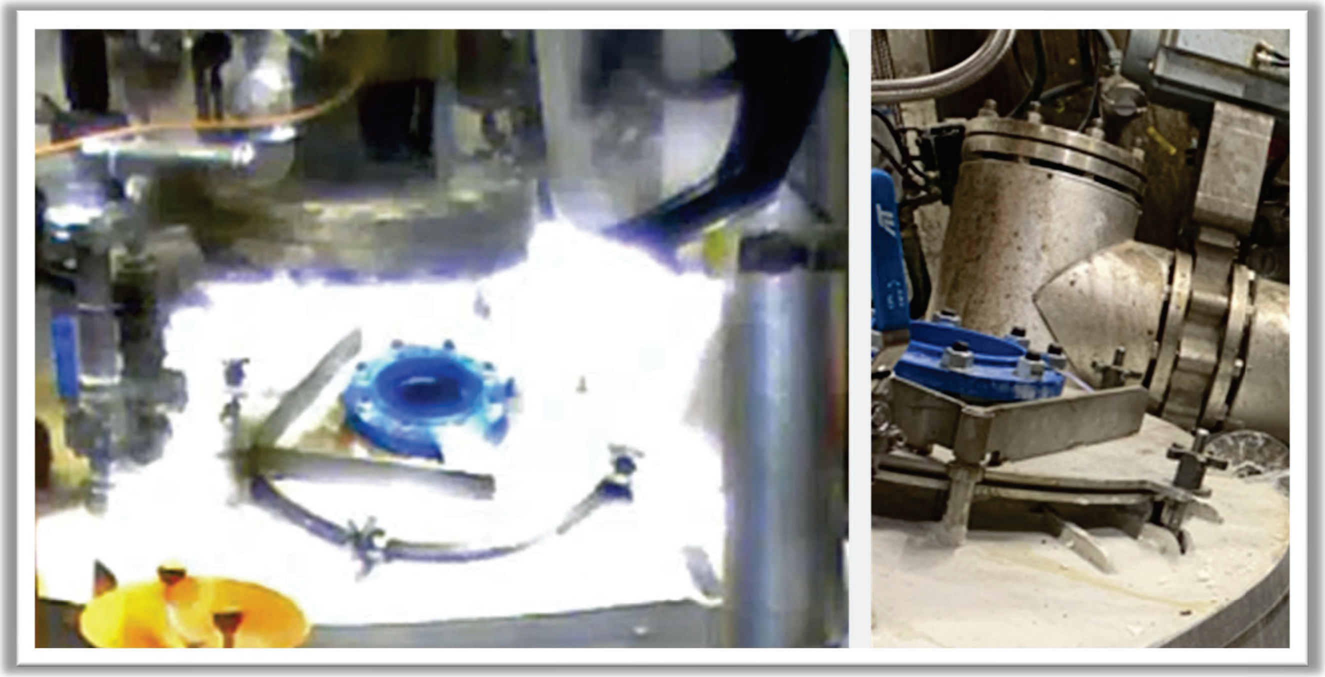

Figure 10. Photos of the new manway during normal operation. (Credit: Yenkin-Majestic)

Figure 11. Photos of the new manway after the incident (closed, *left*; open, *right*). (Credit: Rimkus, with annotations by CSB)

Post-incident, the CSB commissioned an engineering evaluation of the manway's mechanical design. Prior to the incident, Yenkin-Majestic had provided the companies designing the new manway with a design pressure of 16 psig, with the assumption that Kettle 3's rupture disk was set to a marked burst pressure less than 15 psig (discussed further in *Section 4.1.1*). The CSB therefore requested evaluations of whether the manway could withstand 16 psig as Yenkin-Majestic had specified. The consultant evaluated several cases to model the manway's geometry and calculate its possible maximum allowable working pressure (MAWP)[a] based on its design.[b] The consultant concluded:

> None of the [modeled] cases were found to achieve a MAWP of 16 psig. The most likely [case scenario] is seen to [provide a MAWP of] 0.82 to 1.28 psig [...] with [another modeled case] providing a range of 3.27 to 5.11 psig.

The CSB also requested an analysis of the design scenario required for the manway to have a MAWP of 16 psig. The consultant provided the following conclusions:

> For the requested design case, an 8-bolt (0.750-in diameter) design was evaluated [...] at 16 psig MAWP and at 500 F. The required thicknesses [of the lid] for the loose flange, integral flange, and flat cover (blind flange) are 1.75", 1.625", and 0.875", respectively.

In summary, the CSB's consultant estimated that a manway lid design with eight bolts and a thickness of at least 0.875 inches could achieve an MAWP of 16 psig. In contrast, Kettle 3's manway lid was designed with four bolts and a thickness of 0.375 inches.

The CSB concludes that Kettle 3's new manway was not designed to a maximum allowable working pressure (MAWP) of 16 psig as Yenkin-Majestic had specified. At best, it could have been rated for a MAWP of approximately 5 psig. As a result, the manway's sealing surface began to release flammable material when the kettle's pressure reached and exceeded 9 psig during a high-pressure event. Had the new Kettle 3 manway assembly been designed to withstand Kettle 3's internal vessel pressure during the incident, the flammable vapor cloud and explosion could have been prevented.

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[a] The ASME Boiler and Pressure Vessel Code, Section VIII provides the calculations for determining the MAWP of a pressure vessel [22, p. 473], as MAWP is determined from the physical characteristics of the vessel design and construction at the required temperature. During process operations, "[o]nce in service, the vessel can be operated at any pressure up to MAWP without violating any safety limits" [61, p. 34], and the "[p]ressure vessel must always operate at a pressure lower" than the calculated MAWP [61, p. 33]. Because "vessel[s] should be checked and recertified" if the MAWP is exceeded during operations, "[g]enerally, emergency systems such as interlocks and pressure relief valves will be set at a value just below MAWP" [61, p. 34].

[b] The calculations were based off of the ASME Boiler and Pressure Vessel Code, Section VIII, Division 1 Mandatory Appendix 2: *Rules for Bolted Flange Connections with Ring Type Gaskets* [22, p. 378].

4 SAFETY ISSUES

The following sections discuss the safety issues contributing to the incident, which include:

- Mechanical Integrity of Low-Pressure Vessels (Section 4.1);
- Safeguard Selection and the Hierarchy of Controls (Section 4.2); and
- Emergency Preparedness (Section 4.3).

4.1 MECHANICAL INTEGRITY OF LOW-PRESSURE VESSELS

Design, construction, and maintenance guidance for pressure vessels is available through safety codes and standards such as the ASME Boiler and Pressure Vessel Code (BPVC), the National Board Inspection Code (NBIC), and the American Petroleum Institute's (API) 510, *Pressure Vessel Inspection Code* [20, 21, 22]. These codes and standards are discussed in *Section 4.1.2.2* of this report. Typically, pressure vessels that do not exceed 15 psig are exempted from these codes. In the United States, 38 states adopt these safety codes in their pressure vessel regulations.[a] Ohio, the authority having jurisdiction where Yenkin-Majestic operated, has adopted the BPVC and the NBIC[b] for pressure vessels. In this report, the CSB distinguishes pressure vessels that are subject to the code requirements as "code pressure vessels."

4.1.1 KETTLE 3 OPERATION TIMELINE

Yenkin-Majestic's Derating of Kettle 3

When Kettle 3 was built in 1961, it was designed and stamped as a code pressure vessel with a maximum allowable working pressure (MAWP) of 40 psig, and registered with the National Board of Boiler and Pressure Vessel Inspectors (NBBI). By the time of the 2021 incident, however, Yenkin-Majestic had made a number of non-code alterations to Kettle 3 and no longer maintained Kettle 3 as a code pressure vessel.[c] Since Yenkin-Majestic had not maintained Kettle 3 in accordance with the pressure vessel codes, its original design limits and stamped MAWP of 40 psig were no longer valid. This issue was first documented by an engineering firm that

[a] According to one source, approximately 115 countries recognize the ASME and NBBI pressure vessel codes [57].

[b] While the NBIC does not exempt pressure vessels not exceeding 15 psig, Ohio determines NBIC applicability for repairs and alterations based on the scope of the ASME Boiler and Pressure Vessel Code, which exempts vessels with an internal pressure not exceeding 15 psig.

[c] For example, according to the original drawing from 1961, Kettle 3 was originally designed to be heated with a steam jacket and did not have cooling coils. Yenkin-Majestic installed a furnace underneath the kettle around 1972-1974, and installed the cooling coils inside the kettle in 1997. Yenkin-Majestic stated that following a major Kettle 3 project in 1997, the manufacturer's original nameplate was removed in an effort to de-rate the kettle and lower its MAWP. Yenkin-Majestic did not have documentation of this change. NBBI had received no R-2 forms (report of alteration) from Yenkin-Majestic or any contractor over the life of Kettle 3 to document that these alterations were made according to the BPVC and NBIC.

completed a relief study for Kettle 3 in 2013. At the time of the evaluation, the rupture disk's marked burst pressure was documented as 15.4 psig.[a] The engineering firm recommended:

> DISCUSSION – The presently-installed 8" rupture disk offers suitable relieving area for all scenarios examined. The disk, however, is not rated for vacuum and the kettle cannot be assumed to be rated for full vacuum service due to non-code revisions to its structure. Additionally, for similar reasons, the kettle cannot be assumed to be safely operable at the estimated MAWP, and must be viewed as a non-code vessel and limited in its rating to less than 1 atm [14.7 psig] MAWP.[b]
>
> RECOMMENDATION – It would be prudent to replace the existing rupture disk with one suitable for service in both pressure and vacuum relief. Alternatively, it may be simpler to add a second rupture disk to handle the vacuum relief. Additionally, decreasing the set burst pressure to below 15 psig will avoid the need to reclassify the kettle as a pressure vessel.

Yenkin-Majestic elected to keep Kettle 3 as a non-code vessel and documented that the rupture disk burst pressure was less than 15 psig after the 2013 relief study (**Table 2**).

Table 2. Yenkin-Majestic's history of Kettle 3's rupture disk setpoint documentation.

Year	Document	Kettle 3 Rupture Disk Burst Pressure
1994	Kettle Operators' Training Manual	25 psig at 72 °F 21 psig at 500 °F
2009	Standard Operating Procedure	14 psig at 500 °F
2013	Relief Study	15.4 psig
2014	Operating Parameters table	14 psig maximum
2019	Operating Parameters table	13.5 – 15 psig
--	General Kettle Operator Validation Workbook	Approximately 14 psi

In 2018, a third-party PSM compliance auditor also noted the discrepancy of Kettle 3's only documented yet obsolete MAWP of 40 psig due to its non-code inspection and alteration history:

> The PSI [process safety information] for Kettles 3 and 5 list the design pressures for these vessels as 40 psig and 50 psig, respectively; however, the vessels have not been maintained and inspected as pressure vessels.

The auditors recommended "derating Kettles 3 and 5 to atmospheric vessels and updating the PSI accordingly." Yenkin-Majestic reached out to two Ohio-based industrial construction companies that are qualified to work on code pressure vessels, seeking guidance on how to de-rate pressure vessels. One of the construction companies

[a] In its final report, the engineering firm documented Kettle 3's MAWP as 15 psig and its rupture disk set pressure as 15.4 psig, noting: "Values are estimated based on limited data for the purposes of recommending setpoints and should not be construed as final or as-rated."

[b] 1 atm (standard atmosphere) converts to 14.7 psig.

responded, and Yenkin-Majestic noted information on the company's guidance in Yenkin-Majestic's PSM audit action tracker:

> They said standard practice was to remove the name plate which lists the rated pressure. We have done that to both of these kettles, but that did not satisfy the auditors [...]. They suggested putting a note in our files stating that they were no longer rated.

In 2019, Yenkin-Majestic resolved the PSM compliance audit finding by adding a letter with the following statement to the Kettle 3 equipment file and the maintenance files:

> The vessel Kettle 3 has been modified from its original design and not tested to confirm compliance with the original pressure ratings. As a result this vessel should be considered de-rated,[a] operating at atmospheric conditions.

In scientific terms, atmospheric conditions typically refer to the pressure of ambient air, or approximately 0 psig [23]. In practical terms, OSHA and the Center for Chemical Process Safety define an atmospheric storage tank as a storage tank designed to operate at pressures between ambient (atmospheric) pressure and 0.5 psig [24]. Although Kettle 3 typically operated at less than 1 psig during normal operation and with non-condensable vents that were open to the atmosphere, these vents did not prevent the system from building pressure during some upset conditions, as Yenkin-Majestic had documented numerous times in PHAs and incident investigation reports (discussed further in *Section 4.1.2.1*).

At the time of the incident, Yenkin-Majestic had documented that Kettle 3's rupture disk set burst pressure was between 13.5 to 15 psig. Post-incident, however it was discovered that despite the documentation, Yenkin-Majestic actually had installed a rupture disk with a set burst pressure of 16.5 psig. The CSB found that Yenkin-Majestic had continued to order rupture disks with burst pressures of up to 17 psig since 1997.[b] The CSB did not find management of change documentation for Kettle 3 operating parameter and rupture disk setpoint changes within the ten years prior to the April 2021 incident.

[a] There is currently no clear industry guidance on how to de-rate a code pressure vessel—for example, to stop maintaining it at its original rated MAWP as a code pressure vessel but continue to operate it under 15 psig. For re-rating a code pressure vessel (changing its design pressure or MAWP), the NBIC requires activities such as preparing calculations according to construction standards, testing to ensure the structural integrity of the pressure retaining item, and approval by the Jurisdiction. Ohio is one of 38 states that has regulatory coverage of pressure vessels. Out of these 38 states, 10 of them, including Ohio, currently require a code pressure vessel re-rating to go through the NBIC alteration process. De-rating a vessel to a lower MAWP is outside of NBIC scope, however, deferring to the jurisdiction where the object is installed to determine if specific procedures should be followed [21, p. 74]. Ohio does not provide specific guidance on how to de-rate a code pressure vessel.

[b] Yenkin-Majestic's PSI documents indicate various changes to Kettle 3's rupture disk set burst pressure specification over time, and at the time of the incident was documented as 13.5-15 psig. Yet, Yenkin-Majestic had not updated its Kettle 3 rupture disk purchase order specifications since 1997, as it cumulatively ordered 47 rupture disks with a manufacturing design range (MDR) of 15.3-17 psig at various times from 1997 through 2019. In addition, the responsibility for keeping rupture disks stocked had shifted over from the engineering department to the maintenance department around 2013. According to supplier records, of the 48 rupture disks Yenkin-Majestic purchased for Kettle 3 from 1997 through 2019, only one was rated to less than 15 psig. After the incident, the CSB recovered only two 8-inch spare rupture disks (the size only used by Kettle 3) from the maintenance shop. One of these was rated for 13.8 psig at 248 °F and the other was rated for 16.5 psig at 500 °F.

Manway Addition to Kettle 3

In 2020, Yenkin-Majestic implemented an automation project, in which it commissioned the design and installation of a permanent connection from the raw material-addition hopper to the existing (original) manway on Kettle 3. This project, part of a multi-year automation project, reduced manual operation steps during regular kettle operations, allowing material to instead be added from the hopper using automated controls. The new permanent connection from the hopper to Kettle 3 eliminated access to the original manway, so Yenkin-Majestic hired two companies to design and install a new manway for personnel access to Kettle 3. The original manway was rated to 50 psig.

At the time of the automation project and the addition of the new manway, Yenkin-Majestic had documented Kettle 3's maximum operating pressure to be 12 psig, with a rupture disk setpoint within a "range" of "13.5 – 15 psig" (**Figure 12**). With the documentation changes described above in *Section 4.1.1*, and the documented rupture disk setpoint at or below 15 psig, Yenkin-Majestic considered Kettle 3 not to be a code pressure vessel, and as such not covered by the requirements specified in the ASME BPVC and API 510 *Pressure Vessel Inspection Code* (which, as described in *Section 4.1.2.2*, exempt vessels not exceeding 15 psig).

Operating Parameters Kettle 3		
Material of Construction		316 Stainless Steel
Capacity	Plastic basis	18,000 Lbs
	With cooling solvent	20,900 Lbs
Agitation	Minimum Level for Resin*	5,000 Lbs
	Minimum Level for Reflux	550 gals
	Normal Agitator Speed During Batch	70 RPM
	Seal Pressure	25 - 55 psig
Coil Material of Construction		316 Stainless Steel
Coil Coverage	Half Coverage*	8,470 Lbs
	Full Coverage*	14,630 Lbs
Temperature	Maximum	500 F
	Minimum	32 F
Pressure Switch	Alarm	4 psig
Maximum Operating Pressure	Maximum	12 psig
Rupture Disk	Range	13.5 - 15 psig

Figure 12. Kettle 3 operating parameters. (Credit: Yenkin-Majestic)

Yenkin-Majestic supplied the two companies it hired to design and install a new manway onto Kettle 3 with operating parameters to consider during the manway design. Yenkin-Majestic initially communicated that "the worst case that the tank could see [is] 16 [psig]." When one of the contractors asked, "Should this tank see 16 [psig], are we now dealing with a pressure vessel[?]", one Yenkin-Majestic employee replied as follows:

> Just to be clear we operate the vessel under the following conditions:
>
> 1. Normal operation: 0-2 [psig]
>
> 2. High pressure alarm (safety interlock that automatically shuts equipment down): 4 [psig]

> 3. Rupture disk emergency pressure relief (in case something goes wrong and the kettle rapidly pressurizes): ~16 [psig]
>
> Correct me if I'm wrong but installing a manway capable of withstanding 16 [psig] wouldn't make this a pressure vessel. Wouldn't we have to actually operate at that pressure?

The contract companies, who were not R-Stamp holders, then deferred to Yenkin-Majestic's interpretation of pressure vessel code non-applicability to Kettle 3.

To construct the manway, the fabricator cut a 20-inch hole on the top head of Kettle 3, welded on a nozzle, and attached a lid that closed down onto a gasket to seal the assembly. There is no evidence of design calculations for determining lid design parameters to ensure that the flange, gasket, and lid design assembly met the requirements of the purchase specification—most importantly, the specified pressure of 16 psig.[a] Yenkin-Majestic completed a management of change form and a pre-startup safety review for the new installation in conformance with the company's internal management of change process requirements.

Yenkin-Majestic returned Kettle 3 to service on the night shift of January 3, 2021 (three months before the April 8, 2021 incident). At this point, Yenkin-Majestic had not tested the integrity of the manway lid and gasket assembly to ensure it could hold pressure up to the rupture disk's setpoint.[b] The new manway began to leak soon after Kettle 3 began processing its first batch upon startup.[c] Yenkin-Majestic immediately shut down Kettle 3 and took it out of service for repair. The night shift maintenance crew replaced the manway's gasket with different material and attempted to tighten it with a clamp, but could not achieve a good seal. "When that thing was tightened down, it would bow in the middle," a Yenkin-Majestic employee explained (**Figure 13**). "We felt like it needed more structure," another employee later recalled. Unable to seal the manway, Yenkin-Majestic kept Kettle 3 shut down to resolve the issue on the day shift.

[a] One of the two assisting companies, a civil engineering company, evaluated the tensile stresses around the proposed new 20-inch opening to ensure that adding this new opening would not deform Kettle 3. The company concluded that the new opening could withstand 4 psi but would require reinforcement stiffeners to withstand 16 psi. The fabricator incorporated the stiffeners into its drawings and construction (**Figure 10**). There were no other calculations performed for other aspects of the manway assembly, such as flange thickness, gasket design, or the number of bolts used to secure the lid.

[b] An inspection company that Yenkin-Majestic routinely used for its pressure vessels performed dye penetrant testing on the welds around the new nozzle; however, this method was not suitable for providing meaningful results to verify the integrity of the manway gasket and lid.

[c] Post-incident, OSHA cited Yenkin-Majestic for not initiating an incident investigation related to the leak event during the initial startup on January 3, 2021 [26, p. 58].

Figure 13. Bowing on the new manway lid in January 2021. (Credit: Yenkin-Majestic)

The next morning, Yenkin-Majestic installed a thicker gasket,[a] checked for leaks around the gasket while Kettle 3 was pressurized up to 4 psig with nitrogen, and concluded that the manway was not leaking.[b] Satisfied with the leak check results, Yenkin-Majestic returned Kettle 3 to service on January 4, 2021.

After the new manway was initially leak-checked to 4 psig on January 4, 2021, Yenkin-Majestic instructed operators not to open the manway without engineering being consulted, developed a contingency plan to add material through other means (such as the hopper and small addition funnel) so that the manway would not need to be opened during kettle operations, and prepared a spare gasket in case maintenance needed to open the manway and the existing gasket needed to be replaced.

On Sunday, January 17, 2021, an operator entered a work order to clean the Kettle 3 manway sight glass because he could not see inside the kettle. Maintenance workers opened the manway, cleaned the sight glass from the inside, replaced the gasket, and closed the manway. There is no record of Yenkin-Majestic leak-checking the Kettle 3 manway as had been done during the previous gasket installation.

[a] A Yenkin-Majestic employee explained, “Normally it’s a thin gasket, but the one they put in there, that’s a half-inch thick. That is massive,” adding that normally they use 1/8-inch thick gaskets.

[b] To perform the leak check, Yenkin-Majestic closed all the valves on top of Kettle 3, pressured up the kettle with nitrogen until it reached 4 psig, then used a detergent-like material to detect leaks around the manway gasket. According to one employee, testing kettles in this manner was not a typical practice at Yenkin-Majestic. Yenkin-Majestic did not document the leak check.

Yenkin-Majestic performed three monthly routine preventive maintenance external inspections of Kettle 3 in February, March, and April prior to the April 8, 2021, incident. None of the three separate Yenkin-Majestic maintenance technicians who performed these inspections, which included visual inspections for flange leaks, noted any abnormalities with Kettle 3.

Kettle 3 continued to operate, producing over 100 batches of resin over the course of approximately three months after the new manway was installed and leak-checked on January 4, 2021, without subsequent reports of leaks until the new manway leaked during the incident on April 8, 2021, when Kettle 3 reached an internal pressure of 9 psig.

4.1.2 Analysis of Mechanical Integrity Gaps Applicable to Kettle 3

Two issues complicate the analysis of the mechanical integrity concerns identified in this incident:

1. Yenkin-Majestic actively took efforts to de-rate Kettle 3 such that it would be exempted from pressure vessel code requirements. According to Yenkin-Majestic's PSI for Kettle 3, Kettle 3 was not a code pressure vessel, and documentation indicates it had a rupture disk setpoint of 13.5 - 15 psig, which is below the value triggering applicability of pressure vessel code requirements; and

2. After the incident, it was discovered that Kettle 3's rupture disk had a setpoint of 16.5 psig—a pressure that would bring Kettle 3 within the scope of pressure vessel codes as its internal pressure could exceed 15 psig.[a] According to purchase records, Yenkin-Majestic had been ordering rupture disks whose marked burst pressure fell within a manufacturing design range (MDR) of 15.3-17 psig for Kettle 3.[b]

Yenkin-Majestic did not conform to pressure vessel safety requirements, as the rupture disk setpoint was 16.5 psig and Yenkin-Majestic did not perform code-required actions to ensure the integrity of the manway. However Yenkin-Majestic had concluded that Kettle 3 could not reach pressures exceeding 15 psig and therefore was not covered by pressure vessel code requirements. While Yenkin-Majestic certainly could have taken action to voluntarily follow the guidance presented in the ASME BPVC, NBIC, and API 510 that could have prevented the incident, Yenkin-Majestic did not do so. This incident clearly demonstrates that not everyone volunteers to follow standards they are exempted from, and clearly reveals the issues presented by the absence of safety guidance for vessels not exceeding 15 psig. As described below, the CSB determined that improved industry guidance detailing methods to ensure the integrity of process vessels not exceeding 15 psig could have prevented this incident and could help prevent future incidents.

[a] OSHA cited Yenkin-Majestic for not applying pressure vessel codes to Kettle 3 due to its potential to exceed 15 psig of internal pressure [26, p. 65].

[b] When a single pressure relief device is used on a vessel, both the BPVC and NBIC prohibit the set pressure marked on the device from exceeding the maximum allowable working pressure of the vessel [22, p. 95, 69, p. 18].

4.1.2.1 Mechanical Integrity Element of PSM Regulation

Mechanical integrity is an important element of a process safety management program in facilities in highly hazardous chemicals service to ensure that these hazardous chemicals are safely contained within the equipment. For example, OSHA requires PSM-covered facilities to have a mechanical integrity program to manage critical process equipment, to ensure it is designed and installed correctly, and that it is operated and maintained properly. Mechanical integrity requirements include:[a]

- establishing and implementing written procedures to maintain the integrity of process equipment;
- assuring that new equipment fabricated is suitable for the process application, is installed properly, and is consistent with design specifications; and
- correcting deficiencies in equipment that are outside acceptable limits before further use.

As described in this section, Yenkin-Majestic's process safety management program, specifically the mechanical integrity component of the program, failed to prevent this incident. For example, Yenkin-Majestic's mechanical integrity program did not properly address how to ensure the integrity of Kettle 3's new manway.

To help make clear to companies what actions they should take to ensure the safety of their equipment and processes, industry codes and standards have been developed to, for example, provide specific guidance on vessel integrity. With no specific industry code or standard that Yenkin-Majestic believed was applicable to Kettle 3, Yenkin-Majestic did not follow published industry safety guidance to ensure the integrity of Kettle 3. The result was a poorly designed mechanical integrity program for Kettle 3 that ultimately led to this incident.

Manway Installation and Testing

The new manway, as it was first commissioned on January 3, 2021, was not tested to confirm its ability to contain pressure. After passing a leak check up to 4 psig, Yenkin-Majestic believed that the new manway was acceptable for normal operation and returned Kettle 3 to service. The CSB determined that Yenkin-Majestic's testing was not adequate for assuring that the new manway's safe operation across the known range of pressures that Kettle 3 could experience, since it was only tested to a low pressure far below the kettle's rupture disk burst pressure setting. OSHA requires the following for equipment deficiencies:

> The employer shall correct deficiencies in equipment that are outside acceptable limits (defined by the process safety information [...]) before further use or in a safe and timely manner when necessary means are taken to assure safe operation.[b]

OSHA requires PSM-covered facilities to document process safety information (PSI) that includes "safe upper and lower limits for such items as temperatures, pressures, flows or compositions" and "relief system design and design basis."[c] The CCPS describes the "zones of operation" concept to describe how to determine safe

[a] 29 CFR § 1910.119(j).
[b] 29 CFR § 1910.119(j)(5)
[c] 29 CFR § 1910.119(d)

operating limits for process equipment (**Figure 14**) [17, pp. 135-136]. The CCPS asserts that "[safe operating limits] are determined by identifying design limits of equipment within a system" [17, p. 136] and that the safe operating limits should be documented in plant PSI with a technical basis for each limit.

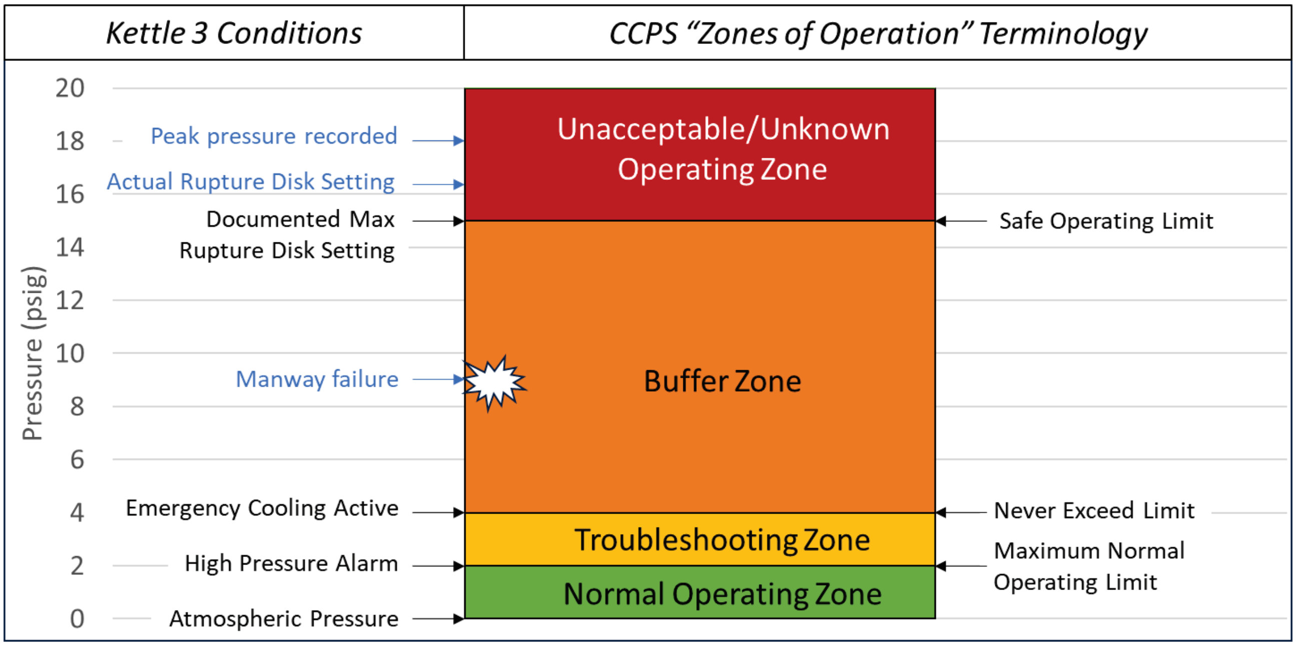

Figure 14. Kettle 3 zones of operation. (Credit: CSB with source material from CCPS [17])

Figure 14 is adapted from the CCPS "zones of operation" diagram to describe how Kettle 3's operating parameters corresponded to the CCPS-defined terminology based on Yenkin-Majestic's documentation. The black text describes Yenkin-Majestic's process safety information for Kettle 3, and the blue text shows actual corresponding pressure recorded on the day of the incident. Although Kettle 3 typically operated at atmospheric pressure, Yenkin-Majestic had configured it with a high-pressure alarm at 2 psig, as well as an emergency cooling interlock and alarm at 4 psig, and had documented that it had a pressure relief device (the rupture disk) set to burst between 13.5 and 15 psig. The incident occurred in what the CCPS describes as a "buffer zone," which should have been Kettle 3's safe operating zone between the emergency cooling interlock activation pressure (4 psig) and the maximum documented rupture disk burst pressure (15 psig).[a]

Kettle 3 had operated for approximately 60 years prior to the new manway project, and Yenkin-Majestic had investigated a number of rupture disk burst events throughout Kettle 3's history.[b] None of the rupture disk burst investigation reports provided to the CSB (all prior to 2021) mentioned leaks from the original manway, which had been rated to an MAWP of 50 psig. High pressure in the kettles was also a hazard that Yenkin-Majestic studied in multiple process hazard analyses (PHAs), most recently in 2015 and in 2020. The 2015 PHA team evaluated numerous potential overpressure scenarios for the kettles, including generic potential scenarios such as "build pressure." A Yenkin-Majestic employee who participated in this PHA told the CSB that when the PHA

[a] Post-incident, OSHA cited Yenkin-Majestic for "failing to compile [...] accurate safe upper and lower limits (pressure) for the technology of the process" [26, p. 7].

[b] For example, according to a Kettle 3 rupture disk burst investigation report from 2015, during a process upset, Kettle 3's pressure increased from 2 psi to 3 psi in about one minute, and then from 3 psi to 13.1 psi in the next minute, until the rupture disk burst and relieved the pressure.

team identified overpressure scenarios, "we said that the equipment on the kettle was all rated for a higher pressure than the rupture disk." In many of these scenarios involving high pressure in a kettle, the PHA team noted, "The team concludes that there are adequate safeguards in place and there are no recommendations at this time." For this statement to have been true for Kettle 3, Yenkin-Majestic should have assured the integrity of the new manway by demonstrating its ability to hold pressure up to the vessel's upper safe limit and at least up to its rupture disk's burst pressure setting.

The CSB concludes that Yenkin-Majestic returned Kettle 3 to service without adequately testing the new manway to ensure that it was installed properly and could hold pressure at least to its rupture disk's burst pressure setting. Kettle 3's operational history, process hazard analysis, and process safety information suggested that Kettle 3 could experience pressure up to the rupture disk's burst pressure setting during some upset conditions, documented as a maximum of 15 psig. Nevertheless, Yenkin-Majestic operated Kettle 3 for the three months preceding the April 8, 2021, incident with a manway that was only leak-checked up to 4 psig. Although the manway did not appear to leak during the 4-psig leak check on January 4, 2021, it did not withstand pressures exceeding 9 psig during the April 8, 2021, incident. Had Yenkin-Majestic pressure tested the manway at least up to its rupture disk's documented burst pressure setting of 15 psig, or actual burst pressure setting of 16.5 psig, it could have identified that the manway could not hold pressure exceeding 9 psig and implemented corrective actions that could have prevented the incident.

KEY LESSON

Facilities should ensure that equipment can safely operate within the safe operating limits that are documented in process safety information. After equipment alterations, quality should be assured for normal operation as well as abnormal and emergency conditions.

Mechanical Integrity Procedures

The OSHA PSM standard requires PSM-covered facilities to "establish and implement written procedures to maintain the on-going integrity of process equipment."[a] In *Guidelines for Mechanical Integrity Systems,* CCPS gives examples of industry codes and standards applicable to repairs and alterations, and states:

> Occasionally, facilities need to repair, alter, or rerate pressure vessels, tanks, and piping. ([...] Alteration is any physical change in equipment that has design implications, such as those changes affecting pressure-containing capabilities. [...]) Because of the potential catastrophic consequences of, and the technical issues involved with, this type of work, special [quality assurance] requirements have been defined in applicable codes and standards [25, p. 101].

[a] 29 CFR § 1910.119(j)(2)

The CCPS summarized these industry standards to generally provide guidance on issues such as authorization, approval, workmanship, inspection and testing, and documentation [25, p. 102]. Pressure vessel design, construction, and alteration standards are further discussed in *Section 4.1.2.2*.

Post-incident, OSHA cited Yenkin-Majestic for not documenting the codes and standards employed "for pressure vessel alteration, for inspection and testing and for compliance with [recognized] and generally accepted good engineering practices (RAGAGEP)" [26, p. 16]. In addition, it issued the following citation:

> On or about and prior to April 8, 2021, the employer's mechanical integrity program for process vessels failed to address qualifications and credentials of the individuals and organizations performing testing/inspection; and the written program failed to address the development of specific inspection plans for process vessels in the covered process; to include the kettle 3 reactor vessel testing, inspection and inspection planning [26, p. 45].

Yenkin-Majestic had not adopted or referenced industry pressure vessel alteration guidance into its mechanical integrity procedures for the resin plant.[a] At the time of the incident, Yenkin-Majestic's mechanical integrity procedure for process vessel inspections required the inspector(s) to "look for evidence that a vessel ha[d] been altered" and "ensure that the management of change process ha[d] been properly completed;" however, it did not include specific inspection requirements for new alterations, such as authorizing plans before alteration work begins and developing a testing plan for quality assurance.

The CSB concludes that Yenkin-Majestic did not have adequate written mechanical integrity procedures for quality assurance of alterations to process vessels in highly hazardous chemicals service or for preparing and maintaining records of inspections, alterations, maintenance or repairs.

The CSB recommends that Yenkin-Majestic update its mechanical integrity procedures for all process vessels in highly hazardous chemicals service, including pressure vessels not exceeding 15 psig, to adopt alteration guidance in API 510 *Pressure Vessel Inspection Code* or Part 3 of the *National Board Inspection Code*. The CSB also recommends that Yenkin- Majestic develop and implement written procedures to document and maintain records of (i) all inspections of, (ii) all alterations to, and (iii) all maintenance and repairs on all pressure vessels in highly hazardous chemicals service.

[a] Yenkin-Majestic's pressure vessel mechanical integrity procedures were drafted in 2014 with the assistance of a third-party consultant. At the time, the document referenced both API 510 and API RP 572, and required that "repairs are to be made in accordance with API 510." In 2019, Yenkin-Majestic updated this document's title from "pressure vessel inspections" to "process vessels inspections," removing all references to the term "pressure vessels," API 510, and API 572. At the time of the incident, the "process vessel inspections" mechanical integrity procedure did not reference any of the API standards.

4.1.2.2 Industry Guidance for Low-Pressure Vessels

Industry guidance for pressure vessels can generally be divided into two categories:

1) *design and construction standards*, which define specific engineering guidance for fabricating the equipment; and

2) *post-construction standards*, which define activities to maintain safe use of the equipment through the equipment's life.

In general, ASME maintains design and construction standards, NBBI maintains post-construction standards, and API maintains both types of standards.

Yenkin-Majestic followed pressure vessel codes only for the vessels that it considered to be code pressure vessels, such as Kettle 4, and hired contractors that were certified to perform code pressure vessel work on those vessels. Because Yenkin-Majestic considered Kettle 3 to be an atmospheric vessel that was exempted from pressure vessel codes, Yenkin-Majestic and its contractors often just used atmospheric storage tank practices. For example, in 2018, an inspection company performed an "Above Ground Storage Tank Inspection" on Kettle 3, which Yenkin-Majestic understood to be based on API Standard 653, *Tank Inspection, Repair, Alteration, and Reconstruction*. In addition, the companies that designed, fabricated, and evaluated the new manway on Kettle 3 had previous experience with working on atmospheric storage tanks, but not code pressure vessels.

The CSB found that there is currently limited industry guidance specifically for safely maintaining, designing, and altering low-pressure process vessels in highly hazardous chemicals service that are intended to not exceed 15 psig like Kettle 3, as will be described in this section.

ASME Standards

The ASME *Boiler and Pressure Vessel Code* (BPVC) is an international code that establishes safety rules for pressure integrity, which govern the construction of boilers, pressure vessels, transport tanks, and nuclear components. According to ASME, "construction is an all-inclusive term comprising materials, design, fabrication, examination, inspection, testing, certification, and overpressure protection" [22, p. xxxv]. Equipment that is constructed in accordance with all applicable requirements of the BPVC can only be stamped with an ASME Certification Mark through formal ASME certification.

ASME's pressure vessel rules are found in Section VIII of the BPVC. The BPVC defines pressure vessels as "containers for the containment of pressure, either internal or external," but, "vessels having an internal or external pressure not exceeding 15 psi" are not covered by this standard. Nevertheless, ASME allows "any pressure vessel which meets all the applicable requirements" to be stamped with the ASME Certification Mark even if they are specifically excluded from the scope [22, pp. 2-3].

The original purpose of the pressure vessel code and organizations such as ASME and NBBI[a] was to prevent catastrophic accidents associated with boilers and steam systems, where high steam pressures and the

[a] NBBI (or the National Board) is an organization that promotes uniformity in the construction, installation, repair, maintenance, and inspection of pressure equipment through its inspection code (NBIC), training, registration, accreditation, certifications, and other services. In addition, its membership oversees adherence to laws, rules, and regulations relating to boilers and pressure vessels [58].

mechanical consequences of failure were the predominant concern instead of the chemical characteristics of the vessel's contents. Coal-fired steam power was "the motive force of the First Industrial Revolution, driving railways, ships and factories" [27, p. 103], but the lack of design and construction codes up to the early twentieth century resulted in "about 350 to 400 boiler explosions… occurring yearly in the United States with a tremendous loss of life and property" [28, p. 250]. ASME was founded in 1880 in response to these catastrophes [27, p. 106], producing the 1914 ASME Boiler Code of Rules which continually evolved into today's BPVC [27, p. 108]. Although pressure vessels are widely utilized in the chemical process industries, the primary intention of the BPVC remains focused on mitigating the mechanical hazards of failures of pressure vessels rather than ensuring the containment of highly hazardous chemicals handled at lower pressures (up to 15 psig).

The current gap in ASME codes for low-pressure vessels was highlighted recently in a 2021 ASME Pressure Vessels & Piping Conference proceeding which acknowledged that "[g]lobally there is not a well-defined design procedure available for low pressure vessels [<15 psig]… result[ing] in inconsistent methodologies being used by different designers or fabricators to design and fabricate low pressure vessels" [29, p. 1]. As a result of this low-pressure vessel coverage gap in the existing codes, the authors featured in the ASME 2021 conference proceeding wrote:

> Whilst some of these established methodologies used for design of [low-pressure vessels] have been generally conservative and have resulted in uneconomical but safe designs and products, there have also been recorded incidents in the industry where low pressure vessels were not designed or fabricated correctly and safely for the intended applied loads which resulted in the failure of the pressure containment [29, p. 1].

Although the authors featured in the ASME 2021 conference proceeding provide an outline of a code for low-pressure vessels intended for the chemical processing industries, the proposal includes service limitations only to "Non-heated, Non-Exothermic Reactions, Non-Hydrogen, Non-Lethal and no unstable gas" [29, p. 6], which would still leave a code gap for low-pressure vessels in many chemical process industry applications where maintaining containment of highly hazardous chemicals is important for preventing catastrophic incidents.

Process Industry Practices (PIP)

Process Industry Practices (PIP) is a consortium of owner and contractor companies that publishes non-binding good industry practices and operates within The University of Texas at Austin [30]. PIP attempts to close the design and construction standard gap for process vessels limited to a maximum MAWP of 15 psig. PIP's industry practice document VSLP001, *Low-Pressure, Welded Vessel Specification*, describes basic requirements for "the construction of low-pressure, welded vessels that in general meet the philosophy and requirements of Section VIII, Division 1 of the ASME [BPVC], but do not require Code inspection or stamping" [31, p. 2]. Unlike ASME and API standards, PIP's products are industry practice-sharing documents that are not created by a process accredited by the American National Standards Institute (ANSI).

In general, VSLP001 requires the materials, welding, and fabrication to be in accordance with the BPVC with certain modifications for low-pressure vessels. Because the practice document requires much of the design and construction to be based on the BPVC, it also requires the pressure vessel manufacturer to be a valid ASME Code stamp holder that complies with all aspects of its code quality control system. Notwithstanding that

VSLP001 applies to new construction of vessels, had Yenkin-Majestic followed the principles in this industry guidance document, it could have hired contractors qualified to perform work on its pressure vessels, even though the ASME BPVC exempts pressure vessels not exceeding 15 psig. For example, Yenkin-Majestic could have utilized a pressure vessel engineer to verify that the manway lid thickness, the number of bolts, and the gasket selected would ensure Kettle 3's safe operation based on the guidance provided by the BPVC.

PIP VESLP001 requires a hydrostatic pressure test in accordance with the BPVC for new constructions; however, this practice does not specifically cover requirements for inspection and testing after alterations. Post-construction alteration rules are found in standards such as the NBIC Part 3 and API 510.

NBBI Standards

NBBI's *National Board Inspection Code* (NBIC) provides rules, information, and guidance for post-construction activities, such as installation, inspection, repairs, and alterations, for pressure-retaining items to maintain their integrity, "thereby ensuring that these items may continue to be safely used" [21, p. X]. The NBIC defines a pressure retaining item as any boiler, pressure vessel, piping, or material used for the containment of pressure [21, p. 269]. Similarly, it defines a pressure vessel as a container other than a boiler or piping used for the containment of pressure [21, p. 269]. It does not place any lower limit for the containment of pressure. Consequently, it can be applied to vessels operating below 15 psig.

Part 3 of the NBIC is dedicated to repair and alteration requirements "regardless of code of construction" [21, p. X]. The NBIC defines an alteration as a change in a pressure-retaining item that affects its pressure containing capability [21, p. 264] and cites "the addition of new nozzles or openings in a [...] pressure vessel" as an example of an alteration [21, p. 76].

Pressure vessels altered in accordance with the NBIC are typically subject to requirements that, among other things, include:

- hiring a certified repair organization that makes repairs in accordance with the applicable construction or repair code;
- having a qualified pressure vessel inspector and a qualified pressure vessel engineer authorize and approve all alteration work before work is started;
- ensuring that new nozzles meet the design requirements of the applicable construction code; and
- performing a pressure test to indicate that the integrity of the pressure components are still compliant with the applicable construction code [21, pp. 74-83].[a]

In addition to requiring the performance of an alteration and its inspection by accredited organizations, Part 3 of the NBIC has the following provisions:

[a] Owners of pressure vessels subject to the NBIC are also required to submit reports of alterations (R-2 forms), signed by an inspector, to the NBBI, and applying a nameplate or stamp adjacent to the original manufacturer's stamping or nameplate [21, pp. 84-87].

- when the MAWP of a pressure vessel is reduced, the user must contact the Jurisdiction to determine if specific procedures are to be followed (Paragraph 3.4.1) [21, p. 74]; and

- activities not conforming to the rules of the original code of construction or the NBIC must receive specific approval from the Jurisdiction, who may establish requirements for design, construction, inspection, testing, and documentation [21, p. XV].

The Ohio State Administrative Code Rule 4101: 4-2-01 determines NBIC applicability for repairs and alterations based on the scope of ASME BVPC applicable for new construction.[a] Since Yenkin-Majestic considered Kettle 3 to be a vessel not exceeding 15 psig, which would have been excluded from the scope of the BPVC, the company determined that Kettle 3 alterations were not required to be performed in accordance with the NBIC Part 3. For example:

- Yenkin-Majestic hired companies that were not certified for pressure vessel construction and repair codes;

- Yenkin-Majestic did not involve qualified inspectors and engineers in authorizing, approving, and overseeing testing of the new manway design, construction, and installation;[b] and

- Yenkin-Majestic did not ensure that a pressure test was performed to verify the integrity of the new manway and lid before Kettle 3 was returned to service.

The CSB concludes that although the NBIC does not exempt pressure vessels not exceeding 15 psig, Ohio bases its code requirements on the ASME Boiler and Pressure Vessel Code exemptions. Since Yenkin-Majestic considered Kettle 3 to be a vessel not exceeding 15 psig, the company determined that Kettle 3 alterations were not required to be performed in accordance with the NBIC Part 3. Had Yenkin-Majestic followed NBIC Part 3 to alter Kettle 3, it would have hired a certified repair organization, authorized the new manway's design through a qualified inspector and engineer, and pressure tested the new manway in accordance with the applicable construction codes. These practices could have ensured the integrity of the new manway and prevented the incident.

As discussed above, the CSB recommends that Yenkin-Majestic update its mechanical integrity procedures for all process vessels in highly hazardous chemicals service, including pressure vessels not exceeding 15 psig, to adopt alteration guidance in API 510 *Pressure Vessel Inspection Code* or Part 3 of the *National Board Inspection Code*.

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[a] Ohio Admin. Code § 4101:4-2-01, Ohio Admin. Code § 4101:4-3-01

[b] An inspection company that Yenkin-Majestic routinely used for its pressure vessels performed dye penetrant testing on the welds around the new nozzle; however, this method was not suitable for providing meaningful results to verify the integrity of the manway gasket and lid. Yenkin-Majestic had told the inspection company that Kettle 3 was an atmospheric vessel and not subject to pressure vessel codes.

API Standards

Design and Construction Standards

The American Petroleum Institute (API) has several design and construction standards for vessels (storage tanks) not exceeding 15 psig; however, they would not have applied to Kettle 3, which was a stainless steel reactor that operated at temperatures up to 600 °F. For example, API Std 650, *Welded Tanks for Oil Storage* applies to storage tanks limited to internal pressures not more than 2.5 psig and temperatures of only up to 500 °F. Similarly, API Std 620, *Design and Construction of Large, Welded, Low-pressure Storage Tanks* applies to storage tanks with pressure in their vapor spaces not more than 15 psig but at metal temperatures not greater than 250 °F.

Post-Construction Standards

API has several industry standards that provide guidance for pressure vessel mechanical integrity, such as API 510, *Pressure Vessel Inspection Code: In-service Inspection, Rating, Repair, and Alteration,* API Recommended Practice (RP) 572, *Inspection Practices for Pressure Vessels*, and the ASME/API joint standard, API 579-1/ASME FFS-1, *Fitness-For-Service* [20, 32, 33].

API 510: Pressure Vessel Inspection Code

API 510 defines an alteration as "a physical change in any component that has design implications that affect the pressure-containing capability of a pressure vessel [...]" [20, p. 4].[a] API 510's pressure vessel alteration requirements are similar to NBIC's requirements, such as hiring qualified repair organizations, authorizing alteration work plans through a qualified inspector and engineer, and pressure testing vessels after alterations [20, pp. 48, 31].

API 510 specifically applies to "all hydrocarbon and chemical process vessels that have been placed in service unless specifically excluded" [20, p. 1]. Unlike the NBIC, which does not exempt equipment based on pressure, API 510 scope excludes "vessels with an internal or external design pressure that cannot exceed 15 psig," [20, p. 65] API 510 also recommends, however:

> Some vessels exempted in accordance with the criteria in ASME [BPVC] should be considered for inclusion based on risk (probability and consequence of failure) as determined by owner/user [20, p. 2].

As discussed above, Yenkin-Majestic chose not to adopt any industry pressure vessel mechanical integrity guidance, such as API 510 or the NBIC, for its low-pressure process vessels, because the text in either the document itself or in applicable regulations exempt vessels not exceeding 15 psig.

[a] The full definition is: "A physical change in any component that has design implications that affect the pressure-containing capability of a pressure vessel beyond the scope described in existing data reports. The following should not be considered alterations: any comparable or duplicate replacement, the addition of any reinforced nozzle less than or equal to the size of existing reinforced nozzles, and the addition of nozzles not requiring reinforcement" [20, p. 4]. At the time of the incident, Yenkin-Majestic did not have a current data report for Kettle 3.

Although API 510's requirements generally apply to all code pressure vessels, some of its guidance may not be appropriate for low-pressure vessels that were not constructed to the ASME pressure vessel codes. For example, API 510 recommends performing a pressure test at 130% to 150% of the vessel's MAWP after an alteration [17, p. 127, 20, p. 31].[a] Vessels built to ASME codes and specifications typically account for substantial safety factors to avoid catastrophic failures that may not always be present or necessary in low-pressure vessels. Further guidance specifically for low-pressure vessels in highly hazardous chemicals service can help ensure that companies like Yenkin-Majestic and their contractors alter and test their low-pressure vessels adequately for their safe operation.

API RP 572: Inspection Practices for Pressure Vessels

API RP 572 *Inspection Practices for Pressure Vessels*, intended for use for all pressure vessels used in petroleum refineries and chemical plants, explicitly states that its scope includes "pressure vessels with a design pressure below 15 psig" and "vessels that operate at lower pressures [than 15 psig]" [32, pp. 1, 5]. Regarding vessel alterations, API 572 defers to API 510:

> Although repair and maintenance are not parts of inspection, repairs that affect the pressure rating of a vessel and that require reinspection for safety reasons are of concern.
>
> API 510 sets forth minimum petroleum and chemical process industry repair requirements and is recognized by several jurisdictions as the proper code for repair or alteration of petroleum or chemical pressure vessels [32, p. 51].[b]

API 510, however, specifically excludes low-pressure vessels like Kettle 3, as described above.

API 579-1/ASME FFS-1 Fitness-For-Service

The ASME and API joint standard, API 579-1/ASME FFS-1 *Fitness-For-Service* (FFS), provides rules for engineering assessments "using methodologies specifically prepared for pressurized equipment" that "offer a sound basis for decisions to continue to run as is or to alter, repair, monitor, retire, or replace the equipment" [33, 34, p. ii].[c]

The FFS standard does not list exemptions in its scope and is meant to complement a broad range of existing standards, as described below:

> The methods and procedures in this Standard are intended to supplement and augment the requirements in API 510, API 570 [Piping Inspection Code], API 653, and other post construction codes that reference FFS evaluations such as

[a] For example, according to Kettle 3's original data sheet from 1961, it had initially been pressure tested up to 70 psig, which is approximately 150% of its original MAWP of 40 psig.

[b] Of the 50 U.S. states, 13 of them reference API 510 in their regulations. Ohio is one of the 38 states that has adopted the NBIC.

[c] The standard, first published as an API recommended practice in 2000, was intended to "provide technically sound consensus approaches that ensure the safety of plant personnel and the public while aging equipment continues to operate, and can be used to optimize maintenance and operation practices […]."ASME had also begun to address post-construction integrity issues around this time, and in 2001, ASME and API formed the Fitness-For-Service Joint Committee "to develop and maintain a Fitness-For-Service standard for equipment operated in a wide range of process, manufacturing and power generation industries" [34, p. ii].

> NB-23 [NBIC]. The assessment procedures in this Standard can be used for FFS Assessments and/or rerating of equipment designed and constructed to the following codes: ASME BPV Codes […]; API Standards [...] 620, & 650. The assessment procedures in this Standard may also be applied to pressure containing equipment constructed to other recognized codes and standards, including international and internal corporate standards. This Standard has broad applications […] [33].

The FFS standard is typically used to evaluate equipment with a "flaw" or "damage," most commonly for in-service damage mechanisms such as corrosion, cracking, or distortions; however, it can also be used for engineering assessments of alterations. For example, API 510 recognizes FFS methodologies for "engineering assessment of in-service pressure vessels" and requires them to be included in the equipment's process safety information documentation [20, p. 2].

Other Standards

National Fire Protection Association (NFPA) Standards

Yenkin-Majestic's resin plant was subject to the NFPA 35 *Standard for the Manufacture of Organic Coatings*. The scope of 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" [35, p. 1.1.1]. NFPA 35 requires that:

> Reactor systems shall be designed to safely manufacture the products assigned to them. Design factors shall include, but not be limited to, materials of construction, pressure rating, emergency vent system, cooling and heating capacity, condenser capacity, instrumentation, and other design features [35, p. 6.3.1.1].

Additionally, "[a]ll piping, valves, and fittings in flammable or combustible liquid service shall be designed for the working pressures and structural stresses to which they will be subjected" [35, p. 6.2.1], which would have applied to Kettle 3's manway. NFPA 30 *Flammable and Combustible Liquids Code* is the general standard used in chemical facilities to ensure fire safety [36]. However, since neither NFPA 30 nor 35 specifies additional design guidance, these standards allow process owners themselves to select appropriate RAGAGEP applicable to their process equipment.

OSHA's Flammable Liquid Standard

OSHA's *Flammable Liquid* standard requires that "[l]ow-pressure tanks shall be built in accordance with acceptable standards of design" and "may be built in accordance with… consensus standards that are incorporated by reference[a]" such as API and ASME.[b,c] Although Yenkin-Majestic did not consider Kettle 3 a code pressure vessel, it was required under both the OSHA standard and NFPA to select and identify which vessel design and construction codes were appropriate RAGAGEP to ensure the safe operation of the equipment. Unfortunately, all typical RAGAGEP (e.g., ASME BPVC and API 510) exempted Kettle 3 from coverage.

European Union Pressure Equipment Directive

The European Union regulates certain pressure equipment that operates at even lower pressures of 7.25 psig. The Pressure Equipment Directive (PED) 2014/68/EU, which applies only to original equipment manufacturers, states, "Pressure equipment subject to a pressure of not more than [7.25 psig] does not pose a significant risk *due to pressure*" (emphasis added) [36].[d] The directive, however, defines technical safety requirements based on an ascending level of hazard that incorporates both mechanical risks (equipment pressure and size) and process risks (type of fluid contained in the equipment).[e] Although this directive would not have applied to existing pressure equipment inside an industrial facility like Yenkin-Majestic,[f] it is an example of a standard that acknowledges that equipment design requirements should take into account both the mechanical (pressure) and the process (hazardous chemical) risks when designing pressure equipment for safety.

[a] 29 CFR §1910.106(b)(1)(iv)(b).

[b] 29 CFR §1910.6.

[c] An OSHA Standard Interpretation letter acknowledges: "NFPA has updated its standard since the 1969 edition, but OSHA has not done the same with its standard." Per this letter, while PSM and other standards require NFPA standards to be followed as RAGAGEP, technically doing so is considered by OSHA to be de minimis violations where "employers are allowed to comply with the most current consensus standard applicable to their operations, rather than with the standard in effect at the time of inspection, when the employer's action provides equal or greater employee protection" [60]. As a result, consensus standard dates in both 29 CFR §1910.6 and §1910.106 are several decades earlier than the current editions.

[d] PED 2014/68/EU also addresses equipment with design pressure less than 7.25 psig. Article 4, paragraph 3 of the Directive requires that such equipment must be designed and manufactured in accordance with the sound engineering practice of a Member State in order to ensure safe use. As stated in the directive guideline I-01, the sound engineering practice is fulfilled when the pressure equipment is designed taking into account all relevant factors influencing its safety and when such equipment is manufactured, verified and delivered with instructions for use in order to ensure its safety during its intended life. Although there are no specific standards specified, the sound engineering practice per guidance I-17 is met when either the product has been legally marketed at least in one Member State of the European Economic Area (EEA) for many years, or the product fulfills technical specifications recognized by one Member State [36]. This implies the use of a recognized code or standard or specification.

[e] The directive defines two groups of fluids: group 1 consists of substances and mixtures that are classified as hazardous, and group 2 covers all other non-hazardous fluids, such as water or air [36, p. Article 13]. The hazard classifications are based on the European Regulation (EC) No 1272/2008 on classification, labelling, and packaging of substances and mixtures [59]. For example, group 1 includes category 1 and 2 flammable liquids, which includes fluids such as the VM&P naphtha that was released from Kettle 3. Pressure equipment containing group 1 fluids require more stringent technical "essential safety requirements" such as designing for adequate strength and providing additional safety features for access doors (such as manways). Requirements include the manufacturers to design for adequate strength either by engineering calculation or by experimental means, such as through pressure testing (Annex I, Section 2) [36]. Regarding access doors (manways), the directive states, "In particular, pressure equipment fitted with an access door shall be equipped with an automatic or manual device enabling the user easily to ascertain that the opening will not present any risk. Furthermore, where the opening can be operated quickly, the pressure equipment shall be fitted with a device to prevent it being opened whenever the pressure or temperature of the fluid presents a risk" [36].

[f] PED 2014/68/EU covers new equipment manufactured and distributed in the European Union; therefore, industrial installations (such as the assembly of a new manway onto an existing vessel) are outside of this directive's scope. PED 2014/68/EU states, "this Directive should not apply to the assembly of pressure equipment on the site and under the responsibility of a user who is not the manufacturer, as in the case of industrial installations" [36].

4.1.2.3 Conclusions

The CSB concludes that Yenkin-Majestic took the position that Kettle 3 was exempt from the ASME pressure vessel codes because Kettle 3 was documented as not exceeding 15 psig. Yenkin-Majestic's decision not to apply pressure vessel codes when altering Kettle 3 allowed the design and construction of a deficient manway that failed to contain pressure exceeding 9 psig on April 8, 2021. For example, had Yenkin-Majestic hired contractors certified to perform work on code pressure vessels, the manway components could have been designed, installed, and tested to contain pressure according to guidance in pressure vessel codes, and the incident could have been prevented.

The CSB also concludes that there is currently inadequate engineering design, construction, and alteration guidance specifically for pressure vessels in highly hazardous chemicals service not exceeding an internal pressure of 15 psig. More specific guidance could have directed Yenkin-Majestic and its contractors to use appropriate design, installation, and testing practices for the addition of the new manway on Kettle 3, which might have prevented the incident.

The CSB makes a recommendation to API to develop specific design, construction, and alteration guidance for low-pressure process vessels in flammable and other highly hazardous chemicals service not exceeding an internal pressure of 15 psig in API 510 *Pressure Vessel Inspection Code*, API RP 572 *Inspection Practices for Pressure Vessels*, and/or other appropriate products. At a minimum, the CSB recommends including guidance for:

(i) determining and documenting the low-pressure vessel's design pressure (such as through a data sheet and a nameplate affixed to the vessel);

(ii) determining when or if all or parts of the ASME Boiler and Pressure Vessel Code should be applied;

(iii) acceptable alternative engineering methods, if applicable; and

(iv) alteration requirements, such as design assessments, inspections, and pressure testing.

The CSB makes a recommendation to ASME to assist API in developing this guidance, and to reference new design and construction guidance, if any in the ASME Boiler and Pressure Vessel Code (BPVC).

KEY LESSON

Equipment design requirements should take into account both the mechanical (pressure) and the process (hazardous chemical) risks when designing pressure equipment for safety. An atmospheric vessel is one that operates at the pressure of ambient air (in practice, typically under 0.5 psig), and a pressure vessel is one that contains pressure. Although API and ASME standards currently exempt pressure vessels not exceeding 15 psig, vessels that have the potential to build any pressure above atmospheric may still have safety implications for personnel in the vicinity, especially for equipment in highly hazardous chemicals service.

The CSB could not determine why Kettle 3 was originally rated to an MAWP of 40 psig. Regardless, rating a reactor to a higher MAWP than typical operating pressures provides inherent safety by making its components more resilient to pressure during potential process upsets. The CCPS discusses the following regarding reactor design pressure in its publication, *Guidelines for Engineering Design for Process Safety*:

> For reactors fabricated of metal (not glass-lined), it is recommended that a minimum design pressure of 50 psig be specified, even if the operating pressure is essentially atmospheric. A 50 psig design pressure will also generally provide some vacuum rating. This provides a measure of inherent safety for unexpected pressure swing events (pressure spikes) [17, p. 190].

The CSB concludes that although Yenkin-Majestic documented Kettle 3 as operating at atmospheric conditions with a maximum operating pressure of 12 psig, maintaining the kettle at its original MAWP of 40 psig could have been inherently safer by making its components more resilient to potential pressure increases during abnormal conditions. Thus, had Yenkin-Majestic continued to maintain Kettle 3 as a code pressure vessel rated to an MAWP of 40 psig, the new manway likely would not have started leaking at 9 psig during a process upset and maintained its integrity until Kettle 3's rupture disk relieved the pressure, and the April 8, 2021, incident could have been prevented.

The CSB recommends that Yenkin-Majestic assess and applicable design, construction, and alteration standards for all pressure vessels in highly hazardous chemicals service in new resin plant designs, including pressure vessels not exceeding 15 psig. The recommendation includes implementing a program to assess the pressure vessels against updated applicable recognized and generally accepted good engineering practices, such as those published by API, ASME, PIP, and other organizations, at least once every five years, and address the gaps identified. The CSB also recommends that Yenkin-Majestic develop and implement written procedures to document and maintain records of (i) all inspections of, (ii) all alterations to, and (iii) all maintenance and repairs on all pressure vessels in highly hazardous chemicals service.

4.2 Safeguard Selection and the Hierarchy of Controls

The hierarchy of controls is a risk management principle based on ranking hazard controls from most to least effective: inherently safer design,[a] engineering controls (layers of protection), and administrative controls (**Figure 15**). In general, designing out the hazard and reducing the risk through engineering controls is more effective than using administrative controls. For example, engineering controls reduce hazards through equipment modifications and safety devices, whereas administrative controls include procedures, training, and warnings [37]. Administrative controls are inherently less reliable, because they depend on the performance of personnel for their effectiveness.

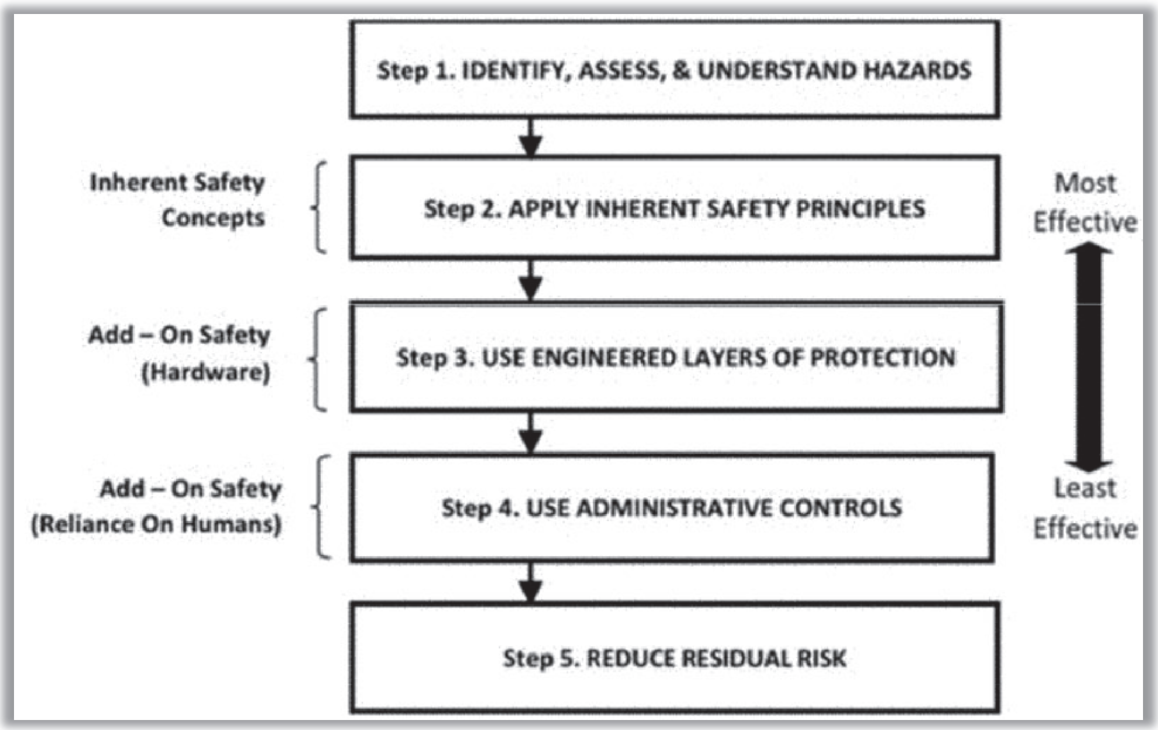

Figure 15. Hierarchy of controls in process safety management. (Credit: CCPS [38, p. 14])

This section discusses Yenkin-Majestic's engineering controls and administrative controls for Kettle 3, which did not prevent the April 8, 2021, incident. The absence of engineering controls to prevent the process upset put the responsibility for preventing the incident solely on the operator. The discussion concludes with suggestions for designing safer process plants that can tolerate human error and equipment failure (e.g., in this case, agitator shutdown) to prevent catastrophic consequences.[b]

[a] The CCPS defines "inherently safer design" as "[a] way of thinking about the design of chemical processes and plants that focuses on the elimination or reduction of hazards, rather than on their management and control" [64]. The CCPS groups inherent safety approaches into four major strategies: minimize, substitute, moderate, and simplify [38, p. 18].

[b] In *An Engineer's View of Human Error*, process safety expert Trevor Kletz writes: "Every accident is due to human error: someone, usually a manager, has to decide what to do; someone, usually a designer, has to decide how to do it; someone, usually an operator, has to do it. All of them can make errors but the operator is at the end of the chain and often gets all the blame. We should consider the people who have opportunities to prevent accidents by changing objectives and methods as well as those who actually carry out operations" [40, p. 2].

4.2.1 Yenkin Majestic's Engineering Controls for Kettle 3

Yenkin-Majestic had added various engineering controls to the Kettle 3 system over the years since it commissioned the kettle in the early 1960s. These engineering controls included interlocks, which are devices that automatically bring the process to a safe state or prevent unsafe actions from occurring, based on the state of the process. In the book *Human Error in Process Plant Design and Operations – A Practitioner's Guide*, the author illustrates the concept of an interlock with two examples that resemble the Yenkin-Majestic incident:

> A typical interlock on a batch reactor will prevent opening of a valve to admit solvent until the reactor is cool enough to avoid immediate boiling or flashing and release of vapour from the reactor loading manhole. Another typical interlock prevents admitting very active reagents such as acid to a reactor until it is established that the stirrer [agitator] is functioning [39, p. 283].

Yenkin-Majestic had already configured the Kettle 3 system with several interlocks, some of which resulted from PHA and/or incident investigation recommendations around 2013 and 2014. One such interlock prevented the startup of the Kettle 3 furnace if the agitator was off. Another such interlock was a Kettle 3 safety relay that activated the kettle's emergency cooling mode if any of these four conditions was met or exceeded: (i) high kettle pressure (4 psig), (ii) high kettle temperature (500 °F), (iii) high furnace temperature (1850 °F), or (iv) pushing the red "Emergency Cooling" button at the kettle control panel.[a] When the emergency cooling mode was activated, the furnace would automatically shut down and water would be circulated through the cooling coils.

More recently, in an effort to improve safety and product consistency, Yenkin-Majestic had been implementing a multi-year project to automate its resin plant operation, which would gradually reduce its dependence on administrative controls. "Previously, everything was done manually," an employee explained, giving examples such as monitoring and controlling temperatures and opening and closing valves. Ultimately, Yenkin-Majestic's goal was to operate the entire batch automatically under operator supervision. An employee described the goal as, "[the control system] would just start that operation and the operator, in turn, would be watching it for alarms and things like that."

Yenkin-Majestic identified additional opportunities for engineering controls during its five-year recurring PHAs as well as during its automation project PHAs. For example, during a PHA on its solvent manifold automation project in 2020,[b] Yenkin-Majestic considered multiple scenarios where solvent could be added to a heated kettle at the wrong time or in the wrong amount, potentially resulting in pressure generation inside the kettle. As an outcome of this evaluation, the project team implemented a safety interlock that prevented solvent addition while a kettle's high pressure alarm was activated at pressures greater than 4 psig. Although this safeguard ensured that solvent could not be added during a pressure excursion that was already taking place, it would not have prevented a pressure excursion in the first place.

[a]The emergency cooling function was added in October 2014. The safety relay did not send an on or off signal to the agitator. In function testing of the emergency cooling button,Yenkin-Majestic tested the function during a normal batch while the agitator was running.

[b]Yenkin-Majestic's kettle automation project was a multi-year effort to convert many of the resin plant's historically manual operations, such as valve position changes, material addition, and temperature setpoint changes over the course of batch recipes, to automated computerized control.

The CSB concludes that while Yenkin-Majestic had equipped Kettle 3 with several interlocks to help allow safe operation of the kettle, Yenkin-Majestic did not add an interlock to prevent solvent addition to the kettle while the agitator was off during batch operations. This gap in engineering controls contributed to solvent addition to the kettle while the agitator was off during batch operations on the night of the incident, which led to the pressure rise in Kettle 3 that preceded the release from the closed manway.

In *Section 4.2.3*, the CSB issues a recommendation to Yenkin-Majestic to address this gap.

4.2.2 Yenkin-Majestic's Administrative Controls for Kettle 3

Yenkin-Majestic trained its kettle operators using written operating procedures, troubleshooting guidelines, and a training guide to qualify them for operating the kettles. Employee A was qualified to work on all the kettles at the resin plant.[a]

Yenkin-Majestic's training guide and troubleshooting guidelines described various ways to respond to a loss of agitation in the kettle. For example, Kettle 3 was equipped with a sparger[b] located at the bottom of the kettle that allowed operators to bubble nitrogen through the kettle. The sparger was used for various purposes, including for troubleshooting and keeping the kettle's contents moving when the agitator was not available.[c] Yenkin-Majestic's troubleshooting guidelines describe the proper response to a loss of kettle agitation as:

- contact management to involve maintenance;
- stop any raw material addition to any vessel;
- cool the kettle immediately; and
- use nitrogen to sparge to help mix the material in the kettle.

Yenkin-Majestic documented that the potential consequences of a loss of agitation were product quality and production delay issues. The company did not identify process safety risks associated with a loss of agitation.

Yenkin-Majestic's kettle operators controlled kettle agitators through a human-machine interface (HMI) panel screen next to each kettle.[d] The HMI panel's "home" screen displayed the agitator's status through an icon that was green when the agitator was running, and red when it was off (**Figure 16**, *left*).[e] Once an operator started an

[a] Having worked at Yenkin-Majestic as a kettle operator for almost two years, Employee A told the CSB that he had not personally seen an agitator that had tripped before, but he had heard of it happening a couple of times on his shift from other kettle operators. Of the six kettle operators working on the night of the incident, two had less than one year of experience, three had less than two years of experience, and one had over ten years of experience. A different Yenkin-Majestic employee who had been working at the company for over ten years told the CSB: "We have experienced a significant turnover every year since I've been here. So that...that front line turns over quite a bit."

[b] A sparger is a device used to inject a gas into a liquid. It is typically a tube or pipe with holes, which bubbles gas through the liquid to promote efficient mixing, aeration, or chemical reactions [65, 66].

[c] A former Yenkin-Majestic employee explained to the CSB: "When you lose agitation during a storm and you can't get it back, you start blowing nitrogen in the bottom. And it gets that stuff at the bottom broke[n] up, gets it moving. And [...] when the power does come back on, you can introduce your agitator."

[d] Each kettle had its own separate HMI. Kettle 3's HMI was installed in December 2018. According to a Yenkin-Majestic employee, the bulk of the HMIs were installed in 2018.

[e] The HMI received the agitator's run status from the variable frequency drive's current output.

agitator at the beginning of a batch, it typically remained running for the duration of the batch. There was no process alarm to warn the operator if the agitator shut down in the middle of a batch.

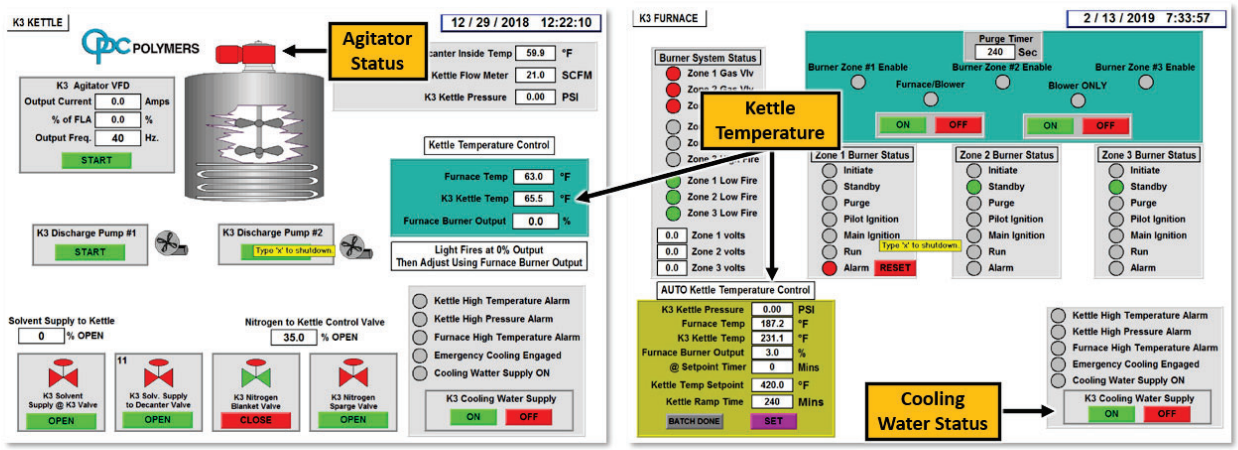

Figure 16. Generic Kettle 3 HMI screen layouts. (Credit: Yenkin-Majestic with annotations by CSB)

On the night of the incident, Employee A did not detect that the agitator had unexpectedly turned off while he was not present in the kettle room. Employee A told the CSB that after he returned and pushed the "Batch Done" button, he monitored Kettle 3's temperature and pressure from the furnace screen, which did not indicate the agitator's on/off status.[a] Employee A noticed that the agitator had turned off only when it became evident that the kettle had not cooled at the expected rate, approximately 100 minutes after the agitator shut down. At that point, he had already added 300 gallons of solvent into the kettle. Furthermore, he did not know how long the agitator had been off—whether it had turned off before he had added the solvent or after. Employee A then turned on the agitator not knowing whether or how much of the solvent had mixed with the resin inside the kettle, thus triggering the uncontrolled pressure increase inside the kettle.

A system should be designed so that a single human action, such as turning on an agitator, cannot set off an irreversible chain of events that leads to a catastrophic explosion and loss of life. Although administrative controls like operating procedures, operator training, and warnings through signs, computer indications, and alarms are essential for reducing risk, they depend on human actions, perception, and judgment and should not be relied on in lieu of engineering controls. In *An Engineer's View of Human Error*, process safety expert Trevor Kletz writes:

> People are actually very reliable but there are many opportunities for error in the course of a day's work and when handling hazardous materials we can tolerate only very low error rates (and equipment failure rates), lower than it may be possible to achieve. We may be able to keep up a tip-top performance for an hour or two while playing a game or a piece of music but we cannot keep it up all day, every day. Whenever possible, therefore, we should design user-friendly plants which can tolerate human error (or equipment failure) without serious effects on safety, output or efficiency [40, p. 3].

[a] The cooling water was also not flowing, because it was programmed to activate only while the agitator was running. The furnace screen would have indicated that the cooling water was not on, but Employee A did not address this indication (**Figure 16**, *right*).

KEY LESSON

Facilities should use hierarchy of controls and prevention through design principles through a plant's entire life cycle to design and maintain fault-tolerant systems, so that a single human action or equipment failure cannot result in a catastrophic incident. During PHAs and design projects, safeguards should be selected using the hierarchy of controls, using inherently safer design and engineering controls instead of administrative controls to prevent process safety incidents. While administrative controls are important in certain scenarios, they depend on human actions, perception, and judgment and should not be relied on in lieu of engineering controls in highly hazardous chemical processes.

Designing "user-friendly plants" can be accomplished through applying the hierarchy of controls, further discussed in *Section 4.2.3*.

The CSB concludes that Yenkin-Majestic relied on the kettle operator to recognize in a timely manner that the Kettle 3 agitator had unexpectedly turned off, without the assistance of audible alarms. The kettle operator ultimately was unaware that the agitator had turned off as he proceeded with subsequent cooling steps while the agitator remained off for approximately 100 minutes. As soon as he realized that the agitator was not running, he attempted to correct that deviation by turning the agitator on, an action that he could not reverse when the kettle's contents began pressuring out of the manway, spraying him with hot resin and obscuring visibility in seconds. This sequence of events was a failure of administrative controls, the least-reliable control for preventing process safety incidents.

In *Section 4.2.3*, the CSB issues a recommendation to Yenkin-Majestic to address this gap.

4.2.3 Prevention Through Design

On the night of the incident, the agitator should have been running when solvent was being added to a hot kettle; however, the process control system performed as designed, allowing the solvent to be added during batch operations regardless of agitator status. This design put Kettle 3 into a vulnerable state under certain conditions.

Designing safer systems that can tolerate human error and equipment failure begins with identifying hazards and the underlying safety specifications. According to the British Health and Safety Executive's (HSE)[a] review of 34 control system failure incidents, 44% of the incidents could be attributed to inadequacies in the specification of the control system [41, p. 31, 42, p. 23]. A subset of these specifications are safety functions, which HSE defines as "requirements that cause a plant or machine to move to or maintain a safe state [...] throughout all operational modes [...]" [41, p. 12].[b]

The American Society of Safety Professionals (ASSP) and American National Standards Institute (ANSI) joint standard, ANSI/ASSP Z590.3-

[a] The HSE is Britain's national regulator for workplace health and safety [62].

[b] In a paper describing a systems approach to process safety, author Nancy Leveson writes: "A control-inspired view of process safety suggests that accidents occur when external disturbances, component failures, or unsafe interactions among processing components are not adequately handled by the existing control systems, leading to a violation of the underlying safety constraints" [63, p. 7]. In Leveson's discussion, control systems include humans who control the physical equipment and socio-technical systems such as organizational and management systems [63, p. 8].

2021, *Prevention through Design* [43], is one resource that outlines a design philosophy to address hazards in the design and redesign phase. This standard requires organizations to identify hazards, determine safety specifications that avoid or reduce risk sources (hazards), then systematically apply the hierarchy of controls to meet the safety specifications. For example, the standard requires the following for establishing safety specifications:

> The organization shall determine safety specifications to be used in new designs, and redesign of existing systems. Safety specifications shall be reviewed and updated periodically [...]. [...]
>
> Safety specifications shall include considerations for avoiding or reducing the potential for human error. [...]
>
> Safety specifications shall include considerations for maintenance, non-routine activities, and expected upset conditions that could present hazards which are not encountered during normal operating conditions [43, pp. 19-20].

One safety engineering textbook published by the American Society of Safety Engineers describes a typical design process using the hierarchy of controls:

> The top priority in the hierarchy of engineering controls is to design out the hazard or reduce the risk to an acceptable level. […] The next course of action, if the hazard cannot be eliminated by an alternative design, is to apply safety devices. An example of a safety device would be an interlocked machine guard […]. When the hazard cannot be eliminated or the risk reduced by incorporating safety devices, then warning devices should be applied. An example of a warning device is a beacon light or horn. If these measures are impractical or ineffective, then warning signs and labels, training, operating procedures, and administrative procedures should be implemented. If the risk cannot be reduced with any of these interventions, then the design should be terminated [44, p. 420].

The above design principles should not be limited to the initial design of a process plant but instead should be used through the plant's entire life cycle. For example, over the course of a process plant's operation, operating data, incident investigations, management of change, and PHAs provide important opportunities to apply the hierarchy of controls. **Figure 17** provides examples of opportunities where these design concepts could be applied across the entire life cycle.

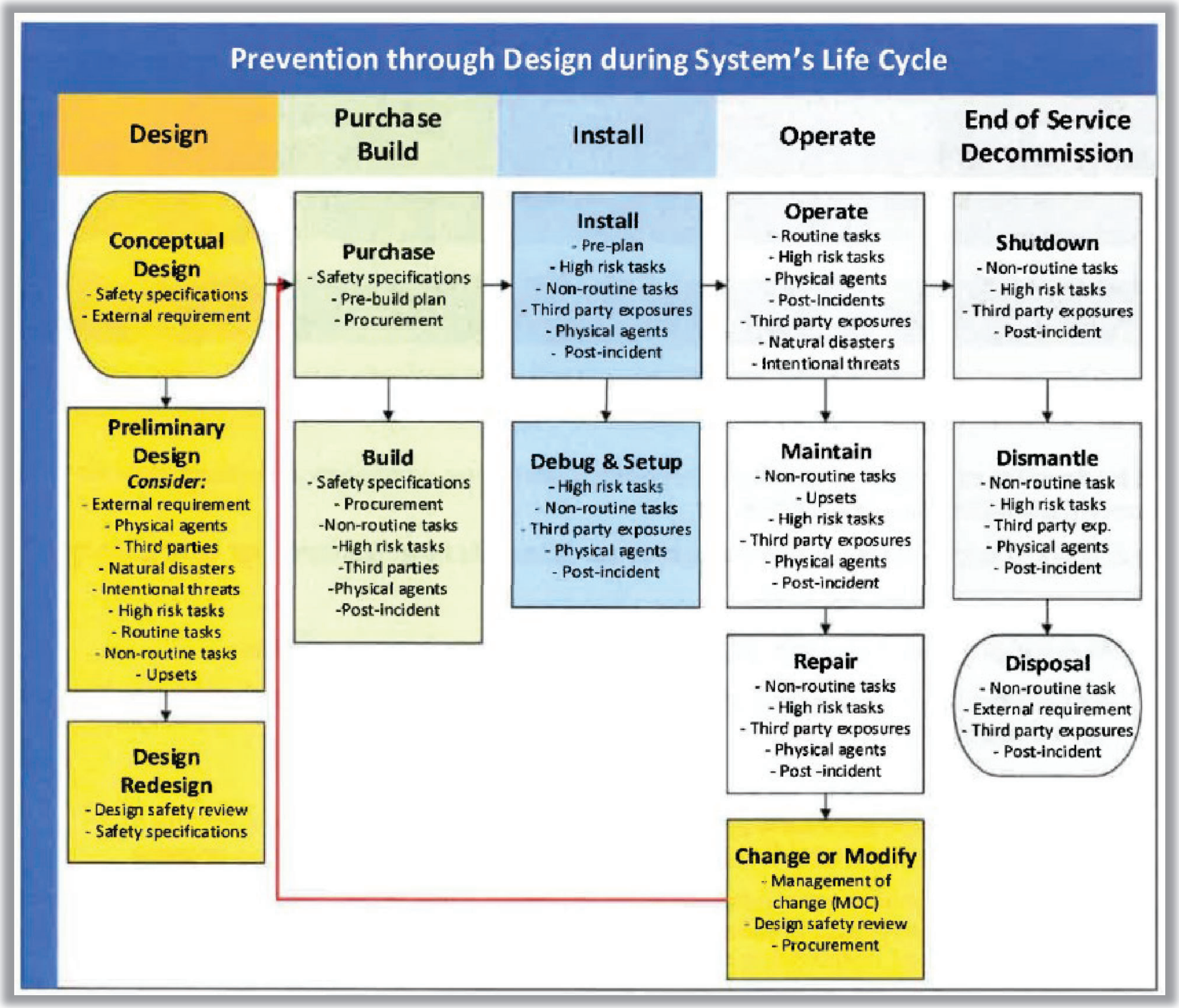

Figure 17. Example of prevention through design opportunities during a system's life cycle. (Credit: ASSP [43])

The CSB concludes that applying the hierarchy of controls at the design phase is the best opportunity to ensure that process hazards are properly analyzed and risks are effectively reduced, before the design is implemented in the field. After the design phase, however, when construction is complete and the process is operating, process safety management system elements such as PHAs, incident investigations, and management of change are important opportunities to apply the hierarchy of controls to further reduce risk throughout the life of a process.

The CSB recommends that Yenkin-Majestic demonstrate the use of prevention through design using the hierarchy of controls in future resin plant designs. Specifically, prioritize inherently safer design and engineering controls to prevent process safety events. Demonstration could include documentation of conceptual design safety reviews, hazard analysis and risk assessments of detailed project designs, and a plan to address the recommendations to control the hazards.

4.3 Emergency Preparedness

Effective emergency response preparedness is crucial in the event of a flammable vapor cloud release and should, among other things, include prompt notification via gas detection and alarms, effective training to ensure personnel know how to safely respond in an emergency, and ensuring personnel wear sufficient personal protective equipment (PPE) if a timely evacuation from the area is not possible. This section discusses how gaps in Yenkin-Majestic's emergency preparedness contributed to the severity of the April 2021 incident.

4.3.1 Flammable Gas Detectors

During the incident, workers had one minute and fifty seconds from the start of the release to evacuate the building before the explosion occurred. While under any circumstances this is a short period of time, evacuation efforts are still possible if workers are alerted to the hazardous condition and are trained to react quickly. Yenkin-Majestic's flammable gas detectors and alarms were not configured to warn plant personnel of flammable material releases from Kettle 3, which contributed to personnel being located inside the facility at the time of the explosion.

Flammable gas detectors are utilized in many industrial facilities to provide "reliable and fast detection of leaks before any accidentally released gas cloud reaches a concentration and size which could cause significant risk to personnel and the plant" [45, p. 103]. Gas detection systems can trigger alarms to provide prompt warning to personnel so that actions may be taken to prevent the formation and ignition of flammable gas mixtures and enable personnel to safely evacuate from the area.

At Yenkin-Majestic, the resin plant's Kettle 3/4/5 furnace room on the ground floor was equipped with five lower explosive limit (LEL) flammable gas detectors. The LEL detectors began detecting increasing levels of flammable vapors at around 12:03:30 a.m., approximately one minute after the Kettle 3 release started. The flammable gas detectors triggered automatic furnace shutdowns and an e-mail notification to a process engineer.[a] However, the detectors were not configured to sound an audible alarm to notify plant personnel of the hazard. Moreover, the process engineer was not working during the night shift and therefore was not available to alert site personnel of the release. Yenkin-Majestic had also installed LEL detection in the Kettle 6/7 control room on the second floor, where high LEL levels would trigger a warning light and a horn.[b] These LEL detectors, however, were located several rooms away from the incident release location and did not detect the flammable vapor releasing from Kettle 3.[c] Post-incident, OSHA cited Yenkin-Majestic for the failure of its PHA to address "engineering and administrative controls applicable to the hazards and their interrelationships such as appropriate application of detection methodologies to provide early warning of releases" [26, p. 23].

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[a] The LEL detectors in the furnace room also triggered a visual alarm on the HMI screens for Kettles 3,4 and 5. However, at approximately one minute after the release began, no operators were present at the HMI terminals to observe these visual alarms.

[b] Unlike the kettle rooms for Kettles 3, 4, and 5, where the control panels were next to the kettles, the Kettle 6/7 control room was separate from the operating kettles. According to the Kettle 6/7 control room LEL monitoring system's operating procedure, this room was positively pressurized, and high LEL levels detected in the fresh air intake to the room would eventually shut down the control room's ventilation system.

[c] Per the OSHA citation, "Acceptable detection methods might include process monitoring and control instrumentation with alarms, and detection hardware such as hydrocarbon sensors." [26, p. 23].

According to the CCPS book *Guidelines for Engineering Design for Process Safety*, "A system for reporting and alerting plant personnel, the plant fire brigade, and outside responders [of an emergency] is important for any site, both large and small. […] The preferred design […] activates visual devices, such as strobes or beacons, and communication and audible notification devices" [17, p. 349]. The CCPS also communicates that the objectives of flammable gas detection programs in the process industries should include:

- alerting personnel to the accumulation of combustible gases in buildings due to releases within the space or the ingress of exterior releases;
- initiating the shutdown of internal process streams / equipment and ventilation systems where combustible gases have accumulated in an enclosed space;
- alerting personnel to releases that may affect highly congested or obstructed areas of the plant from which powerful explosions may propagate;
- alerting personnel to large releases in the area of high-potential release sources;
- alerting personnel to releases that may affect commonly used access routes, normally occupied areas, emergency marshalling points or the public; and,
- alerting personnel to releases that are affecting their immediate location [17, p. 355].

On the night of the incident, one employee saw the vapor release but intentionally entered the building to investigate what he thought was a steam leak, not a highly hazardous flammable vapor release. Once he saw the vapors pouring out of the Kettle 3 operating area, he warned his coworkers, who were inside another control room and were not aware of the release. Surveillance camera footage shows kettle operators re-entering the Kettle 6/7 control room and pushing emergency stop buttons less than five seconds before the explosion. These operators sustained burns and other injuries as a result of their presence in the process building. Other employees suffered more severe injuries. For example, one employee inside the break room on the ground floor lost his leg when it had to be amputated after he was crushed under collapsed debris from the explosion. The employee who was fatally injured by burns and smoke inhalation was on the third floor and became aware of the release by a cell phone call approximately five seconds before the explosion, with little time to assess the situation and evacuate.

The CSB concludes that although the flammable gas detectors inside the furnace room began sensing elevated flammable gas concentrations and triggered automated shutdowns of the operating furnaces, they were not set up with audible and visual alarms to alert the workers to a flammable atmosphere. Had the flammable gas detectors been installed in areas where the flammable material released and configured to trigger an audible and visible alarm, employees could have evacuated the resin plant before the flammable vapor cloud ignited, and the fatality and many injuries could have been prevented.

The CSB recommends that Yenkin-Majestic identify and document all equipment that could release flammable materials and install LEL detectors in accordance with sources and guidance such as *Guidelines for Engineering Design for Process Safety* by the CCPS and *Explosion Hazards in the Process Industries* by Rolf K. Eckhoff [17, 46]. The recommendation includes ensuring that detection of hazardous conditions automatically triggers both visual and audible alarms to alert plant personnel of the hazard, and developing and implementing employee training on actions to take, such as prompt evacuation, when such alarms are activated.

KEY LESSON

Flammable dense gases can form ground-level vapor clouds that can travel large distances to reach an ignition source and explode. Facilities that handle flammable materials should install LEL detectors that trigger automatic shutdowns of process equipment, with audible and visible alarms warning personnel to evacuate, and train employees on actions to take, such as prompt evacuation, when such alarms are activated.

4.3.2 Emergency Training

On the night of the April 2021 incident, even in the absence of evacuation alarms, employee training specific to the hazards of the materials present in the Yenkin-Majestic resin manufacturing area could have prevented the fatality and several serious injuries.

4.3.2.1 Emergency Planning at Yenkin-Majestic

Yenkin-Majestic's plans for handling emergency situations included both a Fire Emergency Evacuation Plan (per 29 C.F.R. §1910.38 *Emergency Action Plans*) and a Hazardous Waste Operations and Emergency Response (HAZWOPER) Plan (per 29 C.F.R. §1910.120 *HAZWOPER*).

Yenkin-Majestic's Fire Emergency and Evacuation Plan, on which all of its employees were trained annually, was intended to "designate responsibilities and to provide the needed information to coordinate response to a fire, explosion or release of a hazardous substance." The Plan, however, emphasized fire response and provided limited guidance for other types of hazardous situations, such as releases of unknown vapors. For example, the Fire Emergency and Evacuation Plan directed employees to react to fire hazards in the following ways:

- "The most important rule in case of fire is SAFETY FIRST. If the flames are licking at your heels – don't stop to tie your shoelaces – exit quickly but safely. On the other hand, if the fire can be contained, take time to turn off your equipment, close valves, shut fire doors and in general do everything to prevent secondary fires or serious unrelated accidents before quickly and safely exiting."
- In a section of the Fire Emergency and Evacuation Plan titled "Resin Plant Fire and Emergency Procedures," the Plan stated "If safe to do so [in the event of a fire]; Kettle Operators will shut down furnaces, steam to kettles, agitators, pumps, etc."

The Fire Emergency and Evacuation Plan provided no specific guidance on how to respond during a vapor/gas release, and included the statement that "[t]hroughout the Plan, a release of a hazardous substance or waste is referred to as a spill." One Yenkin-Majestic employee told the CSB that in the event of a solvent release, the

KEY LESSON

Facilities that handle flammable or other hazardous materials should ensure that they are aware of the specific hazard characteristics of their materials, such as dense gases that can form ground-level vapor clouds. These specific hazards should be reflected within emergency planning processes and procedures. Workers must be trained on how to identify and react to hazardous situations including knowing when and how to evacuate.

operators were trained to "contain it with booms and wick it," but did not remember any safety talks addressing vapor clouds.

Yenkin-Majestic's HAZWOPER First Responder Awareness training also did not make clear what actions workers should take during a vapor/gas release. The training guided workers to be cautious of all types of releases by stating "Don't Go Near It. If you don't know exactly what the dangers are, don't go near it. If you don't know exactly how the chemical will act in an emergency, assume the worst." The training, however, did not provide guided actions specific to vapor/gas releases.

4.3.2.2 Yenkin-Majestic Employees' Lack of Recognition of Vapor Cloud Hazard

Training at the OSHA HAZWOPER First Responder Awareness level requires employers to ensure their workers can demonstrate "[a]n understanding of the potential outcomes associated with an emergency created when hazardous substances are present," "[t]he ability to recognize the presence of hazardous substances in an emergency" and "[t]he ability to identify the hazardous substances, if possible."[a] During the incident, a highly hazardous and visible flammable vapor cloud expanded throughout the facility and was seen by many Yenkin-Majestic employees. However, the employees did not appear to recognize the identity of the flammable vapor or that the vapor escaping from the facility could be hazardous.

For example, surveillance camera footage shows a Yenkin-Majestic employee noticing the releasing vapors and running into the building. This employee told CSB investigators that he initially ran inside to investigate what he thought was a steam leak. "They steam pipes all the time because the resin gets stuck. So I just thought it was normal until [...] I walked up closer," the Yenkin-Majestic employee told CSB investigators.

Another Yenkin-Majestic employee described to the CSB seeing both vapor leaking and liquid pouring down onto the ground floor, "but I never thought that [an] explosion was going to happen. And, if so, one that big."

In addition, the surveillance camera still in **Figure 8** and **Figure 18** show one Yenkin-Majestic employee standing just a few feet away from the edge of the vapor cloud outside the resin plant, watching it spread until the moment it explodes. The overall personnel lack of hazard recognition led to some individuals entering the facility instead of evacuating, as well as personnel not activating emergency alarms or announcing a plant-wide evacuation, which contributed to personnel being in harm's way when the explosion occurred.

[a] 29 CFR §1910.120(q)(6)(i)(B) and (C)

4.3.2.3 Vapor Cloud Characteristics

Vapor clouds are classified according to whether they are lighter than air (positively buoyant), denser than air (negatively buoyant) or of the same density as air (neutrally buoyant) with these characteristics determining their behavior when a hazardous release occurs [46, p. 40]. Because VM&P is four times heavier than air, it will form a dense cloud that "can stay at ground level for a long way downwind and can pose a severe hazard" [46, p. 40]. The SDS for VM&P specifically cautioned that, "The vapor/gas is heavier than air and will spread along the ground. Vapors may accumulate in low or confined areas or travel a considerable distance to a source of ignition and flash back." In addition to VM&P, Yenkin-Majestic utilized a total of 17 other solvents whose SDSs' included either identical or equivalent warnings about flammable dense gas hazard characteristics.

Although upon release a dense vapor cloud may first travel upward, once initial momentum is lost it will start to descend towards the ground due to gravity slumping since it is heavier than the surrounding air [47, p. 284]. **Figure 18** depicts the dispersion behavior of a dense gas compared with a surveillance camera video still of the vapor cloud during the April 2021 release. Comparatively, although saturated high-pressure steam may initially be denser than air upon release, at atmospheric pressure it will begin to rise and dissipate rather than sink and travel at ground level [48].[a]

[a] Operators at some industrial facilities are routinely trained to visually differentiate between steam and other types of vapor clouds. For example, many personnel working at those facilities with EPA Title V Federal Operating Permits are routinely trained to visually identify the difference between steam and contaminant plumes associated with their processes and perform regular quantitative (a measure of opacity percentage) and qualitative Method 9 opacity readings to comply with the permit requirements. The Method 9, *Visual determination of the opacity of emissions from stationary sources*, test procedure is included in Appendix A-4 to 40 CFR §60.

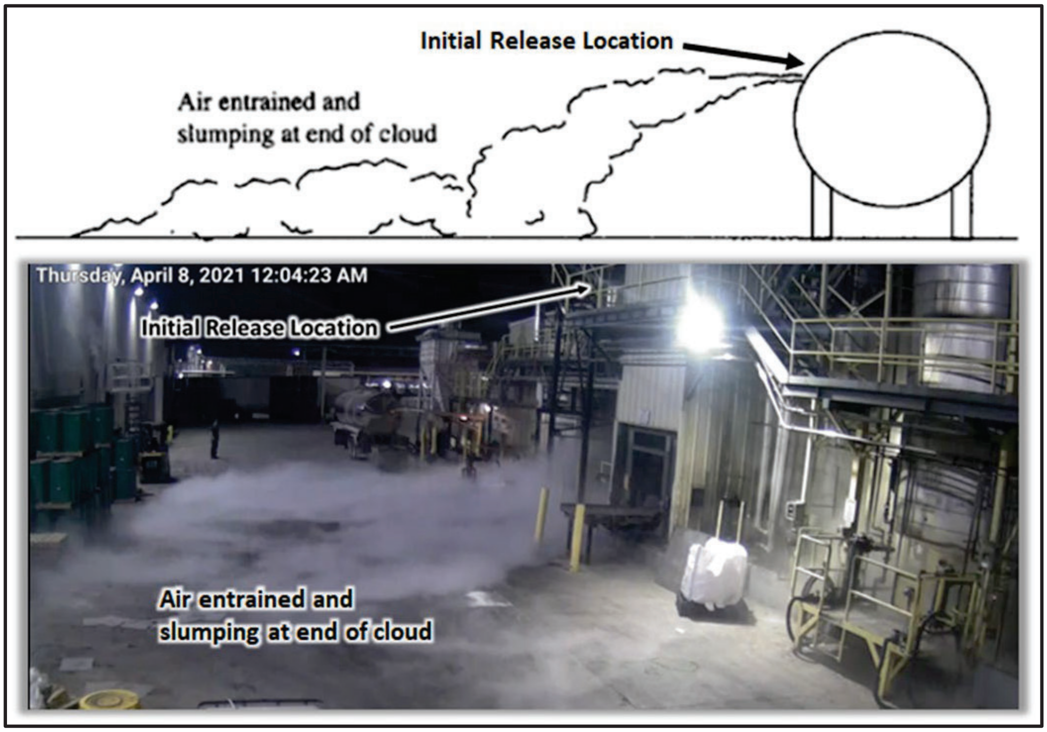


Figure 18. Comparison of April 2021 observed vapor cloud to expected dense gas behavior. (Credit: *top:* CSB, modified from Wells, 1997 [47]; *bottom:* Yenkin-Majestic with annotations by CSB)

Some resin manufacturing companies recognize that "the emergency discharges from process vessels ha[ve] the potential for creating large vapor clouds at ground level, often within operating buildings" and the potential for these flammable clouds to ignite [49, p. 2]. These manufacturers have developed several training videos, including videos on vapor clouds, in order to effectively communicate this information to employees and ensure their knowledge and awareness of the hazards [49].

Post-incident, OSHA cited Yenkin-Majestic for "fail[ing] to specifically address catastrophic hazards, such as an uncontrolled vapor cloud release, that would trigger emergency evacuation" within its emergency procedures [26, p. 41]. Additionally, OSHA cited Yenkin-Majestic for not "ensur[ing] employees were prepared for emergency evacuations for chemical releases from covered process equipment" and "not review[ing] emergency response procedures with employees… such that employees were not aware of how to respond to a chemical release" [26, p. 60].

The CSB concludes that had Yenkin-Majestic's emergency training addressed the hazards of flammable vapor releases, the expected dense gas behavior of solvent vapors, and expected response strategies (such as evacuation), the employees may have been able to recognize the explosion hazard and evacuated from the area before the explosion.

4.3.3 PERSONAL PROTECTIVE EQUIPMENT

Most of the resin plant employees were inside the plant when the explosion occurred, and many of them described to the CSB how they had to evacuate through flames and sustained burn injuries. Around the time of the explosion, most employees in surveillance video footage inside the resin plant were wearing short-sleeved t-shirts. Although PPE should be considered the last line of defense for employees, many of the injuries sustained by Yenkin-Majestic personnel on the night of the incident may have been prevented or reduced in severity if flame resistant (FR) PPE was required.

4.3.3.1 Yenkin-Majestic Uniform and PPE Policy

According to Yenkin-Majestic's uniform policy, Yenkin-Majestic provided cotton long-sleeve button-up uniform shirts and pants to every employee whose primary job responsibilities were in processing areas of the plant. The policy defined the entire resin plant as a processing area. Policies included:

1. All employees who have been issued uniforms, including long-sleeve shirt and pants, are required to wear them while exposed to thermal, chemical or flash fire hazards.
2. When not exposed to these hazards, the long-sleeve uniform shirt is not required. A Yenkin-Majestic or OPC labeled t-shirt is approved for use. Any other cotton t-shirt must be approved by management.

Several Yenkin-Majestic employees explained to CSB investigators that Yenkin-Majestic's PPE policy required resin plant operators to wear upgraded PPE while performing hazardous tasks, such as taking kettle samples or changing filters.[a] When not performing these activities, their understanding was that the operators were not required to wear long-sleeved shirts.

4.3.3.2 Regulatory PPE Requirements

OSHA addresses the employer requirements for PPE under 1910 Subpart I, *Personal Protective Equipment*. Within Subpart I, 29 CFR §1910.132, *General Requirements*, the regulation states:

> Protective equipment, including personal protective equipment for eyes, face, head, and extremities, protective clothing, respiratory devices, and protective shields and barriers, shall be provided, used, and maintained in a sanitary and reliable condition wherever it is necessary by reason of hazards of processes or environment, chemical hazards, radiological hazards, or mechanical irritants encountered in a manner capable of causing injury or impairment in the function of any part of the body through absorption, inhalation or physical contact.[b]

[a] Based on the task, additional PPE could have included gloves, respirators, and Tyvek suits in addition to the work uniforms.

[b] 29 CFR § 1910.132(a)

Additionally, 29 CFR §1910.132(d), *Hazard assessment and equipment selection* requires that the employer "assess the workplace to determine if hazards are present, or are likely to be present, which necessitate the use of [PPE]," and shall:

> 1910.132(d)(1)(i) Select, and have each affected employee use, the types of PPE that will protect the affected employee from the hazards identified in the hazard assessment;
>
> 1910.132(d)(2) The employer shall verify that the required workplace hazard assessment has been performed through a written certification that identifies the workplace evaluated; the person certifying that the evaluation has been performed; the date(s) of the hazard assessment; and, which identifies the document as a certification of hazard assessment.[a]

4.3.3.3 NFPA PPE Guidance

Two NFPA consensus standards provide guidance regarding fire-resistant clothing. NFPA 2112, *Standard on Flame-Resistant Clothing for Protection of Industrial Personnel Against Short-Duration Thermal Exposures from Fire*, addresses the design, construction, and certification of flame-resistant garments. This standard provides requirements of FR clothing to ensure that the PPE is:

> not contributing to the burn injury of the wearer, providing a degree of protection to the wearer, and reducing the severity of burn injuries resulting during egress from or accidental exposure to short-duration thermal exposure from fire [50, p. 1.2.1].

Additionally, NFPA 2113, *Standard on Selection, Care, Use, and Maintenance of Flame-Resistant Garments for Protection of Industrial Personnel Against Flash Fire,* covers the selection, use, and maintenance of flame-resistant clothing. This standard specifies:

> the minimum selection, care, use, and maintenance requirements for flame-resistant garments for use by industrial personnel in areas at risk from short-duration thermal exposures from industrial fires that are compliant with NFPA 2112 [51, p. 1.1.1].

Short-duration thermal exposure from fire is defined in NFPA 2113 as "[a] period of egress from or accidental exposure to thermal events, including, but not limited to, vapor cloud fires, jet flames, liquid fires (pool fires or running liquid fires), solids fires (fires of solid materials or dust fires), or warehouse fires" [51, p. 3.3.38]. Employers should base their selection of flame-resistant garments upon [51, p. 4.1.2]:

> (1) The conduct of a hazard analysis of the workplace to determine the need for the wearing of flame-resistant garments.

[a] 29 CFR §1910.132(d)

> (2) An evaluation of flame-resistant garment designs and characteristics to determine the type of flame-resistant garments suitable for protecting workers.
>
> (3) The development of specifications for purchasing flame-resistant garments.

The FR PPE hazard analysis should be based "on a review of the facility to determine if flammable materials are present in quantities that will present a fire hazard and endanger person(s) [51, p. 4.2.2]," as well as additional considerations including:

> (1) Proximity of the work to be performed to a fire hazard.
>
> (2) The presence of flammable materials in the environment during process operations.
>
> (3) The potential for the task being performed to increase the possibility of a flammable release, which could result from a mechanical failure such as a line breaking.
>
> (4) Operating conditions of the process, for example, the potential for flammable fumes or vapors. […]
>
> (6) Accident history [51, p. 4.2.3].

In addition to FR material requirements, NFPA 2113 also requires that, "Garments shall be selected that cover both the upper and lower body and flammable underlayers as completely as possible [51, p. 4.3.2]."

4.3.3.4 Yenkin-Majestic's PPE Assessments and Usage

According to Yenkin-Majestic's PPE assessment in effect at the time of the April 2021 incident, resin plant operators were required to wear upgraded PPE consisting of "Standard PPE Plus - Protective sleeves, safety glasses, face shield or full faced respirator and nitrile coated gloves" only for specific kettle operator tasks such as sampling and changing strainer baskets. In the event of a solvent spill, the PPE assessment indicates that:

> "Hazards will vary, *[i]f not* an Incident Response, use Standard PPE plus nitrile Gloves. Incident Commander may specify additional PPE."

Throughout Yenkin-Majestic's PPE assessment table, "Solvents" and the presence of heat or hot material is presented as the identified hazard associated with multiple tasks assigned to both the kettle operators and press operator. As described in a BP Process Safety Series[a] document [52, p. 33],

> If flammable materials are handled at the workplace, the coveralls must be able to protect the operator during a flash fire. The temperatures attained by flash fires

[a] The BP Process Safety Series was developed and published to share BP and the Institution of Chemical Engineers' (IChemE) "ongoing commitment to process safety and best practices in the chemical manufacturing and petroleum refinery business [68, p. 460]." This reference series is intended for broad use "by individuals who design, operate, and maintain refineries and chemical plants," and is not specific solely to the petroleum refining sector.

> have been estimated to range from 550 to 1050ºC (1022 to 1922ºF). Most regular clothing fabrics burst into flames at these temperatures. Untreated cotton, polyester, nylon and polycotton blends are inappropriate clothing materials because they have low ignition temperatures, ignite easily and/or melt readily, causing more severe burns than uncovered head and hands. Therefore, coveralls must be made of inherently fire resistant materials and must be anti-static. They protect workers from exposure to intense heat and flames for short periods of time (i.e. flash fires). Statistics show that chances of survival are much higher for victims who were protected from flash fires and able to run to safety.

In its post-incident inspection, OSHA cited Yenkin-Majestic for not "requir[ing] the use of flame-resistant clothing or uniforms that protected the torso and arms against flash fire and other thermal hazards" [26, p. 63]. Based on the fact that the PPE assessment documented the presence of both flammable solvents and heat sources in the workplace, Yenkin-Majestic's PPE policy should have included the requirement for flame-resistant coveralls rather than short-sleeved untreated cotton t-shirts when in the process area regardless of the specific task being performed.

In addition to Yenkin-Majestic's PPE assessment that identified the simultaneous presence of both flammable solvents and heat sources in the process area, the company's incident history records and 2015 PHA study also indicate that FR PPE should have been utilized in advance of the April 2021 incident.

Table 3 presents the occurrence frequency of losses of containment involving Yenkin-Majestic's resin plant process materials, except caustic and condensate, as reflected in the facility's incident history records between 2016 and up to but not including the April 2021 incident.

Table 3. Loss of containment frequency for flammables at Yenkin-Majestic's facility between 2006 and April 2021 incident. (Credit: CSB)

Year	Loss of Containment Type					
	Spills / Overfills	Splash / Spray	Leak / Rupture / Hose Disconnect	Vapor / Fumes	Unspecified "Release"	TOTAL
2016	10	2	5	0	0	17
2017	10	0	1	3	0	14
2018	19	2	5	1	0	27
2019	28	0	11	1	0	40
2020	12	0	1	1	1	15
2021 (March)	2	2	0	0	0	4

As shown by Yenkin-Majestic's recent incident summary, loss of containment of flammables was not an uncommon occurrence, with a total of 117 events occurring within the five-years leading up to the incident. Additionally, several fire incidents occurred over this same timeframe, including "fire/leak incident" on Kettle 4 on 2/1/2017, a "fire incident" on Kettle 5 on 1/5/2020, and a "vapor ignition" on 12/20/2020, only five months before the April 2021 incident. The previous fire and loss of containment incidents should have prompted

KEY LESSON

Workers should be provided PPE that is protective against the hazards they may encounter in a sudden upset condition or emergency. In facilities that process flammable chemicals, flame-resistant PPE can protect workers from intense heat and flames for short periods of time, allowing them to run to safety. Workers should be trained on both the purpose for and the proper use of flame-resistant PPE.

Yenkin-Majestic to reevaluate appropriate PPE for employees working in areas handling flammables in advance of the April 2021 incident.

Finally, the 2015 PHA evaluated multiple scenarios where "possible fire" or "possible fire/explosion" were identified as potential hazards associated with either the kettle pressurizing upon heating or solvent vapor entering the kettle room. In each of these scenarios, PPE was specifically identified as a mitigative safeguard, even though Yenkin-Majestic's PPE requirements for resin plant operators consisted of cotton short-sleeved shirts. Four employees sustained burn injuries during the April 2021 incident, with multiple employees having to directly run through flames to escape from the building. Appropriate FR PPE may have reduced the degree and extent of these burn injuries.

The CSB concludes that Yenkin-Majestic did not require its resin plant employees to wear flame-resistant (FR) clothing, but should have done so based on regulatory requirements, industry guidance, and its own internal assessments and incident history. Had the resin plant employees been wearing FR clothing on the night of the incident, some of the burn injuries resulting from the explosion and fire could have been reduced or prevented.

The CSB recommends that Yenkin-Majestic develop and implement requirements for personnel to wear flame-resistant uniforms in all operating areas that process flammable chemicals, and update employee training material to include the requirement for and purpose of PPE use.

5 Conclusions

5.1 Findings

Technical Analysis

1. After Kettle 3's agitator stopped during a routine resin batch production operation, solvent added into the kettle on top of hot resin did not mix with the resin due to differences in the two liquids' physical properties. When Kettle 3's agitator was later started and could not be subsequently stopped, the bulk of the solvent mixed with the hot resin and vaporized, causing a rapid pressure increase inside Kettle 3.

2. Kettle 3's new manway was not designed to a maximum allowable working pressure (MAWP) of 16 psig as Yenkin-Majestic had specified. At best, it could have been rated for a MAWP of approximately 5 psig. As a result, the manway's sealing surface began to release flammable material when the kettle's pressure reached and exceeded 9 psig during a high-pressure event. Had the new Kettle 3 manway assembly been designed to withstand Kettle 3's internal vessel pressure during the incident, the flammable vapor cloud and explosion could have been prevented.

Mechanical Integrity of Low-Pressure Vessels

3. Yenkin-Majestic returned Kettle 3 to service without adequately testing the new manway to ensure that it was installed properly and could hold pressure at least to its rupture disk's burst pressure setting. Kettle 3's operational history, process hazard analysis, and process safety information suggested that Kettle 3 could experience pressure up to the rupture disk's burst pressure setting during some upset conditions, documented as a maximum of 15 psig. Nevertheless, Yenkin-Majestic operated Kettle 3 for the three months preceding the April 8, 2021, incident with a manway that was only leak-checked up to 4 psig. Although the manway did not appear to leak during the 4-psig leak check on January 4, 2021, it did not withstand pressures exceeding 9 psig during the April 8, 2021, incident. Had Yenkin-Majestic pressure tested the manway at least up to its rupture disk's documented burst pressure setting of 15 psig, or actual burst pressure setting of 16.5 psig, it could have identified that the manway could not hold pressure exceeding 9 psig and implemented corrective actions that could have prevented the incident.

4. Yenkin-Majestic did not have adequate written mechanical integrity procedures for quality assurance of alterations to process vessels in highly hazardous chemicals service or for preparing and maintaining records of inspections, alterations, maintenance or repairs.

5. Although the National Board Inspection Code (NBIC) does not exempt pressure vessels not exceeding 15 psig, Ohio bases its code requirements on the ASME Boiler and Pressure Vessel Code exemptions. Since Yenkin-Majestic considered Kettle 3 to be a vessel not exceeding 15 psig, the company determined that Kettle 3 alterations were not required to be performed in accordance with the NBIC Part 3. Had Yenkin-Majestic followed NBIC Part 3 to alter Kettle 3, it would have hired a certified repair organization, authorized the new manway's design through a qualified inspector and engineer, and pressure tested the new manway in accordance with the applicable construction codes. These practices could have ensured the integrity of the new manway and prevented the incident.

6. Yenkin-Majestic took the position that Kettle 3 was exempt from the ASME pressure vessel codes because Kettle 3 was documented as not exceeding 15 psig. Yenkin-Majestic's decision not to apply pressure vessel codes when altering Kettle 3 allowed the design and construction of a deficient manway that failed to contain pressure exceeding 9 psig on April 8, 2021. For example, had Yenkin-Majestic hired contractors certified to perform work on code pressure vessels, the manway components could have been designed, installed, and tested to contain pressure according to guidance in pressure vessel codes, and the incident could have been prevented.

7. There is currently inadequate engineering design, construction, and alteration guidance specifically for pressure vessels in highly hazardous chemicals service not exceeding an internal pressure of 15 psig. More specific guidance could have directed Yenkin-Majestic and its contractors to use appropriate design, installation, and testing practices for the addition of the new manway on Kettle 3, which might have prevented the incident.

8. Although Yenkin-Majestic documented Kettle 3 as operating at atmospheric conditions with a maximum operating pressure of 12 psig, maintaining the kettle at its original MAWP of 40 psig could have been inherently safer by making its components more resilient to potential pressure increases during abnormal conditions. Thus, had Yenkin-Majestic continued to maintain Kettle 3 as a code pressure vessel rated to an MAWP of 40 psig, the new manway likely would not have started leaking at 9 psig during a process upset and maintained its integrity until Kettle 3’s rupture disk relieved the pressure, and the April 8, 2021, incident could have been prevented.

Safeguard Selection and the Hierarchy of Controls

9. While Yenkin-Majestic had equipped Kettle 3 with several interlocks to help allow safe operation of the kettle, Yenkin-Majestic did not add an interlock to prevent solvent addition to the kettle while the agitator was off during batch operations. This gap in engineering controls contributed to solvent addition to the kettle while the agitator was off during batch operations on the night of the incident, which led to the pressure rise in Kettle 3 that preceded the release from the closed manway.

10. Yenkin-Majestic relied on the kettle operator to recognize in a timely manner that the Kettle 3 agitator had unexpectedly turned off, without the assistance of audible alarms. The kettle operator ultimately was unaware that the agitator had turned off as he proceeded with subsequent cooling steps while the agitator remained off for approximately 100 minutes. As soon as he realized that the agitator was not running, he attempted to correct that deviation by turning the agitator on, an action that he could not reverse when the kettle’s contents began pressuring out of the manway, spraying him with hot resin and obscuring visibility in seconds. This sequence of events was a failure of administrative controls, the least-reliable control for preventing process safety incidents.

11. Applying the hierarchy of controls at the design phase is the best opportunity to ensure that process hazards are properly analyzed and risks are effectively reduced, before the design is implemented in the field. After the design phase, however, when construction is complete and the process is operating, process safety management system elements such as PHAs, incident investigations, and management of change are important opportunities to apply the hierarchy of controls to further reduce risk throughout the life of a process.

Emergency Preparedness

12. Although the flammable gas detectors inside the furnace room began sensing elevated flammable gas concentrations and triggered automated shutdowns of the operating furnaces, they were not set up with audible and visual alarms to alert the workers to a flammable atmosphere. Had the flammable gas detectors been installed in areas where the flammable material released and configured to trigger an audible and visual alarm, employees could have evacuated the resin plant before the flammable vapor cloud ignited, and the fatality and many injuries could have been prevented.

13. Had Yenkin-Majestic's emergency training addressed the hazards of flammable vapor releases, the expected dense gas behavior of solvent vapors, and expected response strategies (such as evacuation), the employees may have been able to recognize the explosion hazard and evacuated from the area before the explosion.

14. Yenkin-Majestic did not require its resin plant employees to wear flame-resistant (FR) clothing, but should have done so based on regulatory requirements, industry guidance, and its own internal assessments and incident history. Had the resin plant employees been wearing FR clothing on the night of the incident, some of the burn injuries resulting from the explosion and fire could have been reduced or prevented.

5.2 Cause

The CSB determined that the cause of the fatal explosion and fire was the release of flammable solvent vapor through the seal of a closed reactor manway that was not designed, constructed, or pressure tested to a design pressure appropriate for the process. The release through the closed manway occurred after the reactor became pressurized by the rapid vaporization of solvent when the reactor's agitator was turned on.

Contributing to the incident was Yenkin-Majestic's failure to adhere to basic pressure vessel integrity quality assurance practices, as well as the absence of clear industry guidance specifically for the design, construction, and alteration of pressure vessels in highly hazardous chemicals service not exceeding 15 psig. Also contributing to the incident was the absence of engineering controls to prevent the incident sequence and the failure of Yenkin-Majestic's administrative controls (overreliance on operator actions).

Contributing to the severity of the incident was Yenkin-Majestic's inadequate emergency preparedness, which led to a lack of a timely evacuation of all employees from the resin plant, lack of audible alarms to alert employees to the presence of flammable vapor concentrations in the resin plant, and a lack of flame-resistant uniforms to protect employees from fire hazards.

6 Recommendations

To prevent future chemical incidents, and in the interest of driving chemical safety excellence to protect communities, workers, and the environment, the CSB makes the following safety recommendations:

6.1 Yenkin-Majestic

2021-04-I-OH-R1

Update mechanical integrity procedures for all process vessels in highly hazardous chemicals service, including pressure vessels not exceeding 15 psig, to adopt alteration guidance in API 510 *Pressure Vessel Inspection Code* or Part 3 of the *National Board Inspection Code*.

2021-04-I-OH-R2

Assess and document applicable design, construction, and alteration standards for all pressure vessels in highly hazardous chemicals service in new resin plant designs, including pressure vessels not exceeding 15 psig. At a minimum, adopt PIP VESLP001 *Low-Pressure, Welded Vessel Specification* as design and construction guidance for pressure vessels not exceeding 15 psig. Implement a program to assess the pressure vessels against updated applicable recognized and generally accepted good engineering practices, such as those published by API, ASME, PIP, and other organizations, at least once every five years, and address the gaps identified. Develop and implement written procedures to document and maintain records of (i) all inspections of, (ii) all alterations to, and (iii) all maintenance and repairs on all pressure vessels in highly hazardous chemicals service.

2021-04-I-OH-R3

Demonstrate the use of prevention through design using the hierarchy of controls in future resin plant designs. Specifically, prioritize inherently safer design and engineering controls to prevent process safety events. Refer to sources such as *Safety Instrumented Systems: A Life-Cycle Approach* by P. Gruhn and S. Lucchini, *Human Error in Process Plant Design and Operations – A Practitioner's Guide* by J. Robert Taylor, *Guidelines for Preventing Human Error in Process Safety* by the Center for Chemical Process Safety (CCPS), *Guidelines for Inherently Safer Chemical Processes – A Life Cycle Approach* by the CCPS, and *Guidelines for Risk Based Process Safety* by the CCPS for guidance. Demonstration could include documentation of conceptual design safety reviews, hazard analysis and risk assessments of detailed project designs, and a plan to address the recommendations to control the hazards.

2021-04-I-OH-R4

Identify and document all equipment that could release flammable materials and install LEL detectors in accordance with sources and guidance such as *Guidelines for Engineering Design for Process Safety* by the Center for Chemical Process Safety and *Explosion Hazards in the Process Industries* by Rolf K. Eckhoff. Ensure that detection of hazardous conditions automatically triggers both visual and audible alarms to alert plant personnel of the hazard. Develop and implement employee training on actions to take, such as prompt evacuation, when such alarms are activated.

2021-04-I-OH-R5

Develop and implement requirements for personnel to wear flame-resistant uniforms in all operating areas that process flammable chemicals. Update employee training material to include the requirement for and purpose of PPE use.

6.2 American Petroleum Institute (API)

2021-04-I-OH-R6

Develop specific design, construction, and alteration guidance for low-pressure process vessels in flammable and other highly hazardous chemicals service not exceeding an internal pressure of 15 psig in API 510 *Pressure Vessel Inspection Code*, API RP 572 *Inspection Practices for Pressure Vessels*, and/or other appropriate products. At a minimum, include guidance for:

(i) determining and documenting the low-pressure vessel's design pressure (such as through a data sheet and a nameplate affixed to the vessel);

(ii) determining when or if all or parts of the ASME Boiler and Pressure Vessel Code should be applied;

(iii) acceptable alternative engineering methods, if applicable; and,

(iv) alteration requirements, such as design assessments, inspections, and pressure testing.

6.3 American Society of Mechanical Engineers (ASME)

2021-04-I-OH-R7

Assist API in developing design, construction, and alteration guidance for low-pressure vessels in flammable and other highly hazardous chemicals service not exceeding an internal pressure of 15 psig. If any new design and construction guidance is specifically developed for pressure vessels in flammable and other highly hazardous chemicals service not exceeding an internal pressure of 15 psig, reference the design and construction guidance in the Section VIII, Division 1 of the ASME Boiler and Pressure Vessel Code (BPVC).

7 KEY LESSONS FOR THE INDUSTRY

To prevent future chemical incidents, and in the interest of driving chemical safety excellence to protect communities, workers, and the environment, the CSB urges companies to review these key lessons:

1. Facilities should ensure that equipment can safely operate within the safe operating limits that are documented in process safety information. After equipment alterations, quality should be assured for normal operation as well as abnormal and emergency conditions.

2. Equipment design requirements should take into account both the mechanical (pressure) and the process (hazardous chemical) risks when designing pressure equipment for safety. An atmospheric vessel is one that operates at the pressure of ambient air (in practice, typically under 0.5 psig), and a pressure vessel is one that contains pressure. Although API and ASME standards currently exempt pressure vessels not exceeding 15 psig, vessels that have the potential to build any pressure above atmospheric may still have safety implications for personnel in the vicinity, especially for equipment in highly hazardous chemicals service.

3. Facilities should use hierarchy of controls and prevention through design principles through a plant's entire life cycle to design and maintain fault-tolerant systems, so that a single human action or equipment failure cannot result in a catastrophic incident. During PHAs and design projects, safeguards should be selected using the hierarchy of controls, using inherently safer design and engineering controls instead of administrative controls to prevent process safety incidents. While administrative controls are important in certain scenarios, they depend on human actions, perception, and judgment and should not be relied on in lieu of engineering controls in highly hazardous chemical processes.

4. Flammable dense gases can form ground-level vapor clouds that can travel large distances to reach an ignition source and explode. Facilities that handle flammable materials should install LEL detectors that trigger automatic shutdowns of process equipment, with audible and visible alarms warning personnel to evacuate, and train employees on actions to take, such as prompt evacuation, when such alarms are activated.

5. Facilities that handle flammable or other hazardous materials should ensure that they are aware of the specific hazard characteristics of their materials, such as dense gases that can form ground-level vapor clouds. These specific hazards should be reflected within emergency planning processes and procedures. Workers must be trained on how to identify and react to hazardous situations including knowing when and how to evacuate.

6. Workers should be provided PPE that is protective against the hazards they may encounter in a sudden upset condition or emergency. In facilities that process flammable chemicals, flame-resistant PPE can protect workers from intense heat and flames for short periods of time, allowing them to run to safety. Workers should be trained on both the purpose for and the proper use of flame-resistant PPE.

8 References

[1] Yenkin-Majestic, "Yenkin-Majestic Paint Corporation," [Online]. Available: https://www.yenkin-majestic.com/. [Accessed 29 July 2021].

[2] OPC Polymers, "OPC Polymers - About Us," [Online]. Available: https://www.opcpolymers.com/about-us/. [Accessed 29 July 2021].

[3] Engineering360, "Specialty Polymers and Resins Suppliers in United States," [Online]. Available: https://www.globalspec.com/local/4044/C_US. [Accessed 11 January 2023].

[4] OPC Polymers, "OPC Polymers Product Reference Guide," 2017. [Online]. Available: https://www.opcpolymers.com/wp-content/uploads/2018/03/OPCPolymers_Catalog.pdf. [Accessed 12 October 2022].

[5] Brittanica, "alkyd resin," [Online]. Available: https://www.britannica.com/science/alkyd-resin. [Accessed 7 August 2023].

[6] G. d. With, Polymer Coatings: A Guide to Chemistry, Characterization, and Selected Applications, Weinheim, Germany: Wiley-VCH Verlag GmbH & Co., 2018.

[7] OPC Polymers, "Polychem 6994-V-50," [Online]. Available: https://www.opcpolymers.com/products/detail/6994-v-50/. [Accessed 9 September 2021].

[8] Census Reporter, "Columbus, OH," [Online]. Available: https://censusreporter.org/profiles/16000US3918000-columbus-oh/. [Accessed 10 August 2023].

[9] 10 WBNS, "Man found dead, 8 injured after explosion in northeast Columbus," 8 April 2021. [Online]. Available: https://www.10tv.com/article/news/local/man-found-dead-8-injured-after-explosion-in-northeast-columbus/530-02f3d2e5-024f-4dac-bb9a-da1de48aa03c. [Accessed 3 April 2023].

[10] WKYC Channel 3, "Frightening Scene | Cameras capture deadly explosion at Columbus paint plant," YouTube, 8 April 2021. [Online]. Available: https://www.youtube.com/watch?v=NznL7uA0aMA. [Accessed 29 September 2021].

[11] Columbus Monthly, "A Forgotten Community Searches for Answers After the Devastating Yenkin-Majestic Fire," 13 December 2022. [Online]. Available: https://www.columbusmonthly.com/story/lifestyle/features/2022/12/13/northeast-columbus-community-seeks-answers-after-devastating-yenkin-majestic-paint-factory-fire/69724501007/. [Accessed 7 April 2023].

[12] FOX28, "Residents' frustrations heighten with neighbor, Yenkin-Majestic, two years after explosion," 10 March 2023. [Online]. Available: https://myfox28columbus.com/news/local/residents-frustrations-heighten-with-neighbor-yenkin-majestic-two-years-after-explosion-fire-paint-factory-lawsuit-damages-columbus-residents-community-benefit-compensation-fund. [Accessed 18 July 2023].

[13] The Columbus Dispatch, "Two years after 2021 paint plant explosion, Columbus Council funds $189k air-quality study," 18 April 2023. [Online]. Available: https://www.dispatch.com/story/news/local/2023/04/18/residents-fears-from-2021-plant-explosion-lead-to-air-quality-testing/70117269007/. [Accessed 18 July 2023].

[14] WKBN27, "Air study approved for neighborhoods near paint factory explosion," 19 April 2023. [Online]. Available: https://www.wkbn.com/news/ohio/air-study-approved-for-neighborhoods-near-paint-factory-explosion/. [Accessed 18 July 2023].

[15] S. S. H. Burmester, C. D. Rielly and M. F. Edwards, "The Mixing of Miscible Liquids with Large Differences in Density and Viscosity," *Fluid Mechanics of Mixing,* vol. 10, pp. 83-90, 1992.

[16] J. A. Barton and P. F. Nolan, "Incidents in the Chemical Industry due to Thermal-Runaway Chemical Reactions," April 1989. [Online]. Available: https://www.icheme.org/media/10474/x-paper-02.pdf. [Accessed 18 August 2023].

[17] Center for Chemical Process Safety, Guidelines for Engineering Design for Process Safety (2nd Edition), New York, NY: Center for Chemical Process Safety/AIChE (CCPS), 2012.

[18] Center for Chemical Process Safety, "Process Safety Beacon: What if your agitator fails?," August 2018. [Online]. Available: https://www.aiche.org/ccps/resources/process-safety-beacon/archives/2018/august/english. [Accessed 15 August 2023].

[19] J. Walker, "Boiling and the Leidenfrost Effect," 1994. [Online]. Available: https://www.reed.edu/physics/courses/Physics332.s18/pdf/Leidenfrost.pdf. [Accessed 15 August 2023].

[20] American Petroleum Institute, API 510: Pressure Vessel Inspection Code: In-service Inspection, Rating, Repair, and Alteration, 10th Ed., Washington, DC: American Petroleum Institute, 2018.

[21] National Board of Boiler and Pressure Vessel Inspectors (NBBI), National Board Inspection Code, Part 3: Repair and Alterations, Columbus, OH: National Board of Boiler and Pressure Vessel Inspectors (NBBI), 2021.

[22] American Society of Mechanical Engineers, ASME Boiler and Pressure Vessel Code, Section VIII - Rules for Construction of Pressure Vessels, New York, NY: The American Society of Mechanical Engineers, 2021.

[23] saVRee, "Absolute, Atmospheric, and Gauge Pressure," [Online]. Available: https://savree.com/en/encyclopedia/absolute-atmospheric-and-gauge-pressure. [Accessed 24 July 2023].

[24] Center for Chemical Process Safety, "Atmospheric Storage Tank," [Online]. Available: https://www.aiche.org/ccps/resources/glossary/process-safety-glossary/atmospheric-storage-tank. [Accessed 25 July 2023].

[25] Center for Chemical Process Safety, Guidelines for Mechanical Integrity Systems, New York, NY: Center for Chemical Process Safety/AIChE, 2006.

[26] U.S. Occupational Safety and Health Administration, "Citation and Notification of Penalty (Inspection #1524024)," 6 October 2021. [Online]. Available: https://www.dol.gov/sites/dolgov/files/OPA/newsreleases/2021/10/OSHA20211816.pdf. [Accessed 24 March 2023].

[27] J. R. Thomson, "Boiler Explosions and Developments in Boiler Technology during the First Industrial Revolution," in *High Integrity Systems and Safety Management in Hazardous Industries*, Elsevier, 2015.

[28] L. E. a. Y. E. H. Brownell, "Antecedents of the ASME Code," in *Process Equipment Design* , John Wiley & Sons, 1959.

[29] B. Millet, K. Ebrahimi, J. Lu and D. Spencer, "A Case for New Low Pressure Vessel (LPV) Codes for Design Pressures Below 15 psi (100 kPA)," in *ASME 2021 Pressure Vessels & Piping Conference*, Virtual, Online, 2021.

[30] Process Industry Practices, "About Us," [Online]. Available: https://pip.org/about-us/. [Accessed 16 August 2023].

[31] Process Industry Practices, PIP VESLP001: Low-Pressure, Welded Vessel Specification, Austin, TX: Process Industry Practices (PIP), Construction Industry Institute, The University of Texas at Austin, 2022.

[32] American Petroleum Institute, API RP 572: Inspection Practices for Pressure Vessels, Washington, DC: American Petroleum Institute, 2009.

[33] American Society of Mechanical Engineers (ASME), "Fitness-for-Service," 2022. [Online]. Available: https://www.asme.org/codes-standards/find-codes-standards/ffs-1-fitness-service/2021/drm-enabled-pdf. [Accessed 3 November 2023].

[34] American Petroleum Institute and American Society of Mechanical Engineers, API 579-1/ASME FFS-1: Fitness-For-Service, Washington, DC: American Petroleum Institute Publishing Services, 2007.

[35] National Fire Protection Association, "NFPA 35: Standard for the Manufacture of Organic Coatings," 2016.

[36] EUR-Lex, "Directive 2014/68/EU of the European Parliament and of the Council of 15 May 2014 on the harmonisation of the laws of the Member States relating to the making available on the market of pressure equipment (recast) Text with EEA relevance," Publications Office of the European Union, 17 July 2014. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32014L0068. [Accessed 14 August 2023].

[37] U.S. Occupational Safety and Health Administration, "Identifying Hazard Control Options: The Hierarchy of Controls," [Online]. Available: https://www.osha.gov/sites/default/files/Hierarchy_of_Controls_02.01.23_form_508_2.pdf. [Accessed 6 October 2023].

[38] Center for Chemical Process Safety, Guidelines for Inherently Safer Chemical Processes - A Life Cycle Approach (3rd Edition), Hoboken, NJ: John Wiley & Sons, Inc., 2020.

[39] J. R. Taylor, Human Error and Process Plant Design and Operations - A Practitioner's Guide, Boca Raton, FL: Taylor & Francis Group, LLC, 2016.

[40] T. Kletz, An Engineer's View of Human Error, Third Edition, Rugby, Warwickshire, UK: IChemE, 2001.

[41] Health and Safety Executive, "Out of Control: Why control systems go wrong and how to prevent failure," 2003. [Online]. Available: https://www.hse.gov.uk/pubns/priced/hsg238.pdf. [Accessed 10 October 2023].

[42] P. Gruhn and S. Lucchini, Safety Instrumented Systems: A Life-Cycle Approach, Research Triangle Park, NC: International Society of Automation (ISA), 2019.

[43] American Society of Safety Professionals, ANSI/ASSP Z590.3-2021: Prevention through Design, Park Ridge, IL: American Society of Safety Professionals, 2021.

[44] J. W. Mroszczyk, Safety Engineering (Fourth Edition), Des Plaines, IL: American Society of Safety Engineers, 2012.

[45] R. K. Eckhoff, Explosion Hazards in the Process Industries, Gulf Publishing Company, 2005.

[46] G. Wells, Major Hazards and Their Management, Institution of Chemical Engineers (ICHEME), 1997.

[47] Center for Chemical Process Safety, Process Safety for Engineers - An Introduction (2nd Edition), Center for Chemical Process Safety/AIChE, 2022.

[48] I. a. K. M. Dincer, "Table B.15. Thermophysical Properties of Water Vapor (Steam) Gas at Atmospheric Pressure," in *Refrigeration Systems and Applications (2nd Edition)*, John Wiley & Sons., 2010, p. 436.

[49] A. S. Balchan, J. A. Klein and F. G. Klein, "Process Safety of Polymer Resin Manufacturing: A 20-Year Perspective," *Loss Prevention and Safety Promotion in the Process Industries,* vol. I, 1995.

[50] National Fire Protection Association, NFPA 2112: Standard on Flame-Resistant Clothing for Protection of Industrial Personnel Against Short-Duration Thermal Exposures from Fire, NFPA, 2023.

[51] National Fire Protection Association, NFPA 2113: Standard on Selection, Care, Use, and Maintenance of Flame-Resistant Garments for Protection of Industrial Personnel Against Short-Duration Thermal Exposures from Fire, NFPA, 2020.

[52] Institution of Chemical Engineers (ICHEME), BP Process Safety Series - Hazardous Substances in Refineries, ICHEME, 2005.

[53] H. Dodiuk and S. H. Goodman, Handbook of Thermoset Plastics, 3rd Edition, San Diego, CA: William Andrew, 2014.

[54] G. Gündüz, Chemistry, Materials, and Properties of Surface Coatings - Traditional and Evolving Technologies, Lancaster, PA: DEStech Publications, Inc., 2015.

[55] B. Elvers, Ullmann's Polymers and Plastics - Products and Processes, Weinheim, Germany: Wiley-VCH, 2016.

[56] T. Kletz and P. Amyotte, What Went Wrong? Case Histories of Process Plant Disasters and How They Could Have Been Avoided, Cambridge, MA: Butterworth-Heinemann, 2019.

[57] TÜV SÜD, "ASME/National Board Inspections of Boiler and Pressure Equipment," [Online]. Available: https://www.tuvsud.com/en-us/services/inspection/arise-inc/asme-national-board-inspections. [Accessed 14 August 2023].

[58] National Board of Boiler and Pressure Vessel Inspectors, "About Us," [Online]. Available: https://www.nationalboard.org/Index.aspx?pageID=102. [Accessed 22 August 2023].

[59] EUR-Lex, "Regulation (EC) No 1272/2008 of the European Parliament and of the Council of 16 December 2008 on classification, labelling and packaging of substances and mixtures," 16 December 2008. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32008R1272. [Accessed 22 August 2023].

[60] Occupational Safety and Health Administration, "Compliance with NFPA 30-2000 ventilation requirements is considered a deminimus violation," in *Standard Intepretation for OSHA 29 CFR 1910.106(e)(3)(v)(a)*, 2001.

[61] I. Sutton, Plant Design and Operations, Elsevier, 2015.

[62] Health and Safety Executive, "Our mission and priorities," [Online]. Available: https://www.hse.gov.uk/aboutus/our-mission-and-priorities.htm. [Accessed 10 October 2023].

[63] N. G. Leveson, "A More Powerful Approach to Process Safety," [Online]. Available: http://sunnyday.mit.edu/overview-COP.pdf. [Accessed 10 October 2023].

[64] Center for Chemical Process Safety, "CCPS Process Safety Glossary," [Online]. Available: https://www.aiche.org/ccps/resources/glossary. [Accessed 2023 17 October].

[65] HENGKO, "What Is Sparger All You Should Know," [Online]. Available: https://www.hengko.com/news/what-is-sparger-all-you-should-know/. [Accessed 16 October 2023].

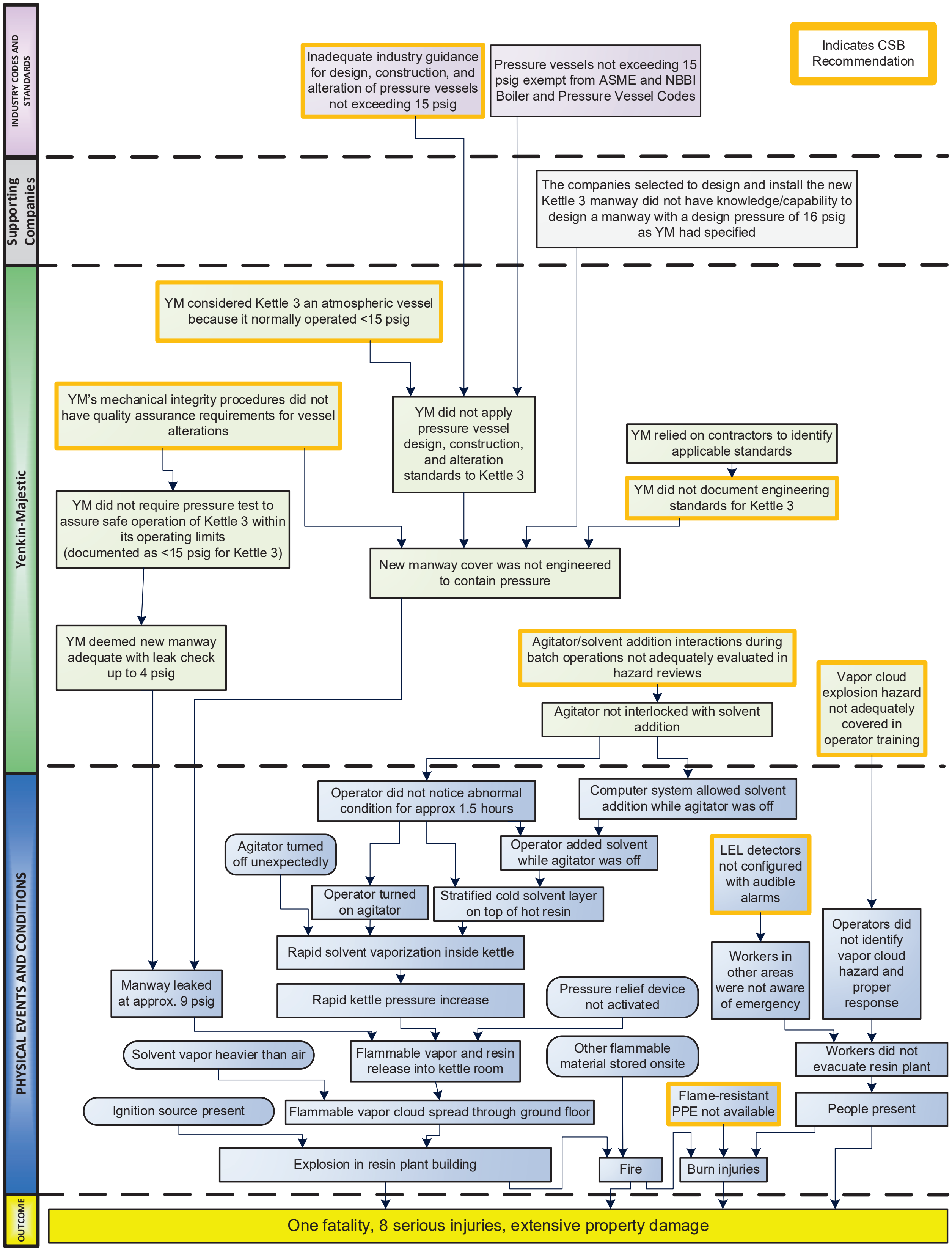
[66] Mott, "5 Steps to Designing a Sparger," [Online]. Available: https://mottcorp.com/5-steps-to-designing-a-sparger/. [Accessed 16 October 2023].

[67] National Fire Protection Association, "NFPA 30: Flammable and Combustible Liquids Code," [Online]. [Accessed 4 April 2023].

[68] R. E. Sanders, Chemical Process Safety - Learning from Case Histories (4th Edition), Elsevier, 2015.

[69] National Board of Boiler and Pressure Vessel Inspectors, National Board Inspection Code, Part 4: Pressure Relief Devices, National Board of Boiler and Pressure Vessel Inspectors, 2021.

Appendix A—Simplified Causal Analysis (AcciMap)



APPENDIX B—DESCRIPTION OF SURROUNDING AREA

The demographic information of the population residing within approximately a three-mile radius of the Yenkin-Majestic facility is contained below in **Figure 19** and **Table 4**.

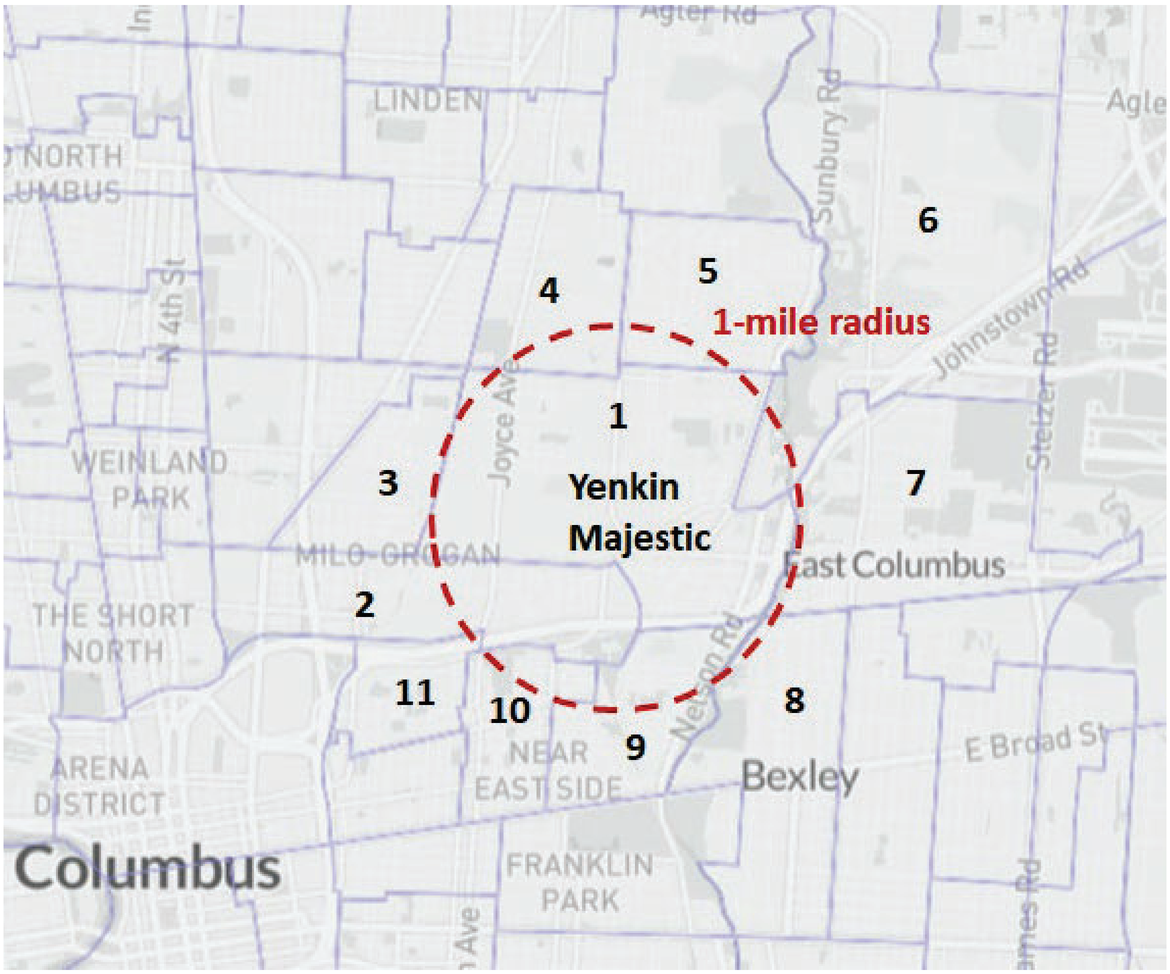


Figure 19. Census blocks within the approximately one mile distance from the Yenkin-Majestic facility. (Credit: Census Reporter, annotations by CSB).

Table 4. Tabulation of demographic data for the populations within the census blocks shown in **Figure 19**. (Credit: Census Reporter, compiled by CSB).

Tract Number	Population	Median Age	Race and Ethnicity		Per Capita Income	% Persons Below Poverty Line	Number of Housing Units	Types of Structures	
1	2,972	35.4	11%	White	$ 18,993	27.6%	1,237	78%	Single Unit
			73%	Black				17%	Multi-Unit
			0%	Native				5%	Mobile Home
			0%	Asian				0%	Boat, RV, van, etc.
			0%	Islander					
			2%	Other					
			6%	Two+					
			8%	Hispanic					
2	1,777	32.9	27%	White	$ 19,763	24.9%	775	87%	Single Unit
			59%	Black				13%	Multi-Unit
			0%	Native				0%	Mobile Home
			2%	Asian				0%	Boat, RV, van, etc.
			0%	Islander					
			4%	Other					
			5%	Two+					
			2%	Hispanic					
3	2,145	27.6	8%	White	$ 13,294	39.0%	885	58%	Single Unit
			85%	Black				42%	Multi-Unit
			0%	Native				0%	Mobile Home
			0%	Asian				0%	Boat, RV, van, etc.
			0%	Islander					
			0%	Other					
			0%	Two+					
			7%	Hispanic					
4	1,661	40.3	8%	White	$ 18,184	29.7%	813	78%	Single Unit
			83%	Black				19%	Multi-Unit
			0%	Native				2%	Mobile Home
			1%	Asian				0%	Boat, RV, van, etc.
			0%	Islander					
			3%	Other					
			2%	Two+					
			3%	Hispanic					
5	4,416	37	10%	White	$ 20,675	20.5%	1,848	90%	Single Unit
			77%	Black				8%	Multi-Unit
			0%	Native				2%	Mobile Home
			0%	Asian				0%	Boat, RV, van, etc.
			0%	Islander					
			0%	Other					
			5%	Two+					
			9%	Hispanic					

Tract Number	Population	Median Age	Race and Ethnicity		Per Capita Income	% Persons Below Poverty Line	Number of Housing Units	Types of Structures	
6	3,393	27.8	30%	White	$ 23,070	17.2%	1,053	82%	Single Unit
			61%	Black				18%	Multi-Unit
			0%	Native				0%	Mobile Home
			2%	Asian				0%	Boat, RV, van, etc.
			0%	Islander					
			0%	Other					
			2%	Two+					
			5%	Hispanic					
7	4,470	30.3	28%	White	$ 15,175	37.6%	2,018	46%	Single Unit
			54%	Black				45%	Multi-Unit
			0%	Native				9%	Mobile Home
			1%	Asian				0%	Boat, RV, van, etc.
			0%	Islander					
			0%	Other					
			4%	Two+					
			13%	Hispanic					
8	3,659	44.5	88%	White	$ 92,114	3.6%	1,423	74%	Single Unit
			5%	Black				26%	Multi-Unit
			0%	Native				0%	Mobile Home
			3%	Asian				0%	Boat, RV, van, etc.
			0%	Islander					
			0%	Other					
			4%	Two+					
			1%	Hispanic					
9	3,241	31.3	28%	White	$ 29,525	29.2%	1,656	48%	Single Unit
			61%	Black				52%	Multi-Unit
			0%	Native				0%	Mobile Home
			2%	Asian				0%	Boat, RV, van, etc.
			0%	Islander					
			1%	Other					
			4%	Two+					
			5%	Hispanic					
10	2,166	36.4	31%	White	$ 24,176	39.2%	1,455	53%	Single Unit
			61%	Black				47%	Multi-Unit
			0%	Native				0%	Mobile Home
			0%	Asian				0%	Boat, RV, van, etc.
			2%	Islander					
			0%	Other					
			6%	Two+					
			1%	Hispanic					
11	3,227	24.7	6%	White	$ 10,477	66.3%	1,588	27%	Single Unit
			85%	Black				74%	Multi-Unit
			0%	Native				0%	Mobile Home
			0%	Asian				0%	Boat, RV, van, etc.
			0%	Islander					
			1%	Other					
			4%	Two+					
			4%	Hispanic					

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