U.S. Chemical Safety and
Hazard Investigation Board

Fatal Equipment Rupture, Explosion, and Fire at the KMCO Chemical Facility

Crosby, Texas | *Incident Date: April 2, 2019* | **No. 2019-02-I-TX**

Investigation Report

Published: December 2023

SAFETY ISSUES:

- **Emergency Response**
- **Remote Isolation**
- **Hazard Evaluation**

U.S. Chemical Safety and Hazard Investigation Board

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The April 2, 2019, explosion and fire at the KMCO facility in Crosby, Texas, fatally injured James Mangum.

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Abbreviations

°F	degrees Fahrenheit
API	American Petroleum Institute
ASME	American Society of Mechanical Engineers
ASTM	American Society of Testing and Materials
CCPS	Center for Chemical Process Safety
CSB	U.S. Chemical Safety and Hazard Investigation Board
EBV	Emergency Block Valve
EIV	Emergency Isolation Valve
EOC	Emergency Operations Center
EPA	Environmental Protection Agency
ERP	Emergency Response Plan
ERT	Emergency Response Team
ESDV	Emergency Shutdown Valve
FNPT	Female National Pipe Thread
HAZAN	Hazard Analysis
HAZMAT	Hazardous Materials
HAZOP	Hazard and Operability study
HAZWOPER	Hazardous Waste Operations and Emergency Response
HSE	Health and Safety Executive
IChemE	Institution of Chemical Engineers
ICI	Imperial Chemical Industries
LLC	Limited Liability Company
LPG	Liquefied Petroleum Gas
MOC	Management of Change
NFPA	National Fire Protection Association
OSHA	Occupational Safety and Health Administration
PHA	Process Hazard Analysis
P&ID	Piping and Instrumentation Diagram
PPE	Personal Protective Equipment

psig	pounds per square inch (gauge)
PSM	Process Safety Management
PSSR	Pre-Startup Safety Review
PTFE	Polytetrafluoroethylene
RBV	Remotely Operated Block Valve
RMP	Risk Management Program
ROEIV	Remotely Operated Emergency Isolation Valve
ROSOV	Remotely Operated Shutoff Valve
SCBA	Self-Contained Breathing Apparatus

Executive Summary

On Tuesday, April 2, 2019, at 10:51 a.m., a flammable isobutylene vapor cloud exploded at the KMCO, LLC ("KMCO" pronounced "chem-co") facility in Crosby, Texas. The event fatally injured one KMCO employee and seriously injured two others. At least 28 other workers were injured, including five KMCO employees and 23 contract workers. On the day of the incident, more than 200 people were onsite, including KMCO employees, contract workers, and visitors. At approximately 11:00 a.m., local authorities issued a shelter-in-place order to residents within a 1-mile radius that was lifted over four hours later at approximately 3:15 p.m.

The incident occurred while KMCO operations staff were making a batch of sulfurized isobutylene, a lubrication additive product.[a] At 10:41 a.m., a fist-sized piece of metal broke away from the body of a 3-inch cast iron y-strainer in the batch reactor's liquid isobutylene supply piping. The field operator (who was a trainee at the time) was walking nearby and immediately stopped after hearing the loud noise created when the y-strainer broke. After a brief communication with a contract insulator who was exiting the area, the field operator contacted his board operator, beginning a series of urgent communications and quick actions by KMCO's operators and operations supervisors to stop the flammable isobutylene release, move other workers away from the danger, and prevent the vapor cloud from igniting.

KMCO's operations staff succeeded in moving other workers out of the immediate area and preventing vehicle traffic from approaching the flammable vapor cloud. Operations team members entered the release area and manually closed valves. This stopped the flow of isobutylene, but more than 10,000 pounds had already been released. The operations team members also opened other valves, allowing firewater to spray throughout the batch reactor area.

These actions were mostly complete when the isobutylene vapor cloud suddenly exploded while two operators were still within the vapor cloud, and a shift supervisor was near it. The explosion fatally injured one of the operators; the other operator and the shift supervisor suffered serious burn injuries.

Portions of the KMCO facility were substantially damaged from the explosion and subsequent fires. News outlets reported that the explosion shook nearby homes and was heard throughout the surrounding community.[b]

KMCO filed for Chapter 7 Bankruptcy (liquidation) in May 2020, and the facility was sold to Altivia Oxide Chemicals, LLC ("Altivia"). In July 2020, Altivia informed the CSB that it planned to dismantle KMCO's sulfurized isobutylene equipment involved in the incident as part of the company's efforts to install and operate new oxide reaction equipment at the Crosby, Texas, facility.

[a] KMCO's sulfurized isobutylene process described in this report was covered by OSHA's Process Safety Management (PSM) standard and the EPA's Risk Management Program (RMP) rule.

[b] *See* ABC News: Deadly Chemical Explosion [93, 9], and KHOU 11 News: Residents Heard, Felt Deadly Crosby Plant Explosion From Miles Away [94].

Safety Issues

The CSB's investigation identified the safety issues below.

1. **Emergency Response**. KMCO's emergency response procedures and training did not properly limit the role of its operators during the emergency response. KMCO's plant culture relied on unit operators taking quick actions to stop a release before the site's emergency response team assembled. KMCO could have reduced the severity of the April 2, 2019, event by establishing clear policies and training its workforce not to put themselves in danger to urgently stop a chemical release. The Occupational Safety and Health Administration's (OSHA) Hazardous Waste Operations and Emergency Response standard, more commonly referred to as HAZWOPER, provides the minimum requirements for emergency response operations involving hazardous materials, such as isobutylene. Effective emergency response operations prioritize life safety. Emergency response procedures and training should clearly communicate which incidents plant operators should respond to and which should be handled by a more qualified emergency response team. (*See* Section 4.1)

2. **Remote Isolation**. When the y-strainer ruptured, KMCO's workers lacked the safety equipment they needed to stop (isolate) the isobutylene release from a safe location, such as from within the blast-resistant control room. For example, had KMCO workers been able to close the actuated block valve installed just upstream of the y-strainer from the control room, the amount of isobutylene released and the subsequent harm to workers could have been greatly reduced. Industry knowledge about the need to provide workers with the capability to remotely isolate a major leak from a safe location dates back to at least 1969—50 years before the isobutylene vapor cloud explosion at KMCO. In fact, KMCO had an existing recommendation from a 2010 report developed for insurance underwriting purposes that called for providing remote isolation equipment for certain flammable liquid systems, including isobutylene. Although KMCO had installed remote isolation equipment for some of these systems, the company had not yet addressed this recommendation for its isobutylene system. (*See* Section 4.2)

3. **Hazard Evaluation**. Hazard evaluation is one of the most important elements of a process safety management program. KMCO's hazard evaluations consistently overlooked or misunderstood that its y-strainer was made from cast iron, a brittle material that existing industry standards and good practice guidance documents either prohibit or warn against using in hazardous applications, such as KMCO's isobutylene system. In addition, none of KMCO's hazard evaluations identified the potential for liquid thermal expansion or other possible scenarios to develop high-pressure conditions within the piping system that included the y-strainer. As a result, unlike other portions of KMCO's isobutylene piping, this piping section was not equipped with a pressure-relief device or otherwise protected from potential high-pressure conditions. (*See* Section 4.3)

Cause

The CSB determined that the cause of the isobutylene release was a brittle overload fracture of the cast iron y-strainer driven by internal pressure. The y-strainer was installed in a segment of the isobutylene piping that was not protected from the high-pressure conditions that developed within this equipment, most likely from liquid thermal expansion. The isobutylene vapor cloud was most likely ignited by electrical equipment within a poorly sealed, nearby building.

KMCO's hazard evaluation programs, including process hazard analysis, pre-startup safety review, and management of change, also contributed to the incident. KMCO's hazard evaluations consistently overlooked or misunderstood that its y-strainer was made from cast iron, a brittle material that existing industry standards and good practice guidance documents either prohibit or warn against using in hazardous applications, such as the company's isobutylene system. In addition, none of KMCO's hazard evaluations identified the potential for liquid thermal expansion or other possible scenarios to develop high-pressure conditions within the piping system that included the y-strainer. As a result, unlike other portions of KMCO's isobutylene piping, this piping section was not equipped with a pressure-relief device to protect it from potential high-pressure conditions.

KMCO did not provide safety equipment that its workers could have used to remotely stop (isolate) the isobutylene release from a safe location, which contributed to the severity of the incident. Deficiencies in KMCO's emergency response system, including its procedures and training, also contributed to the severity of the incident by not effectively distinguishing which events its operators should handle from those incidents that the site's emergency response team must respond to. Because KMCO relied on its unit operators to take quick actions to stop chemical releases, workers who were in a safe location moved toward the flammable isobutylene vapor cloud, which put them in harm's way. KMCO could have reduced the severity of the event by establishing clear policies and training its workforce to respond to a chemical release without putting themselves in harm's way.

Recommendations

Following its April 2, 2019, incident, KMCO filed for bankruptcy, and the company is no longer in business. Altivia Oxide Chemicals, LLC (Altivia) purchased the Crosby, Texas, facility in 2020 and informed the CSB that the process involved in the incident would be dismantled as part of Altivia's efforts to install two new oxide reactors and start production by the end of 2020. As a result, the CSB is not issuing recommendations with this report.

Nevertheless, the CSB urges Altivia to read this report closely and understand the factors that led to the incident at the KMCO facility and the lessons stemming from it. Moreover, if hereafter Altivia reinitiates the process or any equipment involved in this incident, the company should ensure that the facts, conditions, and circumstances that caused the incident—and contributed to its severity—are not repeated.

1 Background

1.1 KMCO

The KMCO, LLC ("KMCO" pronounced "chem-co") facility in Crosby, Texas, employed 164 people to manufacture specialty chemicals and operate its tolling facilities (**Figure 1**) [1].[a] Tolling is an arrangement in which a company processes raw materials or semifinished goods for another company."[b] KMCO purchased the Crosby plant on July 1, 2012, and invested over $50 million in the facility to, among other things, provide new equipment and infrastructure, including:[c]

- Blast-resistant control room (Reaction Control Room);
- Facility alarm system;[d]
- Isobutylene storage tank and piping;
- Distributed Control System ("Control System");
- Increased process automation;
- Motor Control Center;
- Two 350,000-gallon wastewater tanks;
- Boiler and condensate system;
- Firewater system;
- Cooling tower; and
- Plant air system.

[a] Artie McFerrin founded a company that built the plant at the Crosby site in 1975 [96]. In July 2012, the McFerrin family's company (KMCO, LP) sold the plant to KMCO, LLC.

[b] The Center for Chemical Process Safety (CCPS) defines tolling as "[p]roviding manufacturing services for a fee by a contractor (the toller), to a company issuing (letting) a contract for those services. Tolled services can include, reaction processes, formulation, blending, mixing or size reduction, separation, agglomeration, packaging/repackaging, and others or a combination of the above" [86].

[c] ORG Chemical Holdings, a private equity firm, was the parent owner of KMCO, LLC. ORG Chemical Holdings also owned the KMTEX, LLC ("KMTEX"), which operated a facility in Port Arthur, Texas. KMTEX was sold to Monument Chemical in July 2021 [78]. Similar to KMCO, KMTEX was a tolling and specialty chemical manufacturing facility.

[d] KMCO provided a news update about its new emergency alarm system on January 12, 2017 [87].

Figure 1. KMCO Facility in Crosby, Texas.[a] (Source: KMCO)

In June 2016, KMCO announced a new leadership team that, among other changes, sought to implement new management systems to ensure "safe and compliant operations" [2]. At the time of the April 2, 2019, incident, many of KMCO's key leadership positions were held by people who had less than two years of experience with KMCO. These employees were hired to help KMCO improve the site's management systems, and they were responsible for much of the site's process safety management program. The recently filled positions included the vice president of operations, plant manager, safety director, safety manager, emergency response team leader, safety technician, maintenance manager, reliability engineer, maintenance engineer, operations manager, and operations engineer.

1.2 KMCO Bankruptcy

The incident on April 2, 2019, interrupted normal business operations at KMCO and resulted in several rounds of employee layoffs that gradually decreased the number of employees at the Crosby facility over the next 13 months. On May 8, 2020, KMCO filed for bankruptcy under Chapter 7 of the U.S. Bankruptcy Code [3]. Under Chapter 7 bankruptcy (liquidation), KMCO's property was sold to provide money to individuals or companies to whom KMCO owed money [4]. Court records show that KMCO agreed to sell its chemical manufacturing facility in Crosby, Texas, to Altivia Oxide Chemicals, LLC, on the same day that KMCO filed for bankruptcy. The bankruptcy court approved the sale on May 26, 2020 [3]. As a result of the April 2, 2019, incident, KMCO is no longer in business.

[a] Based on the equipment and buildings shown in this photo, this image was likely taken between 2015 and 2016.

1.3 Isobutylene

Isobutylene is a highly flammable, colorless gas with a sweet gasoline odor [5].[a] Under certain (temperature and pressure) conditions, isobutylene can be a liquid.[b] Among other things, isobutylene is used in the production of aviation fuel, resins, chemicals, packaging, plastics, and antioxidants for food [5]. Isobutylene is typically transported and stored in a liquefied form, and it is among the gases referred to as LPG, or liquefied petroleum gas [6].[c] KMCO received isobutylene shipments as a liquid, stored its isobutylene as a liquid, and fed the isobutylene to its batch reaction system as a liquid.

1.4 Isobutylene System

KMCO used isobutylene as a raw material in its batch reaction process (**Figure 3**) to manufacture sulfurized isobutylene lubrication additive products.[d] On the day of the incident, this reaction system ("unit") was producing HiTEC® 3315, a lubrication additive.

The equipment used to produce sulfurized isobutylene at KMCO included an isobutylene storage tank[e] and a batch reactor (**Figure 2**).[f] This report uses the term "batch" because KMCO manufactured its sulfurized isobutylene products in batches rather than continuously.

[a] Isobutylene has a vapor density of 1.94, making it heavier than air. Isobutylene's lower explosive limit is about 1.8 volume percent, and its upper explosive limit is about 9.6 volume percent. The flash point of isobutylene is -105 degrees Fahrenheit (°F) [77].

[b] Isobutylene is a gas at atmospheric pressure and typical outdoor air temperatures. Liquefying isobutylene requires increasing the pressure, significant cooling, or a combination of increasing pressure and cooling. At atmospheric pressure, isobutylene will be a liquid if it is colder than its boiling point of 19.6 °F [68]. Liquefying isobutylene at 20 degrees Celsius (68 °F) requires pressures greater than 2,560 hectopascal (37.1 pounds per square inch) [95, p. 8]. Liquefying isobutylene requires more pressure at warmer temperatures and less pressure at cooler temperatures.

[c] Other LPGs include propane, propylene, and butane [92, p. 365].

[d] Sulfurized isobutylene is an extreme pressure lubrication additive [84, p. 120].

[e] KMCO's 70,000-gallon isobutylene storage tank was built in 2014, and the tank was commissioned and began operating in 2015. The tank was made from SA-516-70 carbon steel, had an inner diameter of 12 feet, and was 80 feet long (seam-to-seam). The tank's 2:1 elliptical "heads" add to the overall length. The maximum allowable working pressure was 200 pounds per square inch at 150 °F. The isobutylene storage tank was designed to meet the 2013 edition of the American Society of Mechanical Engineers (ASME) code, Section VIII, Division 1.

[f] KMCO replaced its isobutylene storage tank and piping system during 2014 and 2015. The primary reason for the new isobutylene system was to improve safety. The previous isobutylene storage tank was located within the unit, not far from the batch reactor. Safety concerns about transferring isobutylene from trucks to the old isobutylene storage tank, which was near a hot oil heater, were among the reasons for installing the new isobutylene storage tank and piping system.

Figure 2. Post-Incident Photos of KMCO's Isobutylene Storage Tank (left) and Batch Reactor System (right). (Credit: CSB)

Figure 3 shows a simplified schematic of KMCO's isobutylene process used to charge the batch reactor periodically with isobutylene to make sulfurized isobutylene.

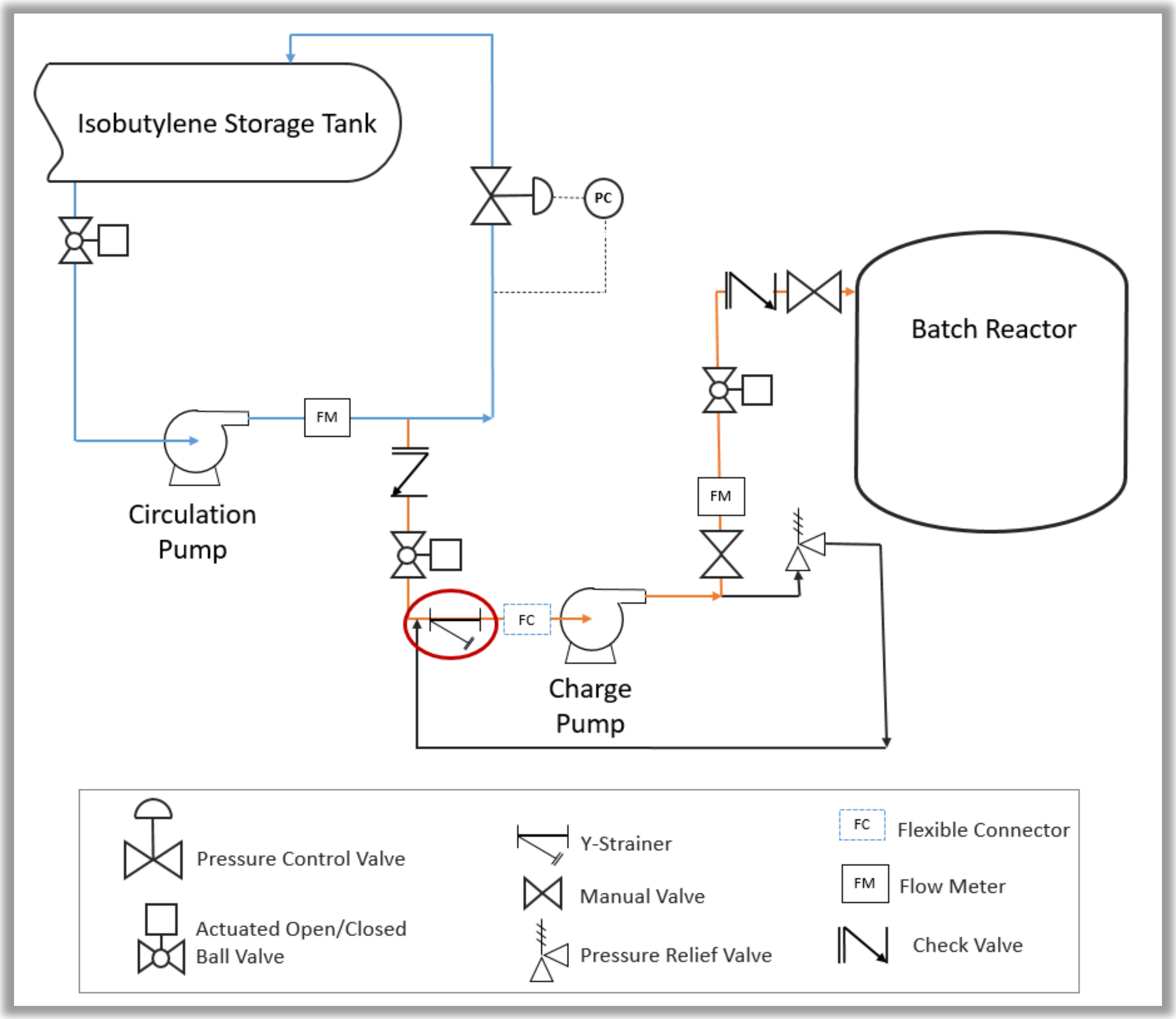

Figure 3. Isobutylene System. This simplified schematic shows the isobutylene system KMCO used to supply (charge) its batch reactor. The red circle shows the location of the y-strainer. (Credit: CSB)

There were two pumps in the isobutylene system: an isobutylene circulation pump and an isobutylene charge pump. The pumps were not operated remotely and could only be started or stopped by operators in the field.

The circulation pump provided a steady supply of isobutylene to help maintain the reliable operation of the charge pump. The isobutylene circulation pump circulated isobutylene through more than 1,200 feet of piping from the storage tank to the batch reactor area and back to the isobutylene storage tank. The isobutylene charge pump was used to charge the batch reactor when the batch reaction procedure called for adding isobutylene. As shown in **Figure 3**, KMCO installed a pressure-relief valve on the charge pump's outlet piping. This pressure-relief valve's outlet (discharge) was typically routed to the charge pump's inlet (suction piping). In addition, the inlet piping to the isobutylene charge pump included a filtration device commonly called a y-strainer (**Figure 4**).

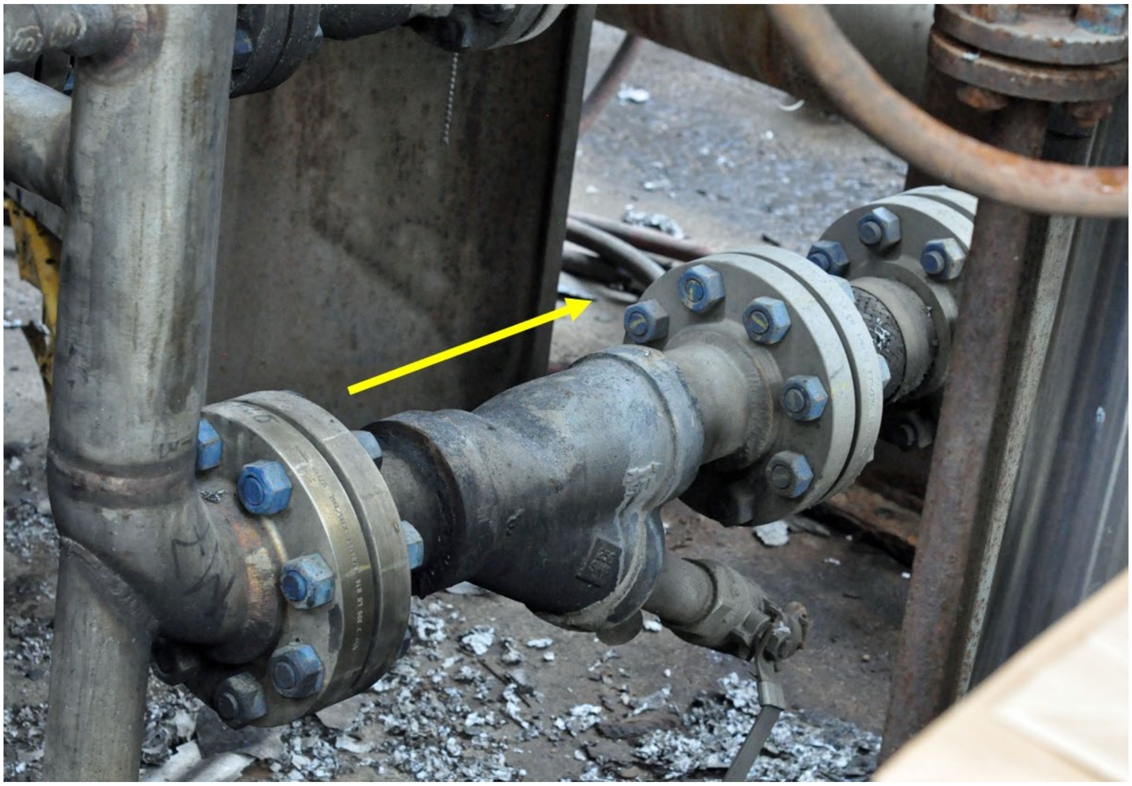

Figure 4. Y-Strainer (East Side). This post-incident photo shows the top and east sides of the 3-inch y-strainer in the inlet piping to the isobutylene charge pump. The orientation of the y-strainer was such that the straight-through flow was headed north. (Credit: CSB)

In addition to manually operated valves, the isobutylene system had several actuated valves. Of these actuated valves, board operators working inside the control room could control only the pressure control valve shown in **Figure 3**. The actuated ball valves could only be opened or closed by operators in the field.[a]

1.5 Shift Operations Staffing

KMCO used a single shift supervisor to oversee all shift operations activities.[b] Depending on the type of operation or reaction chemistry involved, KMCO strategically split its operations group into two major groups—Reaction 1 and Reaction 2.[c] Reaction 1 included five operational areas, and Reaction 2 included two operational areas.

In the Reaction 2 area, the batch reactor system used to make sulfurized isobutylene was one of several operating units assigned to Board Operator 1. Board Operator 2 had a nearly equivalent level of responsibility for other operating units. The Reaction 2 area had several field operators to support each of the two board

[a] The actuated ball valve on the inlet (suction) piping to the isobutylene circulation pump was equipped with a fusible link. This design should allow the valve to automatically close under certain fire conditions [54, p. 97]. The April 2, 2019, incident did not expose this valve to fire conditions.

[b] Additional managers and supervisors were present to support the other work that occurs during the Monday through Friday day shifts.

[c] Not all operations units under "Reactions" involved chemical reactions.

operators. One field operator supported the isobutylene system used to charge the sulfurized isobutylene reaction system. Board Operator 1 and Board Operator 2 conducted most of their work inside the Reaction Control Room, but each board operator also had some field responsibilities. For example, these board operators might go outside to help a field operator or verify a proper valve alignment in the field before starting an operational activity.

1.6 Control Room(s)

There were three buildings at KMCO that workers commonly referred to as "control rooms," but at the time of the April 2, 2019, incident, only one was being used as a formal control room (**Figure 5**).

Figure 5. Reaction Control Room. KMCO's blast-resistant control room. (Credit: CSB)

Following a facility siting study, KMCO built a blast-resistant control room in 2013 to improve safety.[a] After its completion, KMCO relocated the shift supervisor and plant operators from the two previous control rooms—the Reaction 1 Control Room and the Reaction 2 Control Room—to the new Reaction Control Room (**Figure 6**).

[a] Both the Baker Panel report and the CSB's investigation of the 2005 BP America Refinery explosion in Texas City, Texas, discuss the importance of using blast-resistant buildings [90, 91].

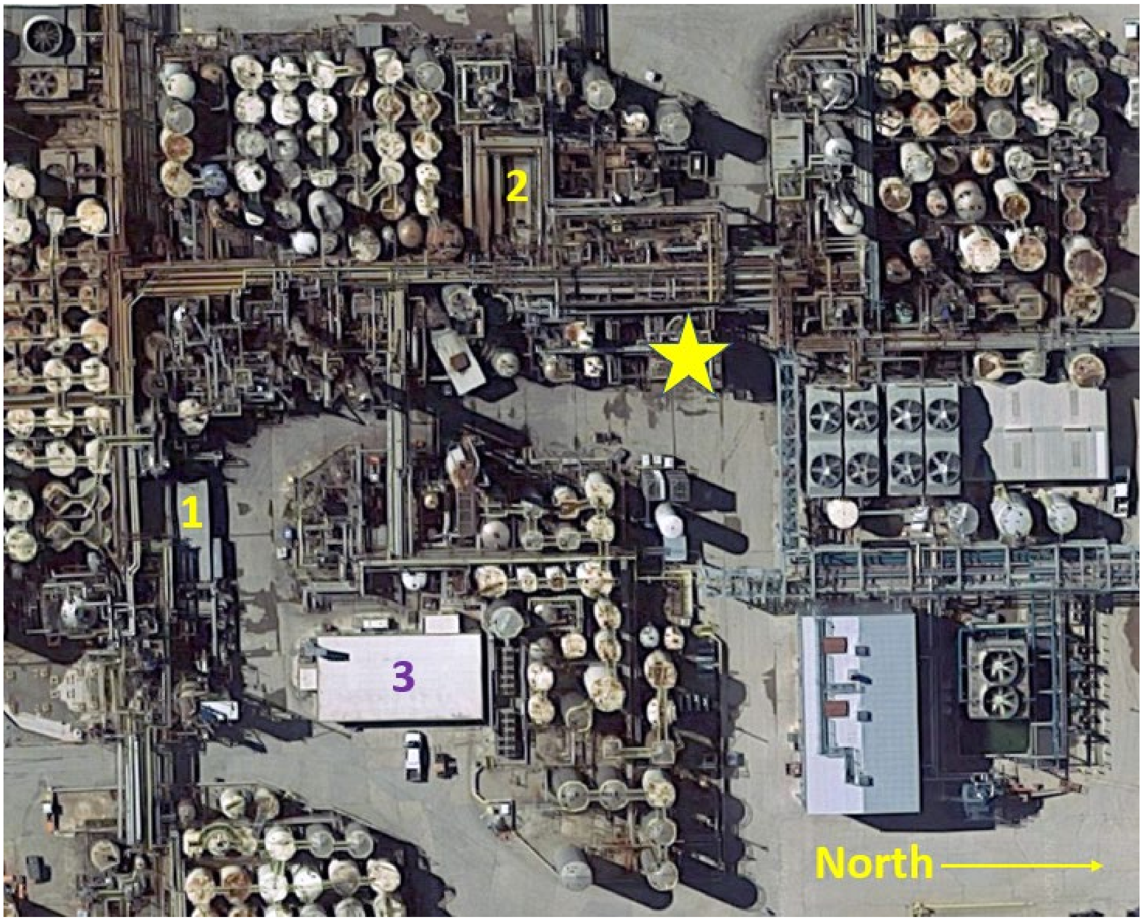

Figure 6. KMCO Control Rooms. This 2019 image of the KMCO facility shows the location of the Reaction 1 Control Room (yellow "1"), the Reaction 2 Control Room (yellow "2"), the new Reaction Control Room (purple "3"), and the location of the isobutylene release (yellow star). (Credit: Google, annotations by CSB)

KMCO later converted the Reaction 1 Control Room to store personal protective equipment (PPE) and renamed this plant building the PPE Room (**Figure 7**).

Figure 7. PPE Room. This photo shows the former Reaction 1 Control Room that KMCO converted to store PPE. The construction of the former Reaction 2 Control Room was similar to this building. (Credit: CSB)

KMCO managers stated that the former Reaction 2 Control Room was "essentially an old electrical building" with load cells, local process data readouts, and motor control equipment to start or stop some pumps. After commissioning the new Reaction Control Room, KMCO renamed the former Reaction 2 Control Room the R-II Motor Control building ("R2 Building"). The R2 Building also housed the equipment needed to stop some of the equipment for Board Operator 2's units. A self-contained breathing apparatus (SCBA) was also located in this building.

KMCO planned to relocate useful equipment from the R2 Building into a new motor control center[a] and then demolish the R2 Building. KMCO's decision to eliminate this building was based on safety concerns with the R2 Building's type of construction and the proximity of this building to reactors, as well as more efficient operation. As one manager stated, "That's a very old method of construction. You find it on chemical plants everywhere, and you want to move that out."

1.7 Altivia Oxide Chemicals

Altivia Oxide Chemicals, LLC ("Altivia") announced its purchase of KMCO's Crosby, Texas, facility on June 1, 2020 [7]. Altivia informed the CSB that it would not seek to operate the batch reactor and isobutylene system involved in the April 2, 2019, incident (**Figure 3**). Altivia further communicated that the process equipment KMCO used to manufacture sulfurized isobutylene lubrication additive products would be dismantled as part of Altivia's efforts to install two new oxide reactors and start production by the end of 2020.[b]

[a] A motor control center is a physical grouping of motor starters in one assembly [69].

[b] In addition, Altivia informed the CSB that it did not intend to conduct its own investigation or complete KMCO's investigation of the April 2, 2019, incident. KMCO's investigation of the incident ended with its bankruptcy filing.

1.8 Surrounding Area Demographics

Figure 8 shows the KMCO facility and depicts the surrounding area. The circles are set at one (blue), three (orange), and five (yellow) miles from the location of the isobutylene release. Summarized demographic data for the five census blocks within a 1-mile vicinity of the KMCO facility are shown below in **Table 1**. There are about 24,000 people residing in about 9,184 housing units. In general, the local population is predominantly white, living in single-unit housing, with five percent below the poverty level. Detailed demographic data are included in Appendix C.

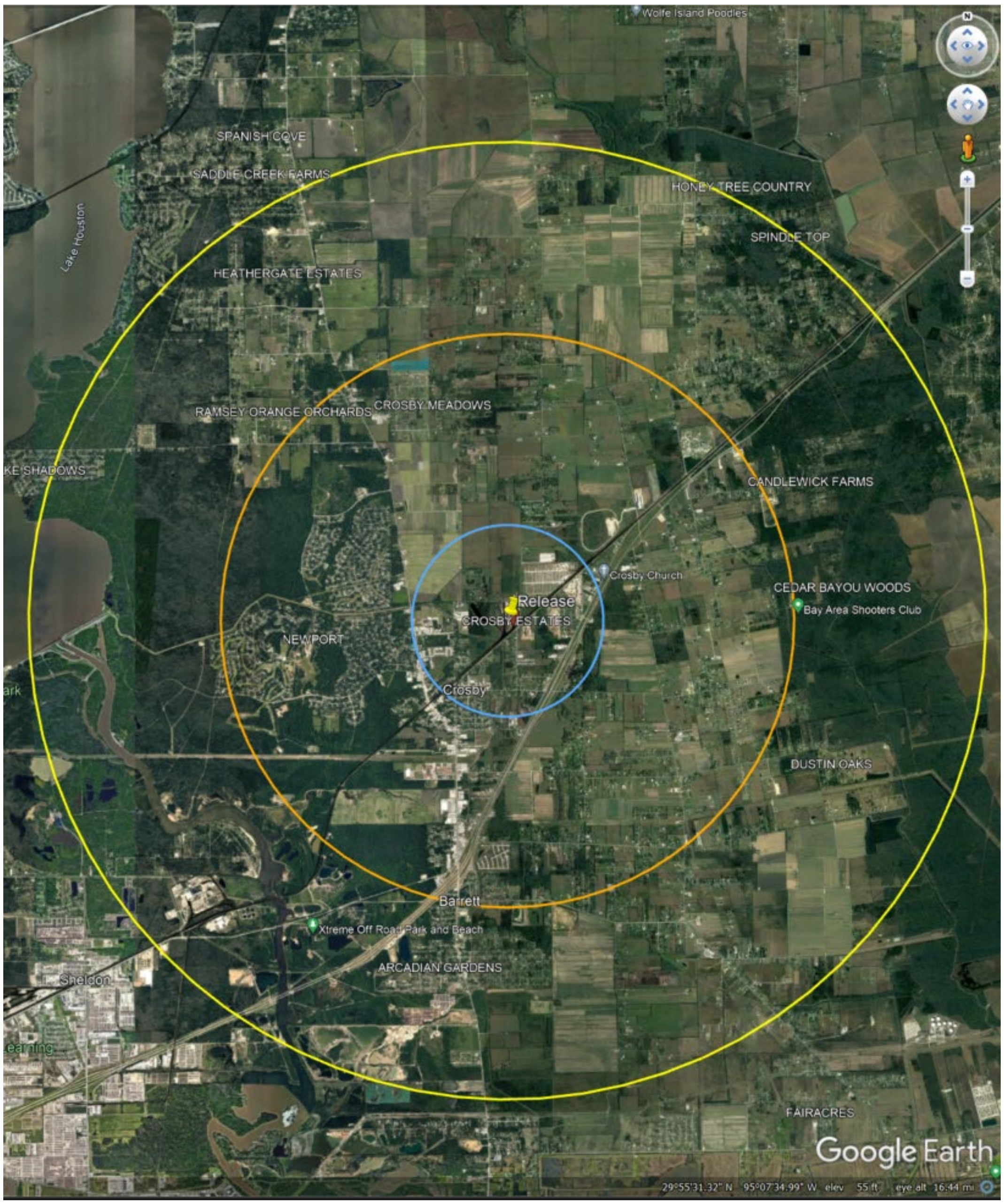

Figure 8. Area Surrounding the KMCO Facility. (Credit: Google Earth, annotations by CSB)

Table 1. Summarized Demographic Data. (Credit: CSB using data obtained from Census Reporter)

Population	Race and Ethnicity (%)		Per Capita Income ($)	Persons Below Poverty Line (%)	Number of Housing Units	Type of Housing Units (%)	
23,992	White	66	36,483[a]	5.0	9,184	Single Unit	85.9
	Black	5				Multi-Unit	5.5
	Native	1				Mobile Home	8.5
	Asian	1				Boat, RV, Van, etc.	0.1
	Islander	0					
	Other	0					
	Two+	2					
	Hispanic	24					

[a] Census Reporter reports that the per capita income for Crosby, Texas, is $27,315 [80]. The Census Bureau reports that the 2022 per capita income for the United States is $37,638 [81].

2 Incident Description

2.1 Sulfurized Isobutylene Operation

On the morning of April 2, 2019, KMCO's operations staff were making a batch of sulfurized isobutylene. Field Operator 1 and Board Operator 1 worked together to complete the isobutylene charge to the batch reactor that KMCO's night shift operators had started. After completing the isobutylene charge, Field Operator 1 closed several valves on the isobutylene charge pump outlet (discharge) piping to the batch reactor. Control system data showed that the isobutylene charge was completed at 6:25 a.m.[a, b]

2.2 Isobutylene Release

Later that morning, Board Operator 1 and Board Operator 2 were working in the Reaction Control Room. Surveillance video showed that the weather was calm and mostly clear, generally unfavorable for dispersing a gas release (**Figure 9**).[c] Shortly before 10:41 a.m.,[d] Field Operator 1 (who was a trainee at the time) was walking by the sulfurized isobutylene batch reactor when he heard a loud "pop" sound followed by a loud whooshing noise similar to "an air hose coming off." Field Operator 1 told CSB investigators that a y-strainer failed. He described the isobutylene release as "coming out quick." A contract worker insulating tubing near the reactor heard the loud sound when the "line blew," saw the vapor pouring into the area, and ran out of the unit. She described the vapor as chest-high and growing larger, flowing down the adjacent road. The contract worker saw Field Operator 1, told him that she did not know what had happened, and then evacuated from the area.

[a] A scrubber pump needed repair, and KMCO suspended the sulfurized isobutylene batch until that maintenance work was completed. While waiting for the maintenance on the scrubber pump, Field Operator 1 performed other tasks, such as helping a coworker connect a railcar for a different process.

[b] This report uses KMCO's control system data as the basis for time. The CSB's factual update for the KMCO incident used surveillance video as the basis for time. Based on the time of the explosion, the CSB estimates that 67 seconds need to be added to surveillance video time to match control system time. See the Timeline of Key Events (Appendix B) for more precise time stamps of certain events.

[c] KMCO did not have weather station equipment to monitor or record weather conditions. Weather conditions are available for the George Bush Intercontinental Airport, a straight-line distance of about 19 miles from KMCO. Five consecutive hourly weather records, from 5:53 a.m. through 9:53 a.m., show calm winds at the airport, with temperatures rising from 38 to 54 °F [72]. The 10:53 a.m. airport weather data shows a temperature of 59 °F, variable wind direction, and a wind speed of three miles per hour [72]. The National Weather Service defines variable wind the same way as variable wind direction. Variable wind means that the wind direction fluctuates by 60 degrees or more during the 2-minute evaluation period and the wind speed is greater than six knots (6.9 miles per hour), or the wind direction is variable, and the wind speed is less than six knots [71].

[d] KMCO control system data for the flow meter on the isobutylene circulation pump (**Figure 3**) shows a significant increase in isobutylene flow shortly before 10:41 a.m., consistent with a hole developing in the y-strainer, releasing isobutylene to the atmosphere.

Figure 9. Surveillance Video Images Showing the Time of Incident Weather Conditions at KMCO. The yellow circle (left) shows a windsock under calm wind conditions. (Credit: KMCO, annotation by CSB)

Field Operator 1 saw a white cloud of vapor hovering near the ground with three to four feet of a wavy, hazy vapor above it that looked "like a water mirage over hot pavement" or "like if you're filling up a gas tank and you see the fumes coming out."

2.3 Operations Response and the Explosion

Since Field Operator 1 had only been with KMCO for about six months, he was not sure what material was being released; so he called Board Operator 1 to come out to the unit to help assess the situation. Field Operator 1 met Board Operator 1 about halfway between the Reaction Control Room and the batch reactor. Board Operator 1 identified the leak as isobutylene and, using the all-call[a] feature on Field Operator 1's radio, which allowed simultaneous communication on all the KMCO radio channels, announced: "Attention KMCO, evacuate the reaction area." Based on KMCO's surveillance video, which shows key people suddenly acting with concern and purpose, this radio call to evacuate the reaction area took place shortly after 10:45 a.m.

Field Operator 1 and Board Operator 1 then retreated to the Reaction Control Room. Board Operator 1 put an SCBA on for respiratory protection, took a radio from Field Operator 1, and headed back to the unit. Soon after 10:46 a.m., the isobutylene release stopped after Board Operator 1 closed a manual isolation valve in the unit.[b] Field Operator 1 then teamed up with a senior field operator to turn on firewater monitors, instruct people using motorized equipment to shut the equipment down and evacuate, and close vehicle gates to prevent workers from driving into the flammable vapor cloud.

At 10:46 a.m., KMCO's Shift Supervisor was attending a meeting in the administration building, which was located about 300 feet from where the release had occurred.[c] The Shift Supervisor heard the radio call from Board Operator 1 about the isobutylene release, immediately left the meeting, and headed toward the sulfurized isobutylene unit. Approaching the unit, the Shift Supervisor described seeing "a two-foot river" of isobutylene

[a] An all-call is a call from an individual radio to every radio on the channel and multiple talk groups. It is often used to make important announcements [70, p. 14].

[b] KMCO control system data shows the isobutylene flow started decreasing at 10:46:13 a.m. and stopped at 10:46:23 a.m. Due to the nature and extent of Board Operator 1's injuries, the CSB was not able to interview Board Operator 1. Based on his experience and other actions he performed, the CSB concluded that Board Operator 1 was most likely the person who closed the isolation valve to stop the isobutylene release.

[c] At the time that the y-strainer ruptured, the Shift Supervisor was attending a meeting to discuss the findings of recent incident investigations at the facility and determine whether effective corrective actions were being developed.

vapor "going all the way down the road."[a] Upon seeing the magnitude of the release, the Shift Supervisor used the all-call feature on his radio to order an evacuation of the plant at about 10:47 a.m. At about this time, the Shift Supervisor saw that Board Operator 1 and Board Operator 2 were responding to the isobutylene release and wearing SCBAs.

The Shift Supervisor turned on a nearby firewater monitor to direct water spray over a portion of the isobutylene vapor cloud, went into the boiler house, shut down the boiler, and told other workers in the area to evacuate. The Shift Supervisor recalled seeing Board Operator 1 and Board Operator 2 turning firewater monitors on and activating water deluge systems in their respective units. The Shift Supervisor said that Board Operator 1 had also manually closed valves to stop the isobutylene release. The Shift Supervisor then went to another nearby firewater monitor and turned it on. After turning on this last firewater monitor, the Shift Supervisor turned to leave the area, and the explosion occurred. KMCO surveillance cameras visibly shook after 10:51 a.m., capturing the time of the explosion. The explosion lifted the Shift Supervisor off the ground. Upon landing, the Shift Supervisor was surrounded by flames and suffered serious burns. When the flames receded, the Shift Supervisor was able to get up and walk to the plant gate, where another KMCO supervisor helped him get medical attention for his burn injuries.

A KMCO manager, who had gone toward the unit following Board Operator 1's radio call at 10:46 a.m., witnessed Board Operator 1 completing some activity near the batch reactor. The manager could not tell whether Board Operator 1 was in the vapor cloud, but the isobutylene vapor cloud was between them. The manager described the vapor cloud as being "knee to … waist-high" and added that "it was rolling." "Not rolling as moving forward but rolling within itself … ." The manager described what happened next. He said:

> So, when I saw [the vapor cloud] … I yelled at [Board Operator 1], motioning him to come on, it's time to come out. I was about 20 yards away, equipment stuff going on, don't know whether he heard me or not. But it appeared to me at that time that for whatever [reason], if he heard me or not, that he was headed toward me in my direction.

As Board Operator 1 began exiting the unit, he was walking through the vapor cloud when it suddenly ignited, and Board Operator 1 was engulfed in a "ball of fire." When the flames subsided, the manager helped Board Operator 1 exit the plant and get medical attention for his burn injuries.

The initial response to the emergency was handled by KMCO's operators and operations management. These activities included manually closing valves to stop (isolate) the isobutylene leak, activating firewater deluge systems, ordering a plant-wide evacuation, turning off equipment, closing vehicle gates, instructing people using motorized equipment to shut the equipment down and evacuate, and assisting the injured out of the plant to get medical attention. The first member of KMCO's emergency response team (ERT) to put on their protective equipment and head toward the unit did so at about 10:54 a.m., about three minutes after the explosion.

[a] The Shift Supervisor wore the normal plant-required personal protective equipment, including flame-resistant clothing, safety glasses, a hard hat, and safety shoes.

2.4 Emergency Notification and Evacuation

After evacuating from the batch reactor area, the contract worker who was insulating tubing in the area where the isobutylene release occurred warned her coworker about the emergency, hurried to her car, and drove away from the plant. She drove about three miles and stopped near a local restaurant to call her company. She described hearing the explosion at KMCO as she was exiting her vehicle.

On the day of the incident, more than 200 KMCO employees, contract workers, and visitors were onsite. KMCO had a plant alarm system that, among other purposes, was supposed to ensure all workers could be notified of emergency situations. But KMCO never activated its plant alarm system during the isobutylene release, explosion, or subsequent fires. Instead, KMCO relied on its plant radio system to make emergency notifications. At KMCO, most employees carried a radio. For contractors, it was typical to have the foreman carry a radio. For a team of contract workers, one member of the team would normally have a radio. But not all workers at the site carried a radio or were with someone carrying a radio. As a result, some workers did not receive the emergency notification radio message to evacuate from the plant.

While discussing which workers carried a radio, one contractor supervisor explained the normal practice and what he experienced on the day of the incident:

> I require all my teams to go out as teams, all my people to go out as teams of at least two. And each team is required to have a radio.
>
> I heard a call over the radio. "Evacuate the reaction area." With a definite sense of urgency in their voice. Then seconds later, "Turn off the fans. Turn off the fans." Seconds later. Then they called for ERT. "We need ERT immediately."
>
> So, from that point, immediately after that, I jumped up out of my desk [chair], left the office, went outside, and made a call on the radio, saying, … "All [name of contractor] employees quickly but safely, please make your way back ... to the warehouse," you know. So I could get accountability for everybody that was here.
>
> Shortly after that, … most everybody was in the warehouse at that point. So I could see that people were here.
>
> We got almost to the [motor control center] building here, and that's when I saw the fire suppression system and knew that this was a serious ... this was a serious something. Something was really bad wrong. A, they've never called an evacuation while we were here before. And, B, with the fire suppression going on in the reaction area, that was bad. That was not going to be good. Seconds later was the first explosion.
>
> I ran back to my office grabbed my keys and my clipboard with my sign-in sheet. I also have everyone that comes to work for me, subs, and engineers and … my field hands, they all sign in on a sign-in sheet. That way, I have accountability for them every day. That was my saving grace that morning. So I grabbed it, and I headed out as well. ... I was the last one out. Made sure everyone else was out, and then I left. I met them over at

> the ... Everyone was over behind ... the [Emergency Response Team] building. So I got a headcount. And not only did I get a headcount, but I checked off the names as I saw them. I physically saw you, made you speak to me, and then I signed their names off.

But hearing the call on the plant radio system was not the signal all the contract workers relied upon to evacuate. A contract insulator, working in a different contractor's crew with two other workers, was walking toward a job site when his foreman suddenly stopped. The insulator described his experience, saying:

> The foreman had a weird look on his face, looking towards the distance. And he was telling us to, you know, 'come here,' you know, 'Do you see what I see?' And we all went towards him, and we saw, towards the distance, the … the disorientation of the … of the air.
>
> And nobody told us anything. Nobody told us on the radio what … if anything was going on. But if it wasn't for him [the foreman], we wouldn't have known. So that's when we just took our own advice and said, this is a leak, you know, we should just walk out. Anybody that we see, we tell them to walk out.
>
> And there are two operators close to the leak, by the way. But they were discussing between themselves, as if they were in shock as well, but didn't know how to react to it […].
>
> And as we got to the gate … it was locked. … And right then and there we saw [the explosion] … like a big ball of fire. And you could just feel the pressure hit you. And that's when everybody panicked, really. So everybody started running. I just followed the crowd. And I don't know what they were going to do at the gate, but they decided to pick it up (**Figure 10**). And I was one of the first ones to go and squeeze under there. I don't even know how I managed to, but … you know, thank God that I … that I did. And, yeah, after that, we just walked away as far as we could to get away from the … the explosion.

Figure 10. Evacuation Under Plant Fencing. This surveillance camera image shows workers helping other workers to exit under plant fencing about 36 seconds after the explosion.[a] (Credit: KMCO)

2.5 Emergency Response

Emergency responders to the incident included KMCO's Emergency Response Team, the Crosby Volunteer Fire Department (**Figure 11**), Mutual Aid Mont Belvieu, and responders from Harris County. Harris County responders included the Sheriff's Office and the Harris County Fire Marshal's Office. KMCO also brought in U.S. Fire Pump to help with the firefighting. The incident triggered a shelter-in-place order for community members within a 1-mile radius [8].[b]

[a] According to KMCO's evacuation plan, this gate was not intended to be an entrance or exit for workers. KMCO periodically unlocked and opened this gate to allow heavy equipment to enter or exit. At the time of the incident, this gate was in its usual position, closed and locked for site security. Only one of KMCO's four rally points was outside the plant fence line.

[b] Officials lifted the shelter-in-place at 3:15 p.m., more than four hours after the explosion.

Figure 11. Emergency Response. This image from a KMCO surveillance camera shows a fire truck entering the facility at about 11:28 a.m. (Credit: KMCO)

Emergency responders transported Board Operator 1 and the Shift Supervisor by helicopter to a hospital in Houston to get medical treatment for the serious burn injuries they suffered (**Figure 12**).

Figure 12. Life Flight Helicopter. One of the two helicopters that responded to the incident to transport injured workers. (Credit: ABC [9])

KMCO conducted a headcount of its employees, contractors, and visitors and found that one KMCO employee, Board Operator 2, was missing. Emergency responders found Board Operator 2 deceased under debris near the entrance to the R2 Building. During an emergency shutdown, one of Board Operator 2's responsibilities included shutting down pumps, which required accessing electrical equipment located inside the R2 Building.

Other than shutting that equipment off, Board Operator 2 may have been entering the R2 Building to make sure no one was in there. At 12:07 p.m., medical responders evaluated Board Operator 2 and did not try to resuscitate him. The Harris County Institute of Forensic Sciences autopsy report shows that Board Operator 2 died from “sharp force injuries of the right upper extremity with transection of the right brachial artery and vein” resulting from an “accident” [10].

2.6 R2 Building

One of the responders described what the R2 Building looked like right after the incident, saying, “Shrapnel. … There was nothing left of it. Wires, there was nothing there. There wasn’t a building there anymore” (**Figure 13**, **Figure 14**, and **Figure 15**).

Figure 13. R2 Building (North Side). This post-incident photo shows the path KMCO workers commonly took to enter the R2 Building. With process units on the left and right, this walkway led to the entrance on the north side of the R2 Building, where emergency responders found Board Operator 2. (Credit: CSB)

Figure 14. R2 Building (South Side). This post-incident photo shows the south side of the R2 Building. (Credit: CSB)

Figure 15. R2 Building (Top View). This photo, taken from the top of adjacent equipment, shows the post-incident condition of the R2 Building. (Credit: CSB)

2.7 Consequences

The explosion fatally injured Board Operator 2. Board Operator 1 and the Shift Supervisor suffered serious burn injuries that resulted in inpatient hospitalization. The incident injured at least 28 other workers—five KMCO employees[a] and 23 contract workers [11, 12, 13, 14, 15]. A shelter-in-place was issued to community members within one mile of the KMCO facility.

[a] In addition to Board Operator 2 being fatally injured, KMCO records show seven employee injuries resulting from the incident. Board Operator 1 and the Shift Supervisor sustained second- and third-degree burn injuries all over their bodies; one employee suffered from a blood clot, one employee experienced a lower back strain, and three employees developed respiratory issues.

3 Technical Analysis

A timeline of key events is provided in Appendix B.

3.1 The Y-Strainer

KMCO installed a filtration strainer (y-strainer) on the inlet (suction) piping to the isobutylene charge pump. A typical application for a y-strainer is to remove solid particles from a liquid stream (**Figure 16**). The 3-inch y-strainer had threaded ends, and KMCO added flange-to-threaded connections to allow the y-strainer to connect to the isobutylene piping flanges (**Figure 4**).

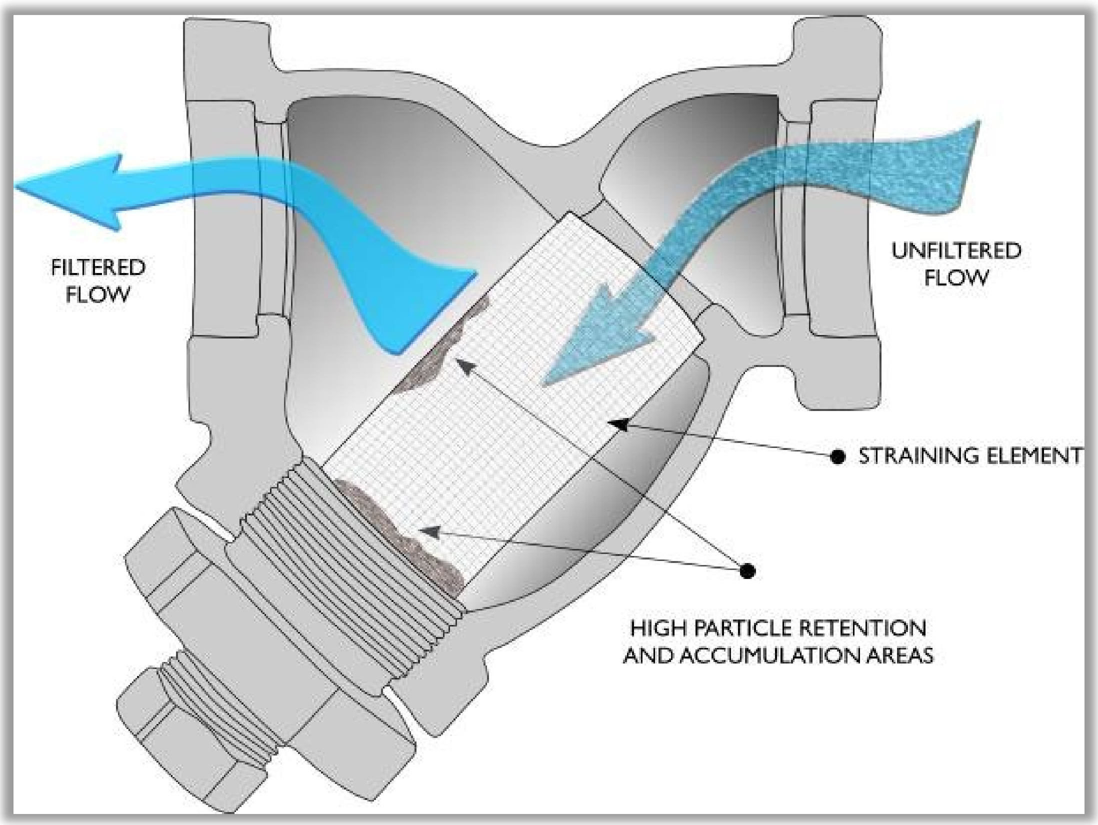

Figure 16. Generic Y-Strainer. This graphic shows a generic depiction of a typical y-strainer application—used to remove solid particles from a liquid stream. (Credit: Warden [16])

The CSB never found a documented reason for KMCO's installation of this y-strainer. In an interview with one of the engineers who worked on the isobutylene project that replaced the isobutylene storage and piping system during 2014 and 2015, the CSB learned that filtration was a significant concern during the early phases of the project when KMCO planned to use carbon steel piping, because the type of pump the team was planning to use had experienced reliability problems in other applications with small rust or sediment particles damaging certain elastomer components within the pump. To address this concern, the KMCO project team had considered using a bag filter to protect the pump, but the importance of filtration was considered to be much lower after the project team decided to use stainless steel piping. The team upgraded the piping to stainless steel to provide a better long-term solution for the pump reliability issues experienced in other KMCO applications. The engineer explained how he thought the cast iron y-strainer got installed:

> I do remember that the strainer or a filter was always on the project. And I remember once I got the stainless [piping] that the need [for] that strainer all of a sudden went from way up here to way down there. So probably what I kind of remember […] thinking, okay, what do we use? And I'm almost sure that that's probably where that [strainer] came from. You know […] we used it in other places in the plant. I believe they even said it came out of spare parts. You know, they just went out there, pulled something off the [warehouse] shelf, you know, and [installed it]. […] We probably had that [strainer model in] other places in the plant. And that's how it came about.

With the upgrade to stainless steel piping, the importance of the strainer as a filtration device did appear to be low. KMCO workers did not recall ever needing to clean accumulated debris from the y-strainer. For example, when asked if the strainer had ever plugged or needed to be cleaned, one supervisor said, "The only time they've ever touched that strainer is when it was leaking."

Post-incident, the source of the isobutylene release was identified as the 3-inch y-strainer on the inlet (suction) piping to the isobutylene charge pump. The y-strainer was found with a hole, which was roughly 3 inches by 5.5 inches, on its west side (**Figure 17**). Field Operator 1 confirmed that the location of this hole was consistent with where he saw the isobutylene escaping.

Figure 17. Y-Strainer. This photo shows the west side of the failed y-strainer involved in the April 2, 2019, incident. (Credit: CSB)

The metal fragment that broke away from the y-strainer was found on the ground, near the sulfurized isobutylene reactor and to the west of the y-strainer (**Figure 18**).

Figure 18. Y-Strainer Piece. This photo shows the single piece that broke away from the failed y-strainer. (Credit: CSB)

The y-strainer involved in the incident was the same make and model as the standard 3-inch gray iron y-strainer that KMCO stocked in its warehouse. Using the KMCO warehouse inventory information, the CSB purchased an exemplar y-strainer for $171 that was the same make and model as the incident y-strainer (**Figure 19**). The CSB used this exemplar y-strainer in the metallurgical testing that determined why the incident y-strainer failed.

Figure 19. Exemplar Y-Strainer. The CSB purchased an exemplar y-strainer (left) using the inventory information available in KMCO's warehouse. The image on the right shows the y-strainer involved in the incident. (Credit: CSB)

The supplier's technical specifications (**Figure 20**) confirmed that the exemplar y-strainer had a gray iron[a] (cast iron) body with an internal stainless-steel strainer. Gray iron is a type of cast iron [17].

Technical Specs

Item	Y Strainer	Width	10"
Pipe Size	3"	Screen Material	Stainless Steel
Connection Type	FNPT x FNPT	Mesh	1/16"
Housing Material	Cast Iron, Stainless Steel,PTFE	Gasket Material	PTFE
Max. Pressure	400 psi @ 150 Degrees F, 250 psi @ 406 Degrees F	Blow-off Port	1-1/2"
Height	6"	Standards	ASTM A126 Class B

Figure 20. Y-Strainer Technical Specifications. (Credit: [18])

3.2 Metallurgical Evaluation of the Y-Strainer

Metallurgical testing commissioned by the CSB determined that the cast iron y-strainer rupture resulted from a brittle overload fracture driven by internal pressure. Brittle overload failures can be catastrophic in that there may be no warning signs before the final fracture. Brittle failures often contain multiple cracks and separated pieces, which is consistent with how the KMCO y-strainer failed [19, p. 369]. Based on the results from the metallurgical testing of the incident and exemplar y-strainers, the CSB concludes that the cast iron y-strainer

[a] The technical specifications show that the y-strainer was manufactured to ASTM A126 Class B [18]. ASTM 126 is a "Standard Specification for Gray Iron Castings for Valves, Flanges, and Pipe Fittings" [76]. ASTM 126 covers three classes (A, B, and C) "for castings intended for use as valve pressure retaining parts, pipe fittings, and flanges" [76].

that catastrophically failed on April 2, 2019, ruptured from a brittle overload fracture driven by internal pressure.

3.2.1 Cast Iron is a Brittle Material

As an equipment design philosophy, it is often desirable for equipment to leak before it breaks ("leak-before-break"). Among other things, a leak-before-break approach strives to provide the opportunity to discover a smaller leak and then take corrective action before a fracture can occur, which would likely result in a larger release [20]. Material that exhibits ductile failure typically experiences significant stretching before separation (breaking) occurs. As a result, equipment made using a ductile material may provide a warning before breaking, such as by bulging, stretching, or leaking [21, p. 92]. Brittle materials typically do not provide such a warning before they fracture [22, p. 56]. As a result, constructing equipment from a ductile material (such as stainless steel) rather than a brittle material (cast iron, for example) is typically in alignment with the leak-before-break design philosophy [19, p. 55].

Cast iron is widely recognized as a brittle material. As a result, numerous publications that provide good practice safety guidance either prohibit or warn against using cast iron equipment in certain hazardous applications, including flammable hydrocarbons such as isobutylene. These publications include:

NFPA 58, *Liquefied Petroleum Gas Code* (Industry Standard):

> "Cast iron shall not be used as the material of construction for strainers…" [23, p. 27].

API Recommended Practice 574: *Inspection Practices for Piping System Components* (Industry Standard):

> "Cast iron piping is generally used for nonhazardous service, such as water; it is generally not recommended for pressurized hydrocarbon service because of its brittle nature" [24, p. 8].

***API Standard 2510: Design and Construction of LPG Installations* (Industry Standard):**

> "Low-ductility material such as cast iron, semisteel, malleable iron, and cast aluminum shall not be used in any pressure-retaining accessory parts" [25, p. 19].

***Albright's Chemical Engineering Handbook* (Book):**

> "Because of its brittleness, cast iron is normally not permitted for hydrocarbon streams" [26, p. 1552].

***BP Process Safety Series: Safe Handling of Light Ends* (Book):**

> "Cast iron should not be used for equipment parts containing light ends [methane to pentane] under pressure. Cast iron is very brittle and is easily broken …" [27, p. 46].

***Chemical Process Safety: Learning from Case Histories* (Book):**

> "Cast iron is undesirable (and prohibited by certain flammable liquid codes) because a brittle fracture can lead to a massive leak" [28, p. 286].

***Corrosion Control in Petroleum Production* (Book):**

> "The cast irons as a family have very low ductility as compared to steels, and the strength is generally lower than that of the higher strength carbon and alloy steels. … Some operators do not allow the use of

the less ductile cast irons in hydrocarbon service because of the chance of a brittle failure in case of an accident" [29, p. 79].

***Ludwig's Applied Process Design for Chemical and Petrochemical Plants* (Book):**

"Never use cast iron fittings or pipe in process situations unless there is only gravity pressure head (or not over 10 psig) or the fluid is non-hazardous" [30, p. 143].

***Metallurgy and Corrosion Control in Oil and Gas Production* (Book):**

"[Cast irons] are seldom used on upstream oil and gas operations except for water service. … The long flakes of graphite … cause gray cast iron (also called cast iron) to be too brittle for any corrosion or fluid-handling service" [22, p. 76].

***Perry's Chemical Engineers' Handbook* (Book):**

"The code [ASME B16.4-1998, Gray Iron Threaded Fittings: Classes 125 and 250] places significant restrictions on the use of cast iron, and its use is typically limited to low-pressure, noncritical, nonflammable services" [31, pp. 10-90].

"The piping system shall have no pressure-containing components of cast iron or other nonductile metal" [31, pp. 10-108].

***Plant Design and Operations* (Book):**

"Cast iron is less expensive and in some cases more corrosion resistant than steel. Nevertheless, the use of cast iron pipe is undesirable in oil or gas service because of its brittleness" [32, p. 288].

***Fire and Quench Tests of Refinery Valves* (1963 Journal Article):**

"[C]ast-iron valves of any type (nodular, gray, or malleable) are not safe for refinery hydrocarbon service …. It has been common practice in recent years to restrict the use of cast-iron valves to refinery locations outside the limits of operating units or to services where failure would not add fuel to a fire" [33].

***Critical Elements in the Design of Piping Systems for Toxic Fluids* (Conference Paper):**

"A worst case failure scenario for a hazardous/toxic system is the catastrophic result of a sudden rupture. The materials selection process should preclude the use of any low-ductility materials such as cast iron …. Their brittle behavior … eliminate their applicability for hazardous/toxic systems" [34, p. 12].

***Inherently Safer Latex Plants* (Conference Paper):**

"Certain materials should be avoided which can lead to catastrophic failure. Cast iron is brittle in nature and it is best not to use it for process service" [35, p. 9].

Safety concerns about using cast iron equipment for chemicals such as isobutylene have been raised for decades. In fact, NFPA 58, the *Liquefied Petroleum Gas Code*, has prohibited the use of cast iron fittings in LPG piping systems since 1931.

The CSB concludes that existing industry standards and good practice safety guidance show that cast iron is a brittle material that should not have been used for an application such as KMCO's liquid isobutylene piping system.

Key Lesson

Cast iron is widely recognized as a brittle material that should not be used in hazardous applications, including applications that involve flammable or toxic chemicals.

3.2.2 Liquid Thermal Expansion

At the time of the catastrophic y-strainer failure, process data showed that the isobutylene circulation loop was operating at less than 120 pounds per square inch (gauge), which was a normal pressure within this piping system. But KMCO did not measure or record the pressure within the charge pump piping, where the y-strainer was located. High-pressure conditions could develop in the charge pump piping from scenarios that include liquid thermal expansion, fluid leaking back from the batch reactor through an isolation valve or from the pressure-relief valve on the charge pump's outlet piping, or a combination of these conditions.[a]

Liquid thermal expansion occurs when liquids are heated.[b] When a system with a fixed volume is filled with a liquid and heated, liquid thermal expansion can generate high pressure within the system as the liquid expands [36, p. 77]. After completing the isobutylene charge to the batch reactor, the charge pump piping was isolated, with a check valve preventing flow back into the circulation loop and a block valve preventing flow into the batch reactor (**Figure 3**). Unlike the isobutylene circulation loop piping, the charge pump's inlet piping—including the y-strainer—lacked a pressure-relief device to protect it from liquid thermal expansion.[c]

In its industry standard, API Standard 521, *Pressure-relieving and Depressuring Systems*, the API explains that ambient heat gain within an isolated piping system is among the most common causes of overpressure from liquid thermal expansion. The API recommends installing a pressure-relief device if liquid thermal expansion is a credible hazard [37, pp. 32-33].[d]

When the isobutylene charge was completed (at 6:25 a.m.), process data showed that the isobutylene temperature was approximately 55 degrees Fahrenheit (°F). At this time, the outdoor air temperature was about 40 °F, cooling the isobutylene within the isolated (and uninsulated) charge piping. Later in the morning, heating of the isobutylene occurred from a combination of warmer outdoor air (approaching 59 °F) and, at some piping

[a] The CSB commissioned testing of the pressure-relief valve from the charge pump's discharge (outlet) piping. Among other results, this testing found that the pressure-relief valve leaked at an average rate of approximately 0.005 to 0.007 gallons per minute. In addition, a previous failure of cast iron equipment at a refinery was attributed to high pressure developed from quickly closing a valve [27, p. 46]. The charge pump piping at KMCO was equipped with two actuated valves. The fast closing of these valves may have been a source of periodic pressure increases with the charge pump piping.

[b] Liquid thermal expansion is sometimes referred to as hydraulic expansion, thermal expansion, or liquid expansion.

[c] KMCO did equip portions of the circulation pump piping, which could be isolated, with pressure-relief valves to protect from liquid thermal expansion.

[d] The API uses "hydraulic expansion" to describe the high-pressure conditions that can be created by the increase in liquid volume that can occur when the temperature of a liquid increases [37, p. 32].

locations, exposure to the sun (solar radiation). This heating likely increased the pressure inside the piping from liquid thermal expansion.[a]

This scenario for developing high pressure inside the charge piping after adding isobutylene to the batch reactor would not have been unique to the morning of April 2, 2019. Indeed, high pressure within the isobutylene charge piping likely developed during a number of previous batches under similar, or even more severe, heating conditions. Any such previous high-pressure events would likely have contributed to the incident through weakening of the y-strainer, such as by creating small cracks within the strainer body that further developed during repeated pressure cycles and ultimately resulted in failure when the internal isobutylene pressure finally exceeded the strainer's ability to contain this pressure. The CSB concludes that the most likely source of pressure contributing to the y-strainer failure was liquid isobutylene thermal expansion that might have periodically occurred within the charge pump's inlet piping, which was not equipped with a pressure-relief device or otherwise protected from high-pressure conditions.

Key Lesson

Piping systems should be equipped with protection from high-pressure conditions, where liquid thermal expansion or other scenarios can create a hazard. For example, API 521 recommends installing a pressure-relief device if liquid thermal expansion is a credible hazard.

3.3 Isobutylene Release

Just before the isobutylene release began, the liquid level within the isobutylene storage tank was about 43.1 percent. After the isobutylene tank was isolated following the incident, the liquid level in the isobutylene storage tank was about 41.5 percent. Based on this change in level and accounting for temperature differences between the initial and final conditions, the CSB determined that more than 10,000 pounds of isobutylene were released during the incident.[b]

3.4 Ignition Source

The area of the greatest explosion damage was the R2 Building, where Board Operator 2 was found deceased. The explosion damage to the R2 Building was consistent with flammable vapor being ignited within that building. This building contained a number of electrical equipment items that were energized and likely capable of igniting the isobutylene vapor cloud, triggering the explosion. Minimal details about the construction of this building were available, but the building was generally understood to be consistent with the construction of the PPE Room, which contained multiple doors, windows, and other obvious potential entry points for flammable isobutylene vapor, including a poorly sealed wall-mounted air conditioner (**Figure 21**).

[a] The outdoor air temperature at 10:40 a.m. was about 59 °F.

[b] The isobutylene storage tank was equipped with two level transmitters. Because one of these was producing an erratic signal, it was excluded from the isobutylene release calculation.

Figure 21. Wall-Mounted Air Conditioner. This photo, taken from outside of the PPE Room, shows an opening to the inside of the PPE Room. (Credit: CSB)

KMCO had identified the area where the R2 Building was located as a Class 1, Division 2 location, one of the hazardous classified locations under the National Fire Protection Association (NFPA) 70, *National Electrical Code*, where the possibility of fire or explosion hazards may exist under abnormal conditions because of the presence of flammable material, such as isobutylene [38, p. 350]. The CSB learned that the R2 Building likely did not meet the NFPA's requirements because it contained unclassified electrical equipment, such as motor starters, and the building was not pressurized to prevent flammable vapor from entering the building.

In addition, KMCO had not implemented its insurance underwriting recommendation from 2013 to "harden" certain electrical equipment inside the R2 Building or relocate this electrical equipment to the new blast-resistant Reaction Control Room. The most recent status update for this insurance recommendation, prepared in 2018, showed a long-term plan to move this equipment into a more robust "blast-resistant" housing.

The CSB concludes that although a number of potential sources of ignition existed in the area of the isobutylene release, the source of ignition that triggered the isobutylene explosion was most likely located within the R2 Building.

3.5 Federal Safety Regulations

KMCO records show that its isobutylene system was covered by both the U.S. Occupational Safety and Health Administration's (OSHA) Process Safety Management (PSM) standard and the U.S. Environmental Protection Agency's (EPA) Risk Management Program (RMP) rule [39].

3.5.1 OSHA Process Safety Management Standard

OSHA's PSM standard was implemented on May 26, 1992. According to OSHA, the PSM standard:

> [E]stablishes procedures for process safety management that will protect employees by preventing or minimizing the consequences of chemical accidents involving highly hazardous chemicals. Employees have been and continue to be exposed to the hazards of toxicity, fires, and explosions from catastrophic releases of highly hazardous chemicals in their workplaces. The requirements in this standard are intended to eliminate or mitigate the consequences of such releases [40].

KMCO considered its isobutylene system covered by the OSHA PSM standard[a] because of the chemical quantities used or stored.[b] KMCO records show that the isobutylene system was likely covered by the PSM standard because it contained more than 10,000 pounds of the flammable chemical.

3.5.2 KMCO's Process Safety Management Program

In January 2017, KMCO's process safety management system was evaluated by an audit team. The audit team assessed the company's conformance with process safety management regulations and industry good practice guidance, including OSHA's PSM standard, EPA's RMP rule, and the Center for Chemical Process Safety (CCPS) book, *Risk Based Process Safety*. In total, the audit team used 370 different questions to evaluate the site's process safety management program and made recommendations for 341 (92 percent) of these questions. For the remaining 29 (8 percent) questions evaluated, the audit team did not make a recommendation.

A number of the audit team's recommendations specifically targeted improving KMCO's process safety management systems, including emergency response and hazard evaluation, that later contributed to the April 2, 2019, incident.

For example, the audit identified that KMCO's emergency response plan did not deal with training requirements and recommended that KMCO conduct an additional audit to evaluate what exactly occurs at the site during an emergency. Another audit recommendation was that KMCO hold routine training to ensure that its employees understood that their role was not to respond to an emergency but that they should evacuate with the understanding that response should only be handled by qualified outside emergency responders.

With respect to KMCO's hazard evaluation programs, the 2017 audit found substantial issues with the site's process hazard analysis (PHA) program, concluding that the existing PHAs were "not in line with industry standards" and recommended that KMCO ensure that an initial PHA had been performed for all covered processes, existing PHAs were replaced by updated (re-do) PHAs, process safety information was compiled, and that KMCO addresses previous incidents in its future PHAs.

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[a] 29 C.F.R. § 1910.119.

[b] The PSM Standard covers chemicals deemed hazardous because of their chemical composition and quantity (listed in Appendix A of 29 C.F.R. § 1910.119) or because of their flammability characteristics. *See* 29 C.F.R. § 1910.119(a)(1)(ii).

KMCO's 2017 audit showed that the company's process safety management program had significant weaknesses, which KMCO's management team was taking action to address. In discussing the recent audit findings with CSB investigators, one senior manager explained that KMCO had been continually trying to raise the level of its process safety performance. He stated:

> We've been working diligently on a lot [of the audit findings] since I've been here. We've re-inspected the entire plant to build new [piping and instrumentation diagrams]. We've installed a new [management of change] process. We've redone the incident investigation. We've been looking very carefully at our mechanical integrity, re-inspecting many things, and trying to work through that. Trying to upgrade all aspects of process safety.

Among the recent improvements, KMCO's management placed an emphasis on reviewing all recent incident investigations to discuss the findings and ensure that effective corrective actions were being developed. On the day of the incident, the Shift Supervisor was attending one of these meetings when the y-strainer ruptured.

Overall, many employees interviewed by the CSB were complimentary of the recent equipment and infrastructure projects along with other management efforts to improve the facility. For example, one experienced operator stated:

> I would say that a lot of like our safe work program and stuff that they … they put in there, they're much more thorough. Our safe works used to have like five lines on it, and now it's a standard form, you know, and covers anything and everything that you can think of on there. And having the 4-gas meters in the field, which we didn't have before. There's … there's a lot of things they've improved on. Like I said, especially in the processes and the safety of the processes have been improved.

But one supervisor explained that although the infrastructure and other improvements were good, KMCO's management needed to do more to keep people out of harm's way. He explained that the ERT's lack of operating experience and their slow response to incidents resulted in site management continually relying on KMCO's operators to react quickly to stop the leak or problem.

Although KMCO had been working to identify gaps and strengthen its process safety management system, persistent weaknesses ultimately contributed to the April 2, 2019, incident. Poorly implemented elements of KMCO's process safety management system, including emergency response and hazard evaluation, were identified as safety issues in the CSB's investigation. These safety issues are further analyzed in Section 4.1 and Section 4.3, respectively.

3.5.3 OSHA Enforcement Actions

On September 30, 2019, OSHA issued citations to KMCO stemming from the April 2, 2019, incident with a proposed penalty of $131,274 [41]. These citations included the following:

- KMCO did not train all employees in safe and orderly evacuation (29 C.F.R. § 1910.38(e)).

- Material of construction information was not maintained for the y-strainer that failed or the isobutylene piping from the storage tank to the reactor system (29 C.F.R. § 1910.119(d)(3)(i)(A)).
- KMCO's process safety information did not include the pressure relief valve design and design basis for certain safety relief valves that provide equipment overpressure protection (29 C.F.R. § 1910.119(d)(3)(i)(D)).
- For certain safety relief valves that provided overpressure protection, KMCO did not document that the equipment complied with recognized and generally accepted good engineering practices such as API 521 (29 C.F.R. § 1910.119(d)(3)(ii)).
- KMCO's PHA did not address the hazards of the y-strainer that failed or the hazards of an isobutylene release without installing remote emergency isolation valves (29 C.F.R. § 1910.119(e)(3)(i)).
- KMCO did not perform inspections and testing of the y-strainer that failed (29 C.F.R. § 1910.119(j)(4)(i)).
- KMCO did not have written procedures to manage changes for the reactor system piping and instrumentation diagrams or for the y-strainer that failed (29 C.F.R. § 1910.119(l)(1)).
- KMCO did not effectively implement its emergency response plan (29 C.F.R. § 1910.120(q)(1)).
- The employee alarm system at KMCO did not provide a warning for necessary emergency action when the alarm system was not activated by the incident commander. In addition, training and drills required by the emergency action plan were not performed (29 C.F.R. § 1910.165(b)(1)).

3.5.4 EPA Risk Management Program Rule

The EPA's RMP rule requires an owner or operator of a stationary source with a process that has more than a threshold quantity of a regulated substance to develop a risk management plan.[a] According to the EPA, these plans:

- Identify the potential effects of a chemical accident;
- Identify the steps the facility is taking to prevent an accident; and
- Spell out emergency response procedures should an accident occur [42].

The EPA's RMP rule defines three Program levels (Program 1, 2, or 3) based on the potential consequences to the public and the effort needed to prevent accidents [43, p. 1]. Of these three Program levels, Program 1 is the least stringent, and Program 3 is the most rigorous.

KMCO filed a risk management plan with the EPA on February 23, 2018 [39]. KMCO included isobutylene in its risk management plan, and the company identified its isobutylene system as being a Program Level 3 [39, p. 5]. KMCO's risk management plan submission also identified that its isobutylene system was regulated by both the EPA RMP rule and the OSHA PSM standard [39, p. 33].

[a] 40 C.F.R. § 68.10.

In its risk management plan, KMCO explained its policies for emergency response and accidental release prevention. KMCO said that if a significant release were to occur, its emergency response personnel would respond and control the release. KMCO's risk management plan states:

> KMCO is committed to the safety of KMCO workers and the public, and to the preservation of the environment, through the prevention of accidental releases of hazardous substances. KMCO implements reasonable controls to prevent foreseeable releases of hazardous substances. In the event of a significant accidental release, our trained Emergency Response personnel will respond to control and contain such releases. KMCO evaluates each situation, evacuates workers as necessary, and contacts the local fire department to control and contain the release and to prevent and/or reduce the consequences of the release [44].

4 Safety Issues

This section includes an analysis of the safety issues that contributed to the incident or its severity, including:

- Emergency Response
- Remote Isolation
- Hazard Evaluation

See Appendix A for the accident map (AcciMap), which provides a graphical analysis of this incident.

4.1 Emergency Response

4.1.1 Emergency Response Plan

KMCO's Emergency Response Plan (ERP) established procedures to follow in the event of an emergency, such as a large release of flammable isobutylene. According to the KMCO's ERP, the steps to be taken during such an emergency included:

- Communicating the nature of the emergency using the plant-wide radio **and** the facility alarm system;
- Unlocking gate turnstiles and gathering visitor sign-in sheets to help account for all personnel at the designated rally points;
- Ensuring nonessential employees evacuate and report to a safe rally point;
- Evacuating operations personnel based on the type and magnitude of the incident;
- Assembling the Emergency Response Team (ERT) members at the ERT muster location;
- Forming an Emergency Operations Center (EOC) with the assigned personnel; and
- Assigning the operations shift supervisor as the initial Incident Commander focused on "life safety and incident stability." The initial goals for the incident commander included:
  - ✓ Focusing on "possible hazards to human health or the environment that may result from the Release, Fire, or Explosion;"
  - ✓ Designating the command center, exclusionary zone, and support zone; and
  - ✓ Ordering a shelter-in-place or evacuation if the incident could threaten human health or the environment.

Like many of the safety management systems at KMCO, the site's ERP was actively being revised and strengthened, but the updated version was not effective on the day of the incident. For example, KMCO's ERP called for the operations shift supervisor to serve as the initial Incident Commander, but the Shift Supervisor on duty at the time of the incident had not been a member of the ERT for about two years.

The site had scheduled an incident command training activity for April 5, 2019, but the April 2, 2019, incident occurred before this training could take place. The April 5, 2019, training was supposed to provide a tabletop drill with the Crosby Volunteer Fire Department. At this training session, KMCO also planned to clarify who would serve as the initial Incident Commander and what their role was during an emergency.

4.1.2 Facility Alarm System

In its book *Guidelines for Risk Based Process Safety*, the CCPS covered both the importance and objectives of a facility's emergency alarm system. Among other good practice safety guidance for emergency alarm systems, the CCPS stated:

> In the event of an emergency, a reliable means must be available to alert those in danger that they should take action, and specifically what action to take.
>
> Regardless of the method used to alert people to an emergency, the alarm must be recognizable, and clearly distinguishable from normal message traffic carried on whatever media is used [45, p. 523].
>
> Ensure that all personnel at the facility, including contractors, can recognize emergency alarms and know what actions to take for each type of alarm [45, p. 537].

After Board Operator 1 left the Reaction Control Room in response to the radio call from Field Operator 1, he appeared to understand the seriousness of the emergency. Board Operator 1 used the radio to inform other workers of the emergency by calling for an evacuation from the area, but nobody activated the facility alarm system. As a result, workers who did not have a radio—or were not with someone who had a radio—were not alerted to the ongoing emergency or the call to evacuate.

KMCO's emergency response plan (ERP) called for using both the facility alarm system and the plant-wide radio to immediately communicate an emergency, including a chemical release, fire, or explosion. KMCO's board operators were not responsible for deciding to sound the facility alarm system during an emergency. In explaining the purpose of the facility alarm system, the emergency response plan explained:

> The primary purpose of the facility alarm system is to put the plant on alert status. The facility alarm system shall be used during an emergency situation that has the potential to impact KMCO employees, contractors, the community, and/or major property loss. The activation of the emergency alarm is at the discretion of the HSSE [Health, Safety, Security, Environmental] Department, Operations and/or Maintenance Department Manager and Supervisors.

KMCO installed its facility alarm system in February 2017 to "notify the entire plant of an emergency situation." The alarm system included:

- An alarm base station in the Reaction Control Room (**Figure 22**);
- Voice options to alert employees to specific emergency events;
- Speakers on concrete poles around the facility;

- Speakers in the administration and maintenance buildings; and
- Radio and mobile phone notification of emergencies.[a]

Figure 22. Base Station for Facility Alarm System. (Credit: CSB)

One operations supervisor stated that the old facility alarm system never worked—or at least, not during his 14 years at KMCO—and that he had never heard a facility alarm until the new system was up and running.

KMCO personnel routinely tested its new facility alarm system each Tuesday, but beyond knowing how to run the weekly test, most workers did not know how to use the alarm for an actual emergency. Workers could activate the evacuation alarm only from the Reaction Control Room. When asked if people knew how to sound the evacuation alarm on the facility alarm system, one operations supervisor said, "No. They know how to use it to do its weekly test."

In discussing the actions to take during a hypothetical isobutylene release, another operations supervisor described how he could use the facility alarm system to evacuate the plant. He said:

> You would turn the key on. And then, it's got a button that you would hit. I don't remember the exact name of it. One is evacuate, one is shelter-in-place, and one is the weekly test. So, you'd hit the evacuate. Hit the appropriate button and hit send. I've never actually hit it, so I can't even tell you what it would sound like. I'm assuming it's the weekly test without the voice saying, "This is a test."

When asked who should activate the facility alarm and how the facility alarm system works, a third operations supervisor stated, "Nobody knows." The supervisor further clarified by saying, "There has been a number of

[a] OSHA provides minimum requirements for employee alarm systems in 29 C.F.R. § 1910.165.

[employment] changes to people that were part of the [facility alarm system] installation. They [no longer work] here."

One of the KMCO safety technicians provided further insight by explaining that, at the time of the incident, the operations staff was not yet capable of reliably activating the facility alarm system during an emergency. He said:

> Yeah, [we have a facility alarm system]. It's a Cadillac, too. It's a really nice one. It was probably put in a couple of years ago, but nobody's up to speed trained on it.
>
> There should be board operators who say I know exactly what to hit [on the facility alarm system] in every situation to sound which alarm and why. But we didn't get that piece [completed] yet.
>
> Because, like I said, it's a really nice alarm, but if you don't know how to use it and you're not training your employees on it, it's useless.

Because KMCO's board operators were not yet fully trained to use the facility alarm system, the safety technician explained how he trained new workers on what to do during a potential emergency. He instructed new workers at the site to rely on the plant radio system or to contact operations, or if they saw people running, he advised that they should run with them. The safety technician said:

> Like, I'll do a lot of the safety orientation when [workers] first come to the site. I show them all the rally points, I point out the windsocks. I'll say in an unlikely event [of an emergency], like, Channel 1 is [the primary radio channel] for safety. But, like, if they don't have a radio, like, get with operations, or if you see a whole bunch of people running one way, it's probably a good idea to run in that same direction.

Based on the interviews that CSB investigators conducted with KMCO employees and contract workers who were at the facility, KMCO did not use its facility alarm system for emergency communication about the isobutylene release. Because not all workers received the plant radio emergency notification, some injured workers were nearer to the explosion than they should have been. In addition, the lack of facility alarm system emergency communication likely made the plant evacuation more hectic than it otherwise could have been. For example, during the isobutylene release, KMCO's operators and supervisors were urgently instructing other workers to shut off vehicles and evacuate when the facility alarm system could have provided a more effective approach for this emergency communication.

The CSB concludes that KMCO never activated its facility alarm system to notify all workers about the isobutylene release emergency. As a result, some injured workers were nearer to the explosion than they should have been. KMCO could have reduced the severity of the event by using its facility alarm system to notify all workers of the isobutylene release emergency and communicate the evacuation order.

Key Lesson

Reliable facility alarm systems can help ensure effective emergency communication to alert people of danger and inform them of what actions are needed to protect life and health.

4.1.3 Response to the Isobutylene Release

Before analyzing KMCO employees' response to the isobutylene release, it is important to clarify that KMCO was responsible for the actions taken (or not taken) during the initial response to this emergency. Employers have a duty to protect their employees from harm. As part of their efforts to conform with OSHA's PSM standard, companies like KMCO decide what their employees will do during an emergency.[a] If a company intends to evacuate all its employees following a major chemical release, the company may develop an "emergency action plan" following 29 C.F.R. 1910.38(a). Otherwise, the company needs to develop an "emergency response plan" under 29 C.F.R. 1910.120(q) (which addresses "emergency response to hazardous substance releases").[b]

KMCO chose to develop an emergency response plan. In doing so, KMCO accepted responsibility for implementing an emergency response plan under 29 C.F.R. 1910.120(q) because some of its employees were expected to handle an emergency release rather than evacuate [46, p. 11]. As such, the actions that KMCO workers took in response to the April 2, 2019, incident were the product of KMCO's policies and procedures and how the company prepared and trained these workers to respond to this emergency.

Good practice guidance for emergency response is widely available from a number of sources. Among these, the U.S. Department of Health and Human Services has developed *6 Steps for Initial Response to a Chemical HAZMAT Incident* that prioritizes life safety using plain language.[c] The six steps are:

1. **Recognize the Incident:** Quickly size up the situation and recognize the type and scale of incident you are responding to. Activate the response system.
2. **Protect Yourself and Others:** Establish an Isolation Zone and move outside it. Alert others in the danger area to do the same. Take only actions that you are equipped and trained to take. Do not allow yourself to become a victim!
3. **Determine Initial Response Objectives:** Remind yourself of the critical objectives that should be addressed in the first minutes. Life safety is always your first priority.
4. **Decide and Take Immediate Actions:** Make the decisions that will support your objectives - and take the actions you safely can.
5. **Manage the Incident Until Relieved:** The first arriving responder is, by default, the Incident Commander until relieved. You should control the incident scene and manage and apply resources as they arrive.
6. **Transition Command:** Formally turn over incident command when more senior or more qualified responders arrive [47].[d]

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[a] The EPA also has emergency response requirements under 40 C.F.R. §§ 68.90 - 68.96. The provisions for emergency response exercises under 40 C.F.R. § 68.96 were not in effect at the time of the incident at KMCO [88].

[b] 29 C.F.R. § 1910.38(a) and 29.C.F.R. § 1910.120(q).

[c] HAZMAT is an abbreviation for hazardous materials. Quick Response Guide - CHEMM (hhs.gov)

[d] Quick Response Guide - CHEMM (hhs.gov)

When the y-strainer ruptured, which initiated the release of flammable isobutylene, the three KMCO workers who were fatally or seriously injured (Board Operator 2, Board Operator 1, and the Shift Supervisor) were all in a safe location. The two board operators were working inside the blast-resistant Reaction Control Room, and the supervisor was attending a safety meeting in a conference room within the plant's administration building. When the flammable isobutylene vapor cloud exploded 11 minutes later, all of these workers were in harm's way; and were fatally or seriously injured while performing actions either within or near the flammable isobutylene vapor cloud.

4.1.3.1 HAZWOPER

On March 6, 1989, OSHA issued its Hazardous Waste Operations and Emergency Response standard, more commonly referred to as HAZWOPER.[a] Among other things, this safety regulation provides minimum requirements for emergency response operations involving hazardous materials, such as isobutylene. In the preamble to its HAZWOPER standard, OSHA stated that there was a "clear need for training and other provisions to protect workers engaged in all emergency responses when there is the possibility of hazardous substance spills" [48, p. 9297]. OSHA further stated that its decision to cover all emergency response, including petrochemical and similar manufacturing facilities, "was based upon the high risk associated with emergency response by untrained and unprotected employees and the need for proper training and equipment to be provided for emergency response to hazardous substance releases" [48, p. 9298].

OSHA requires emergency responders to be trained before taking part in emergency response operations. This training must be based on the duties they will perform [49, p. 30]. In its HAZWOPER standard, OSHA identified five emergency response levels and the minimum training requirements for each level. These emergency response levels are:

1. **First Responder Awareness Level**
   These are employees who might witness or discover a hazardous substance release and have been trained to report the release to start the emergency response process.

2. **First Responder Operations Level**
   These are employees who respond for the purpose of protecting other people nearby, property, or the environment from the effects of the release. They do not try to stop the release. From a safe distance, they try to contain the release and prevent exposure to released material.

3. **Hazardous Materials Technician**
   These responders can approach the release to close valves or take other, more aggressive actions to stop the release.

4. **Hazardous Materials Specialist**

[a] 29 C.F.R. § 1910.120.

These responders support the hazardous materials technicians. They have duties similar to the hazardous materials technician but have more knowledge about hazardous materials, and they also coordinate with other officials about emergency response.

5. **On Scene Incident Commander**
The incident commander controls the emergency response to the incident beyond the first responder awareness level [49, pp. 30-32].[a]

The three KMCO workers who were fatally or seriously injured (Board Operator 2, Board Operator 1, and the Shift Supervisor) had approached or entered the isobutylene vapor cloud in response to the release, but they were not formal members of the site's ERT. Some of the actions these workers took, such as closing valves to stop the release, were the duties of a hazardous materials technician under OSHA's HAZWOPER standard. But because these workers were not trained to that response level, KMCO should have limited the role of these employees to the first responder awareness level.[b]

Key Lesson

Where remote isolation is not provided or is otherwise not available, clear policies and effective training are needed to help ensure that workers do not put themselves in danger to stop a chemical release.

4.1.3.2 Response to Hazardous Material Incidents at KMCO

Industrial safety and accident analysis expert Andrew Hopkins has stated that the most useful definition of culture in the context of company safety practices is "The way we do things around here," a definition that refers to the collective practices of a group [50, 51].[c] This definition of culture is helpful in describing the actions KMCO workers took when responding to the isobutylene release.

KMCO hired its ERT Fire Chief roughly two years before the April 2, 2019, incident. The Fire Chief told CSB investigators that, among other challenges, "we had to build [the emergency response program] from the ground up." The Fire Chief also stated that the plant culture at KMCO was that operations staff should take offensive actions to stop a release quickly. In discussing the isobutylene release on April 2, 2019, the Fire Chief said, "they [operations staff] are going to respond to it and try to mitigate it as fast as possible so they can contain it." The Fire Chief further explained:

> If [the operators] can go out there and block it in, theoretically, real quick and, like, neutralize it or keep it contained, that's going to be their primary thought pattern. A Good Samaritan, they want to do the right thing right away.

[a] 29 C.F.R § 1910.120(q)(6)(i) – 1910.120(q)(6)(v).

[b] 29 C.F.R. § 1910.120 (q)(6)(i).

[c] The CSB had previously found that the phrase "the way we do things around here" might originate in Marvin Bower's 1966 book, *The Will to Manage*, in which Bower used the phrase to explain how top executives at successful firms referred to the company's philosophy [85, pp. 22-41]. At the time, Marvin Bower was the managing director for the consulting firm McKinsey & Company, Inc. *See* Company philosophy: 'The way we do things around here'.

> But if it's out of control, they're going to still call ERT because we're going to be HAZMAT trained. We'll help clean it up, start the dike walls and all that, but like to say, "Oh, there's a leak, ERT emergency leak," you know, it's not always that way.
>
> But if they can contain it themselves, they'll just block it in and try to fix it. Plug it up most of the time.

The ERT Fire Chief's explanation that KMCO's plant culture called for operators to quickly respond to try to stop a release closely aligned with how the Shift Supervisor recalled the events that transpired. After being released from the hospital, the Shift Supervisor described the incident in an interview with a CSB investigator:

> I get a call on the radio [saying that] we have [an isobutylene] leak. So, at this point, you know, being used to what happens normally at [the batch reactor], an [isobutylene] leak normally is a very small leak coming from a valve or coming from a … the [charge] pump itself. But we still go down there. And as I'm going down there, I can see in the middle … on the road that separates the […] tank farm and [the batch reactor] area, there's a two-foot river high that goes all the way down the road, of isobutylene [vapor]. At that point, when I had seen that, I got on the [plant radio] and ordered the evacuation of the plant. And as I ordered the evacuation of the plant, that's when I [saw Board Operator 1 and Board Operator 2] going towards the units with the SCBA on.

Board Operators 1 and 2 each wore an SCBA and their standard everyday flame-resistant clothing. When asked about the personal protective equipment that Board Operator 1 and Board Operator 2 were wearing, the Shift Supervisor explained that this was the only personal protective equipment they had for that response. The Shift Supervisor also stated that Board Operator 1 and Board Operator 2 were "doing what they were trained to do."

> So, the outside operators had already been out of the area. And one was sent to go shut the [circulation] pump off. And [Board Operator 1] went in there and shut the valves so the leak would stop. And then [he] opened up the overhead … the deluge system. Which is something that, you know, if we ever have leaks like this, the best thing to do is drown it in water. So that's what he was doing.

The Shift Supervisor also explained that Board Operator 2 may have gone into the R2 Building to push the stop button for two reactor feed pumps in his area and to make sure that no one else was in that building.

The explosion occurred just after the Shift Supervisor had turned on a firewater monitor to keep the isobutylene vapor away from a hot oil furnace that was to the south and east of the release location.

4.1.3.3 CCPS Safety Guidance

In its book, *Guidelines for Risk Based Process Safety*, the CCPS recommends that written emergency response programs "clearly delineate" which incidents operators should respond to and which incidents should be handled by the site's emergency response team. The CCPS explained that:

> The written emergency response program, or a subordinate document, should clearly delineate between those incidents that operators should respond to and those that should be handled by the facility's emergency response team (ERT) or equivalently trained outside responders. Failure to address this issue will require that operators and other front line employees make instant decisions on how to respond to an emergency, likely leading to unacceptable risk because people generally do a poor job of considering a wide range of factors when making decisions in a crisis [45, p. 514].

The CCPS also discussed the natural tendency for some operators to feel ownership of the unit and want to take quick action during an emergency. The CCPS explained:

> Operators normally have a much deeper understanding of the process and its hazards than do emergency responders and can normally act more quickly in terms of both (1) formulating a response action and (2) executing the action. However, operators are generally not as well equipped as emergency responders (in terms of response and personal protective equipment) and are almost certainly not as well trained in emergency response activities. Because they feel a certain ownership of the process, some operators may accept more personal risk while responding to an emergency than the company might endorse. This ownership issue, and the need to understand tolerable risk when responding to emergencies, can best be managed if the range of acceptable actions is documented, reviewed, and communicated to operators and other affected workers in writing, and reinforced in training situations [45, p. 514].

In addition, the CCPS compared operators who might put themselves in harm's way during an emergency to the "confined space rescue" problem, where workers who lack the right training and equipment put themselves in harm's way by trying to rescue an unresponsive coworker during a confined space work activity. The CCPS explained:

> In addition to being trained on what to do, all personnel should understand management's intent for emergency response. What actions are acceptable and what are not? Many workers, when faced with an emergency, will pursue unsafe actions to mitigate the consequences, particularly if a co-worker could be injured. For example, a high incidence of double fatalities occurs for confined space incidents: first the person working in the confined space collapses, and shortly afterward, a co-worker collapses while attempting to rescue the first victim. Policy issues such as, "Do not attempt to take offensive actions such as …." should be clearly communicated to all personnel and reinforced periodically through training or other communication modes [45, p. 523].

The CSB concludes that KMCO's emergency response system, including its procedures and training, contributed to the severity of the incident. KMCO did not establish procedures or provide training that effectively distinguished the incidents that its operators should respond to from the emergency events that the site's emergency response team must respond to. As a result of KMCO's emergency response program, the emergency actions taken by KMCO operations staff to stop the isobutylene release adhered to the unwritten culture at KMCO that relied on unit operators taking quick actions to stop a chemical release. When the isobutylene release began, workers who were in a safe location moved toward the isobutylene vapor cloud, which put them in harm's way. KMCO could have reduced the severity of the event by establishing clear policies and training its workforce to respond to a chemical release without putting themselves in harm's way.

Key Lesson

Emergency response plans, including procedures and training, need to effectively distinguish between incidents that plant workers should respond to and emergency events that must be handled by a qualified emergency response team.

4.2 Remote Isolation

In his interview with the CSB, the Shift Supervisor was asked what changes he would want to see implemented to prevent this type of event from occurring in the future. The Shift Supervisor stated:

> You should have had valves that you can close inside [the Reaction Control Room]. I mean, when you have an incident … when you have [ethylene oxide, propylene oxide], [isobutylene], any kind of flammable liquid, you should be able to [stop it remotely] and, you know, not send someone in to have to do it.

When the y-strainer ruptured, the closest person to it was the contract worker who was insulating tubing associated with the batch reactor. She described that when the y-strainer failed, the flammable isobutylene vapor was chest-high, growing, and flowing down the adjacent road. In her interview with Harris County Fire Marshal investigators, she opined about how to prevent a similar event in the future, stating:

> Shut the line. … There should be a way to shut the line. … Once we know what it is, shut the line. … Is there such a thing that they could have went somewhere and just, like shut it all down? Then [Board Operator 2] could have been saved. No one should have went back out there [into that flammable vapor cloud].

The Shift Supervisor and the contract insulator each identified the need for safety equipment that KMCO workers could have used to stop the isobutylene release from a safe location. This type of safety equipment is called remote isolation (among other names), and it is not a new safety concept. Nearly 50 years before the explosion at KMCO, process safety pioneer Trevor Kletz published a safety newsletter that called for installing remotely operated isolation valves to isolate hazardous material leaks from a safe distance.[a]

[a] *See* Safety Newsletter Introduction and Issue 14. The Institution of Chemical Engineers (IChemE) provides the entire series of ICI Newsletters on its website.

The CSB refers to the equipment needed to isolate a flammable or toxic release from a safe (remote) location as a remotely operated emergency isolation valve (ROEIV). While a remotely operated emergency isolation valve will not prevent a loss-of-containment event, correctly applying remote isolation equipment should reduce the severity of a hazardous chemical release [52, p. 4].[a]

4.2.1 Health and Safety Executive (HSE) Safety Guidance

The Health and Safety Executive (HSE), a United Kingdom government agency, published HSG244, *Remotely Operated Shutoff Valves (ROSOVs)* in 2004 [53]. HSE issued its guidance on remotely operated shutoff valves because of two major incidents:

- The Associated Octel Company Limited at Ellesmere Port (February 1994);[b] and
- The BP Grangemouth Refinery (June 2000) [53, pp. 4-5].[c]

In explaining the purpose of its ROSOV guidance document, HSE says, "In an emergency, rapid isolation of vessels or process plant is one of the most effective means of preventing loss of containment, or limiting its size" [53, p. 4]. ROSOVs are safety devices that HSE defines as:

> A valve designed, installed and maintained for the primary purpose of achieving rapid isolation of plant items containing hazardous substances in the event of a failure of the primary containment system (including, but not limited to, leaks from pipework, flanges, and pump seals). Closure of the valve can be initiated from a point remote from the valve itself. The valve should be capable of closing and maintaining tight shutoff under foreseeable conditions following such a failure (which may include fire) [53, p. 4].

HSG244 provides four primary selection criteria for eliminating "low-risk cases where the hazard potential" is low enough that remote isolation equipment is probably not justified. But if any of the four primary selection criteria apply, remote isolation equipment should be installed as a precautionary approach [53, pp. 7, 17-18]. Applying the HSG244 selection criteria to KMCO's isobutylene system shows that remote isolation should have been added in this case, because three of the four criteria for remote isolation applied:

- The maximum foreseeable release in the event of failure to manually isolate the release was more than 1,100 pounds of isobutylene (an extremely flammable material);
- Manual isolation required employees to enter a flammable atmosphere, exposing them to a serious injury risk; and
- The rate and duration of the release created a danger of a fatality or serious injury [53, p. 18].[d]

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[a] Other industry standards, good practice guidance, and earlier CSB reports have described similar isolation equipment using different names, including emergency block valve (EBV), emergency isolation valve (EIV), remotely operated block valve (RBV), emergency shutdown valve (ESDV), or remotely operated shutoff valve (ROSOV).

[b] HSE says, "One of the conclusions of the Associated Octel report was that the incident escalated rapidly because it was not possible to stop the initial release" [53, p. 5, 74].

[c] HSE's report on the Grangemouth incident noted, "The control room operator was limited in the extent to which he could assist to isolate inventories remotely because many isolations could only be done manually" [97, p. 44].

[d] The fourth selection criteria applied to toxic chemical releases.

In HSG244, HSE warns, “Manual valves should **never** be used in situations where the employee effecting the isolation would be placed in danger. This is a major consideration in deciding when to use ROSOVs” [53, p. 14] (emphasis in the original). For flammable substances, HSE further says, “employees should not be required to deliberately enter a flammable atmosphere to isolate plant manually, especially as personal protective equipment (PPE), is not a practicable solution” [53, p. 14].

Among the benefits of using remote isolation, HSG244 highlights the importance of preventing vapor cloud explosions that could harm people and cause substantial property damage. HSG244 states:

> The potential for escalation is much greater for flammable substances, particularly in complex plant with significant areas of congestion due to closely spaced plant, pipework and other structures. When ignition occurs in a congested area there is an increased risk of a vapour cloud explosion. The overpressure from a vapour cloud explosion may be capable of critically damaging other plant, leading to further loss of containment and potential casualties [53, p. 14].

4.2.2 American Petroleum Institute (API) Safety Guidance

In October 2012, the API published its second edition of API Recommended Practice 553, *Refinery Valves and Accessories for Control and Safety Instrumented Systems* [54]. In API RP 553, the API notes that its safety guidance captures industry knowledge and experience and provides proven solutions to well-known problems, such as remote isolation [54, p. 1]. The API uses the term emergency block valve to describe the equipment used to isolate flammable or toxic materials remotely in the event of a leak or fire [54, p. 94]. The API recommends placing control stations for emergency block valves at least 50 to 100 feet away from the valve in a “remote manned location” (safe location) [54, p. 97].

API RP 553 states that remote isolation is “needed” for vessels containing isobutylene [54, p. 95]. For pumps, API RP 553 says that an emergency block valve is “needed” if the upstream vessel contains more than 4,000 gallons of liquid hydrocarbon and is “typically required” where the upstream vessel contains more than 2,000 gallons of light ends, such as isobutylene [54, p. 95]. At the time of the April 2, 2019, incident, KMCO’s isobutylene storage tank contained more than 29,000 gallons of liquid isobutylene. Had KMCO followed the existing safety guidance for remote isolation in API RP 553, *Refinery Valves and Accessories for Control and Safety Instrumented Systems*, the isobutylene system should have been equipped with emergency block valves.

4.2.3 CCPS Safety Guidance

In 2003, the CCPS provided guidance for remote isolation equipment in its book *Guidelines for Fire Protection in Chemical, Petrochemical, and Hydrocarbon Processing Facilities* [55]. In the book, the CCPS explains that process unit fires continue until the flow of fuel can be stopped, the fuel is consumed, or the fire is extinguished [55, p. 123]. The CCPS also provides general guidance on when to provide remote isolation capability. For example, the CCPS states:

> Equipment such as pumps, compressors, tanks, and vessels associated with large inventories of flammable gas or liquid (>5,000 gallons) should be provided with

equipment emergency isolation valves to stop the flow of material if a leak occurs [55, p. 123].

In addition, the CCPS provides a decision flowchart as an example of a tool that companies could use to decide where remote isolation equipment should be installed [55, p. 267]. As illustrated in **Figure 23**, applying this tool to KMCO's isobutylene system shows that remote isolation equipment should have been provided.

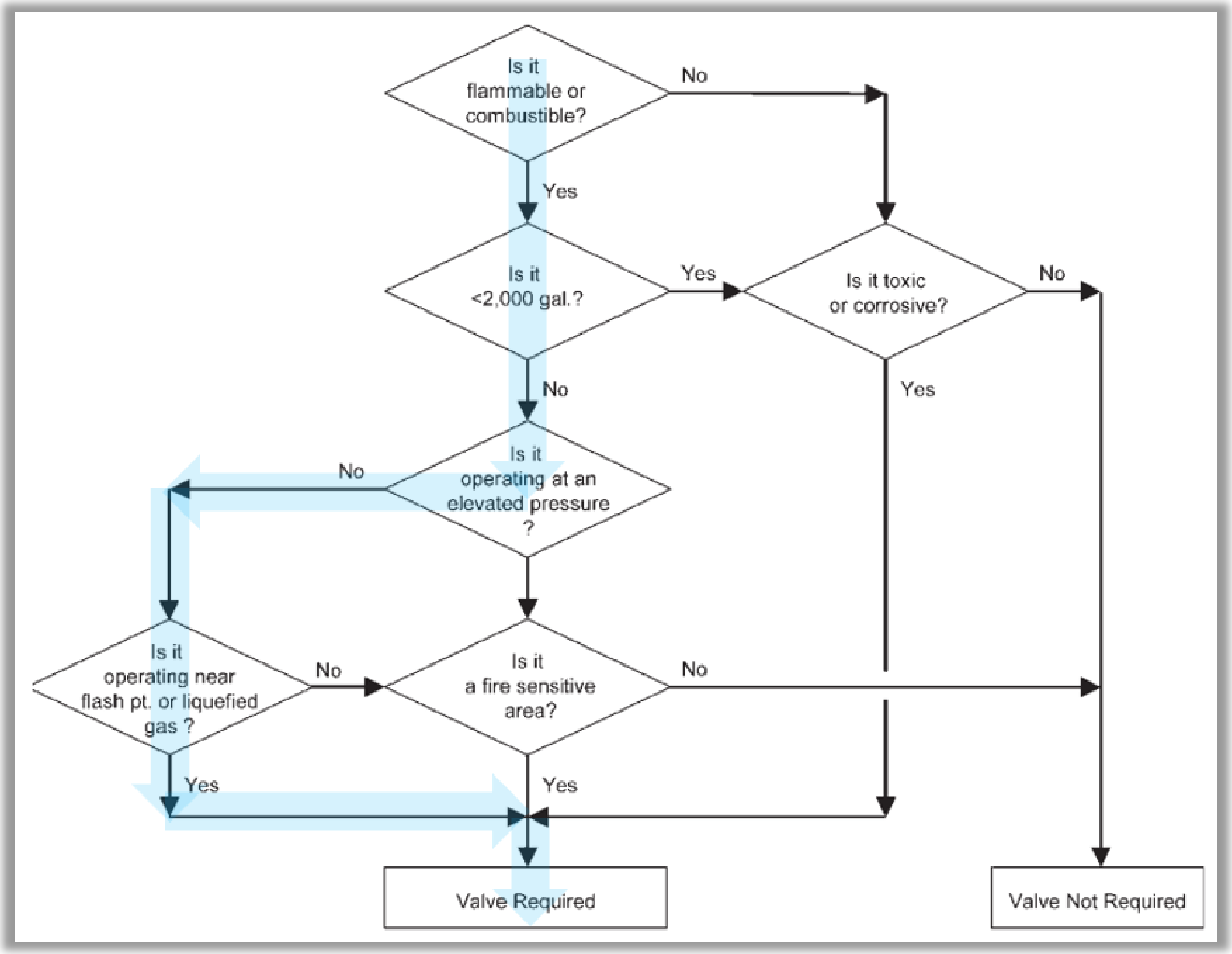

Figure 23. Remote Isolation Decision Flowchart. (Credit: CCPS, annotations by CSB)

The CSB concludes that although the need to provide workers with effective remote isolation capability has been well established by existing industry standards and good practice safety guidance documents, KMCO's isobutylene system remained unprotected. As a result, when the y-strainer ruptured on April 2, 2019, KMCO workers did not stop the isobutylene release remotely, from a safe location.[a] KMCO could have reduced the severity of its April 2, 2019, incident if the company had provided its Board Operators with the capability to remotely isolate the isobutylene release from within the blast-resistant Reaction Control Room—a safe location.

Key Lesson

The goal of keeping workers safe and the goal of quickly isolating releases to minimize the consequences of an incident should not be mutually exclusive. Both can be achieved by applying robust safety systems and establishing effective emergency response programs. Providing remotely operated emergency isolation valves in strategic locations can allow workers to stop a release quickly from a safe location.

4.2.4 2010 Insurance Recommendation

In February 2017, an engineering firm prepared a risk assessment report about the KMCO facility for insurance underwriting purposes. This report details that there was an existing recommendation from a previous insurance report in 2010 to provide remote isolation capability for certain equipment with the potential to have a spill of flammable liquid or that could result in a flammable vapor cloud, including isobutylene. The 2010 recommendation was included in the 2017 report and states:

> Expand the existing PHA program to include the analysis of the largest flammable liquid release sources and commit to the installation of fire-safe, remote-actuated automatic isolation valves in strategic process areas that will best achieve spill prevention especially those involving ethylene oxide, propylene oxide, and isobutylene that create a flammable liquid / vapor cloud spill potential due to large liquid hold-up inventories from vessels and transfer piping. Reference API 553 for additional details.
>
> Note: Once the study is completed a policy should be developed for any future installation of EIVs.
>
> **Observations & Issues**
>
> The placement of EIVs on vessels with significant hold-up inventories of hazardous materials within them would limit the amount released in an emergency thus reducing the possibility of a major incident.

The report stated that the lack of remote isolation capability has the potential for a significant incident and recommends providing remote isolation capability at the "earliest opportunity." The 2017 report indicated that KMCO had installed remote isolation valves for five vessels, but these vessels were not associated with the

[a] The isobutylene release could have been stopped from a safe location by turning off the circulation pump in the field near the isobutylene storage tank. KMCO designed the actuated on/off ball valve at the inlet to the charge pump to close automatically if the flow meter at the outlet of the circulation pump registered low flow (**Figure 3**).

April 2, 2019, incident. The status update also noted that additional EIVs were planned in the future, but the report did not specify which vessels were included in this plan.

A different company conducted an insurance assessment and produced a report in March 2018. The 2010 recommendation to provide remote isolation capability was reiterated in this 2018 report, including the status identified in the 2017 report. The 2018 report stated:

> The facility indicates that when risk and hazard reviews are conducted consideration based on risk and exposures determine whether additional EIV or interlocks shall be added for existing or new installations. It may be of benefit for KMCO/KMTEX to develop a formal procedure/policy to address where retrofit conditions, MOC or new [construction] requires the installation of EIVs.

Despite the 2010 insurance audit recommendation that KMCO use its PHA program to provide remote isolation capability for high-hazard systems, including isobutylene, neither the 2014 PHA nor the 2015 PHA included any discussion of remote isolation or recommendations to equip the isobutylene system with remote isolation valves. In addition, KMCO's PHA procedure in place at the time of the April 2, 2019, incident was last updated in October 2017. This policy did not include any requirements or guidance for KMCO's PHA teams to evaluate the need for remote isolation valves. Furthermore, the 2018 PHA team did not document any discussion or consideration about the potential need for remote isolation equipment for the isobutylene storage tank, piping, or batch reactor system.

The CSB concludes that KMCO did not complete the implementation of the 2010 insurance recommendation to provide remote isolation capability in strategic process areas, including the isobutylene system. Had KMCO fully implemented this recommendation, for example by providing remote shutoff capability for the actuated on/off ball valve installed on the charge pump's inlet piping, Board Operator 1 could have isolated the isobutylene release from a safe location—the blast-resistant Reaction Control Room. The quantity of isobutylene released and the severity of the incident could have been significantly reduced.

Although the need to provide workers with effective remote isolation equipment has been well-established, some facilities in the U.S. chemical industry remain unprotected. The CSB deployed investigation teams to four incidents in 2019. One common safety issue identified in each of the CSB investigation reports for these accidental release events is that effective remote isolation equipment could have reduced the amount of flammable material released and prevented great harm to people and neighboring communities. These incidents were:

- *Storage Tank Fire at Intercontinental Terminals Company, LLC (ITC) Terminal* in Deer Park, Texas on March 17, 2019;
- *Fatal Equipment Rupture, Explosion, and Fire at the KMCO Chemical Facility* in Crosby, Texas on April 2, 2019. (The subject of this report);
- *Fire and Explosions at Philadelphia Energy Solutions Refinery Hydrofluoric Acid Alkylation Unit* in Philadelphia, Pennsylvania on June 21, 2019; and
- *Popcorn Polymer Accumulation, Pipe Rupture, Explosions, and Fires at TPC Group Chemical Plant Butadiene Unit* in Port Neches, Texas on November 27, 2019.

Due to the frequency in which remote isolation has been identified as a safety issue in recent investigation reports, the CSB plans to develop and issue a remote isolation advocacy product in 2024.

4.3 Hazard Evaluation

Hazard evaluation is a broad topic. This term is used to describe efforts to identify and control hazards in everyday work tasks (job hazard analysis) as well as the formal multi-day efforts specifically designed to assemble a multi-disciplinary team of experts for the specific purpose of trying to locate and control potential hazards in a new process unit (process hazard analysis).

In addition, hazard evaluation is not a new process safety concept within the chemical industry. Trevor Kletz's book, *HAZOP AND HAZAN: Identifying and Assessing Process Industry Hazards*, devotes a chapter to reviewing the history of how this now-common hazard evaluation technique was developed at ICI (Imperial Chemical Industries) during the 1960s [56, 57].

OSHA considers hazard evaluation to be among the most important elements of its PSM standard.[a] According to OSHA, hazard evaluation involves an organized "effort to identify and analyze the significance of potential hazards associated with the processing or handling of highly hazardous chemicals," including isobutylene [58, p. 6412]. For processes like KMCO's isobutylene system, OSHA's PSM standard establishes the minimum requirements for preventing or minimizing catastrophic releases, including the major fire or explosion hazards from flammable chemical releases that present a danger to workers. Among these requirements, the OSHA PSM standard includes hazard evaluation requirements for the process hazard analysis (PHA), management of change (MOC), and pre-startup safety review (PSSR) elements.[b]

In its book, *Guidelines for Hazard Evaluation Procedures*, the CCPS emphasizes the importance of hazard evaluation. The CCPS states that "Hazard evaluation is the cornerstone of an organization's overall process safety management (PSM) program" [59, p. 11].[c]

This section reviews and analyzes the hazard evaluation efforts that KMCO applied to its isobutylene system between 2014 and 2018.

4.3.1 2014 PHA

On September 29, 2014, KMCO performed a PHA as part of its project to install the new isobutylene system, including the storage tank, circulation pump and piping, and charge pump and piping. This PHA identified the potential for high-pressure conditions to develop within portions of the piping from liquid thermal expansion, and also identified the need for pressure-relief valves to protect the inlet and outlet piping for the circulation

[a] 29 C.F.R. § 1910.119.

[b] 29 C.F.R. § 1910.119.

[c] The CCPS identified 10 different names (synonyms) that have been used for hazard evaluation. Some of the names have slight variations in meaning, but all of them relate back to the concept of identifying a hazard and making some assessment about its significance. These other names for "hazard evaluation" included process hazard(s) analysis, process hazard(s) review, process safety review, process risk review, predictive hazard evaluation, hazard assessment, process risk survey, hazard study, hazard and risk analysis, and hazard identification and risk analysis [59, p. 16].

pump. No thermal expansion hazards were identified for the charge pump piping, but at that time, the project's piping and instrumentation diagram (P&ID) did not include a check valve, y-strainer, or manual isolation valves on the inlet piping to the charge pump.

4.3.2 2015 PHA

In January 2015, KMCO performed a PHA of the isobutylene system that existed before the new system (shown in **Figure 3**) was commissioned. This PHA was poorly documented. For example, of the 16 nodes evaluated, only two nodes were labeled to show the part of the system that was being analyzed.[a] The PHA contained no information to support a conclusion that the team evaluated liquid thermal expansion hazards for the isobutylene piping system.

4.3.3 Isobutylene System MOC and PSSR

In its PSM standard, OSHA highlights the importance of performing a safety review before any highly hazardous chemicals like isobutylene are introduced into a process [60, p. 18].[b] To address this need for a safety review, OSHA requires employers to perform a pre-startup safety review (PSSR) for new or modified facilities (such as KMCO's new isobutylene system) when the modification is significant enough that it requires a change in the process safety information. Among other requirements, the PSSR requires a hazard evaluation (PHA), management of change (MOC), and confirmation that construction and equipment followed design specifications.[c]

On January 26, 2015, KMCO initiated its MOC documentation for the new isobutylene system project. This MOC described the reasons for installing the new system, which included:

- Relocating the isobutylene storage away from the process equipment area and increasing the isobutylene storage capacity from 20,000 gallons to 70,000 gallons;
- Providing the capability to receive isobutylene shipments from railcars instead of tank trucks, which reduced truck traffic and addressed safety concerns raised about unloading isobutylene trucks next to a hot oil furnace; and
- Increasing production capacity of its sulfurized isobutylene product.

KMCO management approved the MOC document in May 2015. Notably, the MOC package included the same piping and instrumentation diagram (P&ID) that was used in the 2014 PHA, which did not show a check valve, y-strainer, or manual isolation valves on the inlet piping to the charge pump. The P&ID showed that the isobutylene circulation piping and charge pump's inlet piping would be made from type 304 stainless steel. The MOC package also included a list of materials and their estimated cost. The construction material identified in the project materials list for piping or similar components was 304 stainless steel.

[a] The CCPS defines a node as "Sections of equipment with definite boundaries (e.g., a line between two vessels) within which process parameters are investigated for deviations. The locations on P&IDs at which the process parameters are investigated for deviations (e.g., a reactor). The concept of dividing a process into nodes for analysis is commonly, but not exclusively, used in HAZOPs" [86].

[b] 29 C.F.R. § 1910.119(i).

[c] 29 C.F.R. § 1910.119(i).

The project PSSR was initiated on September 1, 2015, and completed on October 21, 2015. One item on the PSSR checklist addressed the construction material. This item indicated that the piping system was constructed of 304 stainless steel. Nothing in the PSSR discussed the y-strainer or identified that it was not constructed from 304 stainless steel. In addition, nothing in the PSSR identified that the check valve or y-strainer had been installed in the charge pump's inlet piping.

4.3.4 Y-Strainer Cracked in 2015

"It is tragic the number of times people are harmed in accidents where earlier warning signs had been overlooked" [61, p. 120].

In 2012, the CCPS published *Recognizing Catastrophic Incident Warning Signs in the Process Industries*, a book focused on recognizing "indicators that something is wrong or about to go wrong" and taking action to prevent a major incident [62, pp. 1-3]. In the book's Introduction, the CCPS states:

> Warning signs are indicators that something is wrong or about to go wrong. When we recognize and act on these indicators, a loss may be prevented. Of course, this will only happen when we know what to look for and are willing to take the initiative to do something about it. A review of significant incidents in the process industries suggests that most if not all incidents were preceded by warning signs. Some of these signs were clearly visible but not acted upon because their significance was not understood. Other warning signs were less obvious, but observant personnel may have detected them [62, p. 1].

The y-strainer that catastrophically failed on April 2, 2019, was not the original strainer that KMCO installed for this application during the 2014–2015 isobutylene storage tank and piping project.

KMCO's incident and maintenance records show that on December 10, 2015, an operator and his trainee detected an isobutylene odor near the sulfurized isobutylene reactor system. The two workers found that the cast iron y-strainer was leaking. The operator responded to the leak by spraying the area with water to knock down the flammable vapor. The operator then called the shift supervisor and lead operator, who came out to the batch reactor system, evaluated the situation, and decided to shut down all work in the unit. KMCO workers then isolated the leaking equipment and vented the isobutylene into the flare system. After removing the isobutylene from the equipment, KMCO workers flushed the system with water and prepared it for maintenance. KMCO maintenance workers replaced the leaking y-strainer (in kind replacement) that same day.

The y-strainer that failed in December 2015 was later leak-tested with water and found to have a crack through a wall of the body in the same general area where the April 2019 strainer ruptured. KMCO did not provide the CSB with an investigation report or corrective actions that addressed the causes of the 2015 incident. Based on the equipment configuration at the time of the catastrophic y-strainer rupture in 2019, the CSB concludes that after the isobutylene system y-strainer failed in 2015, KMCO's investigation did not result in any significant changes or obvious improvements specifically intended to prevent a future y-strainer failure.

Key Lesson

Previous incidents can provide a warning sign of problems that exist in a system. Companies can prevent future incidents by effectively recognizing and acting on these earlier warnings to identify and correct the underlying issues.

4.3.5 2018 PHA

As part of the company's efforts to strengthen its safety management systems, KMCO performed a "re-do" of its isobutylene system process hazard analysis in November 2018. A re-do PHA is an approach in which the PHA revalidation is essentially a new PHA, "where the team starts from the beginning and performs the entire PHA in detail as if it were an initial PHA" [63, p. 92]. The PHA team consisted of eight members. Seven of the PHA members were KMCO employees with an average of 16 years of professional experience. The PHA was facilitated by a contractor with 42 years of professional experience.

KMCO's 2018 PHA report clearly stated that the isobutylene system was a covered process under both the OSHA PSM standard and the EPA RMP rule. In addition, this PHA clarified that the pressure-relief valve on the charge pump's outlet piping was normally aligned to relieve (discharge) back into the charge pump's inlet piping, as shown in **Figure 3**. As part of its facility siting evaluation, the PHA team documented that the R2 Building still contained electrical equipment that could ignite flammable vapors. The team identified that the doors to the R2 Building "are always closed but not tightly." The team noted that a new motor control center was being built and made no additional recommendations about this building.

KMCO's 2018 PHA did not document an analysis of the potential high-pressure scenarios that could develop in the isobutylene piping from liquid thermal expansion hazards. As a result, the two pressure-relief valves in the isobutylene circulation piping, installed following the project hazard evaluation in 2014, were not identified as safeguards. In addition, the 2018 PHA documentation did not specifically discuss the potential for liquid thermal expansion to occur in the charge pump's inlet piping.

Furthermore, the 2018 PHA used a P&ID that showed the charge pump's inlet piping was constructed from stainless steel. The CSB did not identify any information in the PHA documentation indicating that the y-strainer material of construction was cast iron or that the strainer was made from a different material than the 304 stainless steel piping.

4.3.6 KMCO's Hazard Evaluations

Warning signs are indicators that something is wrong or may soon go wrong. KMCO's 2018 PHA team did not evaluate the incident on December 10, 2015, in which a crack developed in the body of the y-strainer, releasing isobutylene. The 2018 PHA report stated: “Previous incidents and near misses for the [isobutylene system] since 2016 were discussed by the PHA team.” The report did not elaborate or otherwise explain why the incidents or near misses from 2015 were not reviewed. Because the 2015 PHA was conducted in January 2015, the 2015 PHA team could not have included a review of the failed y-strainer event on December 10, 2015, because that event had not yet happened.

The CSB concludes that KMCO’s y-strainer failure in 2015 should have served as a warning sign of the potential for liquid thermal expansion or other high-pressure scenarios within the charge pump’s inlet piping. Had KMCO effectively recognized and acted on this earlier warning through an incident investigation or PHA revalidation, the company could have taken corrective actions that may have prevented the April 2, 2019, incident.

Of all the hazard evaluations KMCO performed for its isobutylene system, only the hazard evaluation carried out for the isobutylene system project in 2014 documented an evaluation of liquid thermal expansion hazards for the isobutylene piping, and that study used an engineering drawing for the charge pump piping that did not include the check valve, the y-strainer, or manual isolation valves. The full history of the isobutylene system hazard evaluations shows that KMCO never identified or controlled the potential for liquid thermal expansion to develop high-pressure conditions within the charge pump’s inlet piping.

The CSB concludes that KMCO never protected the charge pump’s inlet piping from liquid thermal expansion or high-pressure conditions that could develop from other potential scenarios that could have weakened or otherwise damaged the cast iron y-strainer.

PHA teams rely on process safety information such as P&IDs during review meetings. For example, in its book *Guidelines for Revalidating a Process Hazard Analysis*, the CCPS states: “P&IDs serve as the ‘road map’ for study sessions” [63, p. 115]. The CSB found that none of the KMCO hazard evaluations included any specific discussion, mention, or reference about the cast iron y-strainer installed in the inlet piping to the charge pump. KMCO’s P&IDs did not specifically identify that this y-strainer was constructed from cast iron. In fact, these drawings indicated that the y-strainer’s construction material was stainless steel. KMCO had two different P&IDs that showed the charge pump and the y-strainer. One of these P&IDs showed “SS,” a common abbreviation for stainless steel, directly above the y-strainer symbol. The second P&ID identified the charge pump’s inlet piping as being 3-inch, schedule 40 stainless steel piping with 300-lb flanges, using the abbreviation 3”-SS-300#SCH 40. Since the P&ID did not indicate a piping specification break at the y-strainer, a reviewer of this drawing would likely conclude that the y-strainer material of construction was stainless steel.

In its *Guidelines for Hazard Evaluation Procedures* book, the CCPS explained that performing a successful hazard evaluation requires the study team to have access to accurate information, such as P&IDs. The CCPS stated:

> Hazard evaluations are based on existing knowledge of a process or operation. If the process chemistry is not well known, if the relevant drawings or procedures are not accurate, or if the process knowledge available from a study team does not reflect the way the system is actually operated, then the results of a hazard evaluation may be invalid [59, p. 13].

The CSB concludes that KMCO's hazard evaluations consistently overlooked or misunderstood the hazards introduced when the cast iron y-strainer was added to the charge pump's inlet piping. Most of KMCO's hazard evaluations used drawings that did not include the y-strainer, and although the 2018 re-do PHA used drawings showing the y-strainer, these drawings showed it to be made from stainless steel. Had any of these previous hazard evaluations identified that the y-strainer was constructed from cast iron and recognized that good practice safety guidance either prohibited or warned against using cast iron in hazardous applications, including flammable hydrocarbons such as isobutylene, KMCO might have installed a y-strainer made from a ductile material, which could have reduced the severity of the incident and may have prevented it.

5 Conclusions

5.1 Findings

Technical Analysis

1. The cast iron y-strainer that catastrophically failed on April 2, 2019, ruptured from a brittle overload fracture driven by internal pressure.

2. Existing industry standards and good practice safety guidance show that cast iron is a brittle material that should not have been used for an application such as KMCO's liquid isobutylene piping system.

3. The most likely source of pressure contributing to the y-strainer failure was liquid isobutylene thermal expansion that might have periodically occurred within the charge pump's inlet piping, which was not equipped with a pressure-relief device or otherwise protected from high-pressure conditions.

4. Although a number of potential sources of ignition existed in the area of the isobutylene release, the source of ignition that triggered the isobutylene explosion was most likely located within the R2 Building.

Emergency Response

5. KMCO never activated its facility alarm system to notify all workers about the isobutylene release emergency. As a result, some injured workers were nearer to the explosion than they should have been. KMCO could have reduced the severity of the event by using its facility alarm system to notify all workers of the isobutylene release emergency and communicate the evacuation order.

6. KMCO's emergency response system, including its procedures and training, contributed to the severity of the incident. KMCO did not establish procedures or provide training that effectively distinguished the incidents that its operators should respond to from the emergency events that the site's emergency response team must respond to. As a result of KMCO's emergency response program, the emergency actions taken by KMCO operations staff to stop the isobutylene release adhered to the unwritten culture at KMCO that relied on unit operators taking quick actions to stop a chemical release. When the isobutylene release began, workers who were in a safe location moved toward the isobutylene vapor cloud, which put them in harm's way. KMCO could have reduced the severity of the event by establishing clear policies and training its workforce to respond to a chemical release without putting themselves in harm's way.

Remote Isolation

7. Although the need to provide workers with effective remote isolation capability has been well established by existing industry standards and good practice safety guidance documents, KMCO's isobutylene system remained unprotected. As a result, when the y-strainer ruptured on April 2, 2019, KMCO workers did not stop the isobutylene release remotely, from a safe location. KMCO could have reduced the severity of its April 2, 2019, incident if the company had provided its Board Operators with the capability to remotely isolate the isobutylene release from within the blast-resistant Reaction Control Room—a safe location.

8. KMCO did not complete the implementation of the 2010 insurance recommendation to provide remote isolation capability in strategic process areas, including the isobutylene system. Had KMCO fully implemented this recommendation, for example by providing remote shutoff capability for the actuated on/off ball valve installed on the charge pump's inlet piping, Board Operator 1 could have isolated the isobutylene release from a safe location—the blast-resistant Reaction Control Room. The quantity of isobutylene released and the severity of the incident could have been significantly reduced.

Hazard Evaluation

9. After the isobutylene system y-strainer failed in 2015, KMCO's investigation did not result in any significant changes or obvious improvements specifically intended to prevent a future y-strainer failure.

10. KMCO's y-strainer failure in 2015 should have served as a warning sign of the potential for liquid thermal expansion or other high-pressure scenarios within the charge pump's inlet piping. Had KMCO effectively recognized and acted on this earlier warning through an incident investigation or PHA revalidation, the company could have taken corrective actions that may have prevented the April 2, 2019, incident.

11. KMCO never protected the charge pump's inlet piping from liquid thermal expansion or high-pressure conditions that could develop from other potential scenarios that could have weakened or otherwise damaged the cast iron y-strainer.

12. KMCO's hazard evaluations consistently overlooked or misunderstood the hazards introduced when the cast iron y-strainer was added to the charge pump's inlet piping. Most of KMCO's hazard evaluations used drawings that did not include the y-strainer, and although the 2018 re-do PHA used drawings showing the y-strainer, these drawings showed it to be made from stainless steel. Had any of these previous hazard evaluations identified that the y-strainer was constructed from cast iron and recognized that good practice safety guidance either prohibited or warned against using cast iron in hazardous applications, including flammable hydrocarbons such as isobutylene, KMCO might have installed a y-strainer made from a ductile material, which could have reduced the severity of the incident and may have prevented it.

5.2 Cause

The CSB determined that the cause of the isobutylene release was a brittle overload fracture of the cast iron y-strainer driven by internal pressure. The y-strainer was installed in a segment of the isobutylene piping that was not protected from the high-pressure conditions that developed within this equipment, most likely from liquid thermal expansion. The isobutylene vapor cloud was most likely ignited by electrical equipment within a poorly sealed, nearby building.

KMCO's hazard evaluation programs, including process hazard analysis, pre-startup safety review, and management of change, also contributed to the incident. KMCO's hazard evaluations consistently overlooked or misunderstood that its y-strainer was made from cast iron, a brittle material that existing industry standards and good practice guidance documents either prohibit or warn against using in hazardous applications, such as the company's isobutylene system. In addition, none of KMCO's hazard evaluations identified the potential for liquid thermal expansion or other possible scenarios to develop high-pressure conditions within the piping system that included the y-strainer. As a result, unlike other portions of KMCO's isobutylene piping, this piping section was not equipped with a pressure-relief device to protect it from potential high-pressure conditions.

KMCO did not provide safety equipment that its workers could have used to remotely stop (isolate) the isobutylene release from a safe location, which contributed to the severity of the incident. Deficiencies in KMCO's emergency response system, including its procedures and training, also contributed to the severity of the incident by not effectively distinguishing which events its operators should handle from those incidents that the site's emergency response team must respond to. Because KMCO relied on its unit operators to take quick actions to stop chemical releases, workers who were in a safe location moved toward the flammable isobutylene vapor cloud, which put them in harm's way. KMCO could have reduced the severity of the event by establishing clear policies and training its workforce to respond to a chemical release without putting themselves in harm's way.

6 Recommendations

Following its April 2, 2019, incident, KMCO filed for bankruptcy, and the company is no longer in business. Altivia Oxide Chemicals, LLC (Altivia) purchased the Crosby, Texas, facility in 2020 and informed the CSB that the process involved in the incident would be dismantled as part of Altivia's efforts to install two new oxide reactors and start production by the end of 2020. As a result, the CSB is not issuing recommendations with this report.

Nevertheless, the CSB urges Altivia to read this report closely and understand the factors that led to the incident at the KMCO facility and the lessons stemming from it. Moreover, if hereafter Altivia reinitiates the process or any equipment involved in this incident, the company should ensure that the facts, conditions, and circumstances that caused the incident—and contributed to its severity—are not repeated.

7 Key Lessons

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. Cast iron is widely recognized as a brittle material that should not be used in hazardous applications, including applications that involve flammable or toxic chemicals.

2. Piping systems should be equipped with protection from high-pressure conditions, where liquid thermal expansion or other scenarios can create a hazard. For example, API 521 recommends installing a pressure-relief device if liquid thermal expansion is a credible hazard.

3. Reliable facility alarm systems can help ensure effective emergency communication to alert people of danger and inform them of what actions are needed to protect life and health.

4. Where remote isolation is not provided or is otherwise not available, clear policies and effective training are needed to help ensure that workers do not put themselves in danger to stop a chemical release.

5. Emergency response plans, including procedures and training, need to effectively distinguish between incidents that plant workers should respond to and emergency events that must be handled by a qualified emergency response team.

6. The goal of keeping workers safe and the goal of quickly isolating releases to minimize the consequences of an incident should not be mutually exclusive. Both can be achieved by applying robust safety systems and establishing effective emergency response programs. Providing remotely operated emergency isolation valves in strategic locations can allow workers to stop a release quickly from a safe location.

7. Previous incidents can provide a warning sign of problems that exist in a system. Companies can prevent future incidents by effectively recognizing and acting on these earlier warnings to identify and correct the underlying issues.

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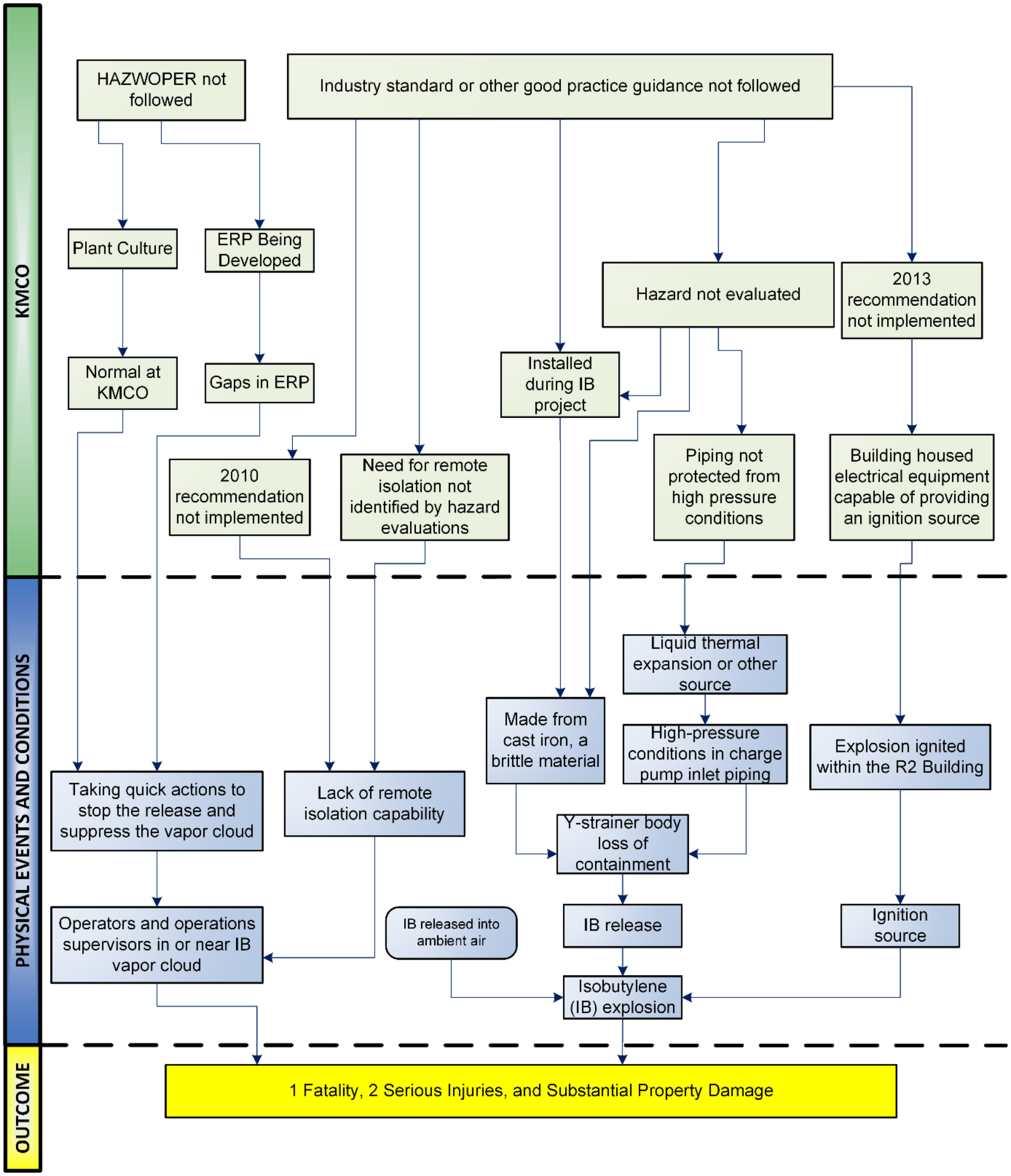
Appendix A: Simplified Causal Analysis



Appendix B: Timeline of Key Events

- 1975, Arthur McFerrin started KMCO, LP in Crosby, Texas [64].[a]
- 2012, KMCO, LLC (owned by ORG Chemical Holdings) purchased the Crosby, Texas facility.
- 2014–2015, KMCO replaced its isobutylene storage tank and piping system.
- September 29, 2014, KMCO PHA for the isobutylene system project.
- January 21, 2015, KMCO PHA for the previous isobutylene system.
- October 2015, KMCO completed its MOC and PSSR for the isobutylene system project.
- December 10, 2015, the y-strainer leaked (crack in the body) and was replaced.
- January 2017, KMCO audited its process safety management systems.
- November 5–8, 2018, KMCO re-do of PHA for the new isobutylene system.
- April 2, 2019, at 6:25 a.m. (control system: 6:25:03), batch reactor isobutylene charge completed.
- April 2, 2019, at 10:41 a.m. (control system: 10:40:43), the y-strainer ruptured, releasing isobutylene. The y-strainer ruptured about 4 hours and 16 minutes after the isobutylene charge was completed.
- April 2, 2019, at 10:45 a.m. (control system: 10:45:28 (calculation) | Video 10:44:21 (estimate)), Board Operator 1 makes a radio call to evacuate from the reaction area.[b]
- April 2, 2019, at about 10:46 a.m. (control system: 10:46:08), manual valves were closed to stop the isobutylene release. About 10,000 pounds of isobutylene were released in 5 minutes and 25 seconds.
- April 2, 2019, at 10:47 a.m. (control system: 10:46:52 (calculation) | Video 10:45:45 (estimate)), the Shift Supervisor made a radio call ordering a plant evacuation.
- April 2, 2019, at 10:51 a.m. (control system: 10:51:28 | Video: 10:50:21), the isobutylene vapor cloud ignited and exploded. The explosion occurred about 10 minutes and 45 seconds after the y-strainer ruptured and 5 minutes and 20 seconds after the isobutylene release was stopped.
- April 2, 2019, at 10:54 a.m., (control system: 10:54:12 (calculation) | Video: 10:53:05) three minutes after the explosion, the first member of KMCO's ERT was wearing their protective gear and headed toward the unit.
- May 8, 2020, KMCO filed for bankruptcy under Chapter 7 of the U.S. Bankruptcy Code.
- May 29, 2020, Crosby, Texas, facility sold to Altivia Oxide Chemicals, LLC.

[a] Former Student Spotlight Arthur "Artie" McFerrin Jr. [96].

[b] Surveillance video estimates are based on witness interviews describing key people being in an office or conference room, hearing the radio call, and then leaving the office or conference room to take some action. The video shows when they left the office or conference room. The estimate is that the plant radio call occurred five seconds before they appeared in the video. The time difference between the control system and the video is about 67 seconds and is based on the visible shaking of the video image and the loss of key data signals within the control system.

Appendix C: Surrounding Area Demographics

Figure 24 shows the census blocks within one mile of the KMCO facility. The census information for the blocks shown in **Figure 24** is presented in **Table 2**.

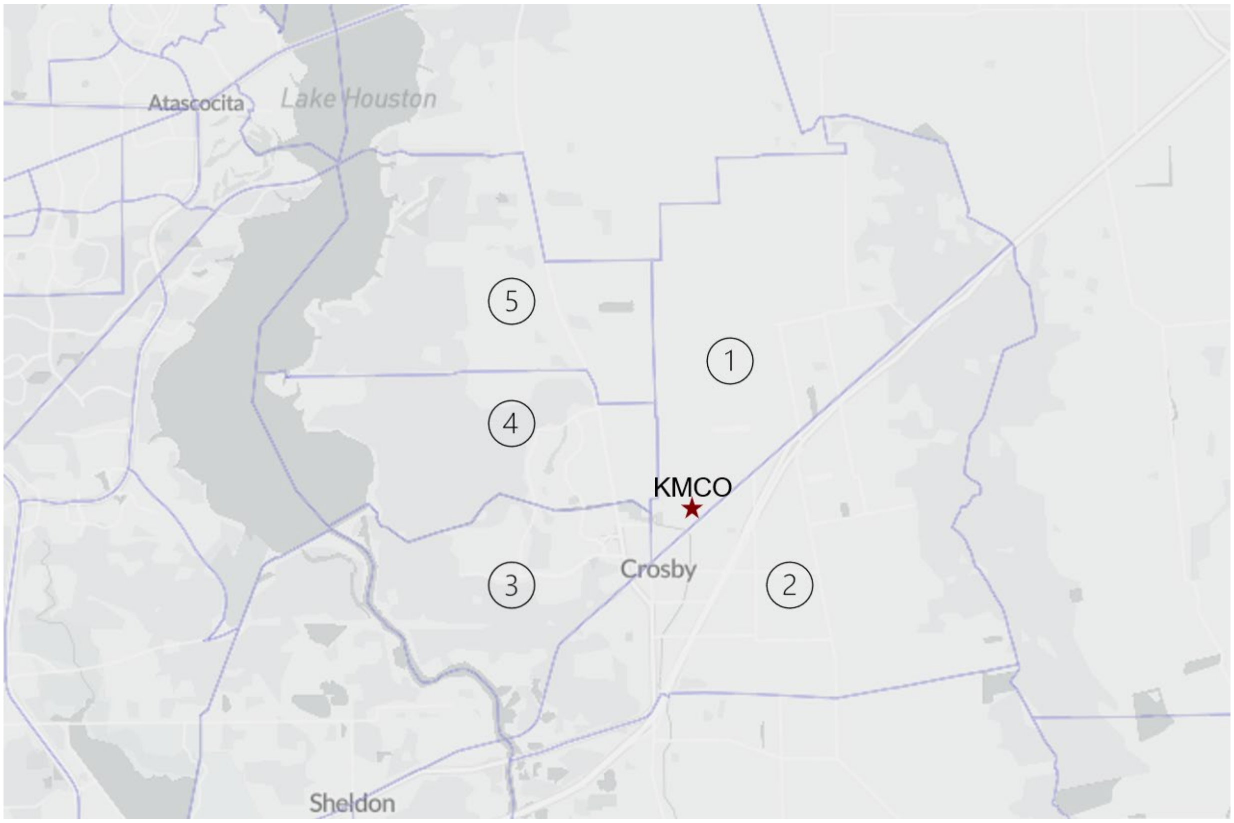


Figure 24. Census Blocks Near KMCO Facility. (Credit: Census Reporter, annotations by CSB)

Table 2. Demographic Data for the **Figure 24** Census Blocks.[a] (Credit: CSB, using Census Reporter Data)

Tract Number	Population	Median Age	Race and Ethnicity		Per Capita Income ($)	% Persons Below Poverty Line	Number of Housing Units	Number of Housing Units By Type	
1	1,724	42.8	1,257	White	35,781	7.4	755	502	Single Unit
			51	Black				23	Multi-Unit
			0	Native				221	Mobile Home
			7	Asian				9	Boat, RV, van, etc.
			3	Islander					
			0	Other					
			33	Two+					
			373	Hispanic					
2	3,863	41.8	1,965	White	31,809	10.2	1,916	1,228	Single Unit
			576	Black				384	Multi-Unit
			0	Native				304	Mobile Home
			83	Asian				0	Boat, RV, van, etc.
			0	Islander					
			0	Other					
			0	Two+					
			1,239	Hispanic					
3	6,969	38.6	4,860	White	40,571	2.2	2,327	2,185	Single Unit
			370	Black				90	Multi-Unit
			197	Native				52	Mobile Home
			103	Asian				0	Boat, RV, van, etc.
			0	Islander					
			16	Other					
			118	Two+					
			1,305	Hispanic					
4	7,235	31	4,992	White	32,996	4.8	2,262	2,262	Single Unit
			284	Black				0	Multi-Unit
			22	Native				0	Mobile Home
			25	Asian				0	Boat, RV, van, etc.
			0	Islander					
			0	Other					
			276	Two+					
			1,636	Hispanic					
5	4,201	43.2	2,831	White	40,291	4.5	1,924	1,716	Single Unit
			0	Black				5	Multi-Unit
			28	Native				203	Mobile Home
			12	Asian				0	Boat, RV, van, etc.
			0	Islander					
			0	Other					
			165	Two+					
			1,165	Hispanic					

[a] This information was compiled using 2020 Census data as presented by Census Reporter [82]. "Census Reporter is an independent project to make data from the American Community Survey (ACS) easier to use. [It is] unaffiliated with the U.S. Census Bureau. A News Challenge grant from the Knight Foundation funded the initial build-out of the site. … Support for [Census Reporter's] 2020 Decennial Census features was provided by the Google News Initiative. … [T]he Medill School of Journalism at Northwestern University, home of the Knight Lab, … provides in-kind support for some of Census Reporter's ongoing development. Most of [Census Reporter's] server hosting infrastructure is … provided by the Oregon State University Open Source Lab" [83].

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